Razvoj rješenja za rukovanje i oblikovanje žičanih snopova

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MASTER THESIS

DEVELOPMENT OF A SOLUTION FOR HANDLING AND FORMING OF WIRE BUNDLES

RAZVOJ RJEŠENJA ZA RUKOVANJE I OBLIKOVANJE ŽIČANIH SNOPOVA

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I declare that I wrote this thesis independently, using the knowledge I gained through my studies and the cited references.

Hereby I would like to thank to Volker Henrichs and Daniel Gremmel from the company Robert Bosch GmbH for the trust they showed me by giving me this task and support they provided during the task execution. I would like to thank Junhan Feng for help in conducting the experiments as well as all other colleagues from the company Robert Bosch GmbH who supported me both morally and with useful advice. I would like to thank my mentor prof. Nenad Bojčetić for leading me through the work and all the professors of the Faculty of Mechanical Engineering who put their effort to transfer me their knowledge.

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Petra Močibov

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Naslov rada na hrvatskom jeziku: **RAZVOJ RJEŠENJA ZA RUKOVANJE I OBLIKOVANJE ŽIČANIH SNOPOVA**

Naslov rada na engleskom jeziku: **DEVELOPMENT OF SOLUTION FOR HANDLING AND FORMING OF WIRE BUNDLES**

Opis zadatka:

In the production of stators of electrical motors, several production steps, which include handling and forming of wire bundles after the winding, are still done manually. In order to enhance the process, a part of manual work should be automated. For electrical motors with a stator winding and a power range from 20 to 100 kW, the solution to handle and form a wire bundle has to be independent from the specific stator type and from the number of wire bundles. At the same time the solution has to be adjustable in order to form the wire bundle around different specified radii and around different specified angles (considering the elasticity of the material).

The thesis should contain:

- Definition of the range of size of wire bundles that need to be handled and formed.
- Definition of the range of shape of wire bundles that should be possible to achieve.
- Analysis of experimental results of wire bundle handling and forming.
- Concepts of alternative approaches, their evaluation and the choice of the most appropriate one.
- Detailed concept and related CAD models.
- Technical drawings in a range that will be defined during the work.

The thesis will be done in cooperation with the company Robert Bosch GmbH using their equipment and experimental results.

In the thesis all the used references need to be cited as well as the obtained help.

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Symbol	Unit	Description
A	-	Start point for forming a bundle; Fixed bundle end
A	mm^2	Area of cross section
a	mm	Length of a side of a polygon
B	-	End point for forming a curved part of a bundle; Start point for forming a straight part of a bundle
D_b	mm	Diameter of a wire bundle
d_h	mm	Inner diameter of a winding head
D_h	mm	Outer diameter of a winding head
d_s	mm	Inner diameter of a stator package
D_s	mm	Outer diameter of a stator package
D_t	mm	Diameter of a forming tool
d_w	mm	Diameter of a single wire
e	mm	Distance
F	N	Force
h_{hn}	mm	Height of a winding head (not formed)
h_{hp}	mm	Height of a winding head (preformed)
I	mm^4	Cross sectional moment of inertia
i	-	Counter
j	-	Counter
l_b	mm	Length of a wire bundle in initial position
l_p	mm	Length of the straight part of a bundle for phase outputs
l_s	mm	Length of the straight part of a bundle for star-point forming
M	Nm	Moment
n	-	Number fo sides of a polygon
n_b	-	Number of wire bundles
n_c	-	Number of collection points
n_p	-	Number of bundles that need to be collected in one phase
n_s	-	Number of bundles that need to be collected to form one star point
n_w	-	Number of wires in a wire bundle
R_h	mm	Mean radius of a winding head
r_i	mm	Radial distance of any point of a formed wire bundle
R_t	mm	Radius of a forming tool

T	Nm	Torque
t	mm	Tolerance field
w_b	mm	Width of a wire bundle
w_h	mm	Width of a winding head
α_0	°	Angular dispplacement of a position of a first wire bundle
α_b	°	Angular position of a wire bundle
α_c	°	Angular position of a collection point
α_i	°	Angle defining a length of a curved part of a bundle
α	°	Angle
η	-	Efficiency
σ	N/mm^2	Stress
τ	N/mm^2	Shear stress

Index	**Description**
b	Wire bundle
c	Collection point
c	Cylinder
f	Bending
h	Winding head
max	Maximum
min	Minimum
mot	Motor
p	Phase
s	Stator package; Star-point
t	Tool
w	Single wire
x	Coordinate system direction x
y	Coordinate system direction y
Y	Yield
z	Coordinate system direction z

SUMMARY

When winding of a stator is done by the process of inserting coils, extended ends of pre-winded coils stay not inserted in the slots of stator package, thus creating wire bundles. In further steps of serial production wire bundles need to be formed around the winding head and collected in pre-defined collection points in order to be connected together to form phase outputs and star-points. In an existing production line, it is noticed that the manual forming of wire bundles is one of the line's bottlenecks. For that reason, there is a wish to automate the wire bundle forming process.

According to combined systems engineering and engineering design approach, through the analysis of the given problem, wire bundle forming system is decomposed into several subsystems that can be developed separately. Hereby, the focus of the work is set to planar forming of the curved part of a bundle and implicit requirements of the system are detected. As a first step of a solution search, an overview of existing solutions to similar problems of wire, pipe and sheet metal bending is given. In addition, theoretical information about mechanical properties of enamelled copper wire and springback are provided.

To build a concept for planar forming of wire bundles, a bottom-up approach is chosen. *Deforming of wire bundle* is identified as a core function, therefore it is investigated through systematic solution search as well as experimental validation. In the next step, the most appropriate forming methods are extended with additional functions considering *gripping the bundle* and *handling the bundle until the collection point is reached*. Alternative solutions are then combined and nine concepts for planar forming procedure are developed. After concept evaluation, as the last step, technical realisation of the highest rated concept is further developed more into a detail. In the end, next steps are explained that are required in order to prepare the given solution for implementation in the production line.

Key words: systems engineering, concept development, concept selection, metal forming methods, springback, wire bundle forming

PROŠIRENI SAŽETAK

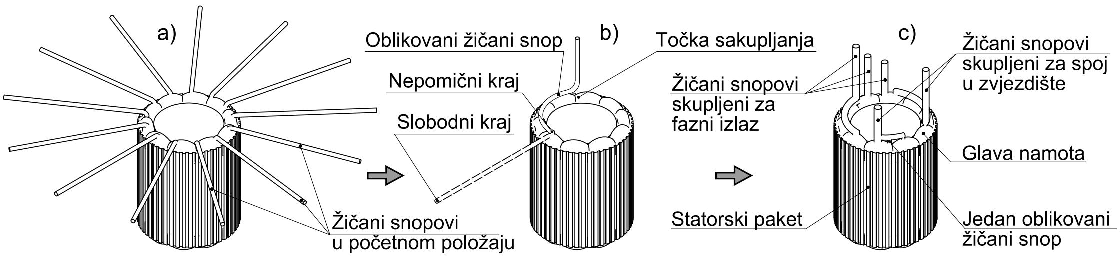
U serijskoj proizvodnji statora elektromotora, potreba za oblikovanjem žičanih snopova javlja se kada se za namotavanje statora koristi metoda umetanja prethodno pripremljenih svitaka. Jedan od primjera proizvodne linije statora ima ciljanu proizvodnju od sto tisuća statora godišnje s taktom proizvodnje od tri minute. Da bi se postigao željeni takt, potrebno je nekoliko manualnih radnika koji istovremeno ručno oblikuju snopove žica što predstavlja usko grlo u proizvodnji. Iz tog se razloga javlja ne samo želja već i potreba za automatizacijom procesa oblikovanja.

1. Uvod

Sljedeća slika prikazuje dio proizvodne linije statora s radnim postajama od pojave žičanih snopova u procesu proizvodnje do njihova preoblikovanja u fazne izlaze i zvjezdišta te konačnog oblikovanja glave namotaja.

Slika 1. Dio proizvodne linije statora

Snopovi žica pojavljuju se nakon *namotavanja* statora električnog motora umetanjem prethodno pripremljenih svitaka u utore statorskog paketa. Budući da se za oblikovanje višefaznog namotaja pojedini krajevi svitaka moraju naknadno spojiti u fazne izlaze i zvjezdišta, krajevi svitaka, po završetku umetanja, zaostaju izvan utora statorskog paketa. Za elektromotore snage između 20 kW i 100 kW sa statorskim višefaznim namotajem i opisanim načinom namotavanja, u pripremi svitaka se, umjesto žica većeg promjera, koriste snopovi tanjih izoliranih bakrenih žica s optimiranim omjerom broja žica i njihove veličine. Iz tog se razloga krajevi svitaka, koji ostaju izvan statorskog paketa, nalaze u formi žičanih snopova koje je u sljedećim koracima proizvodnje potrebno *oblikovati* povrh glave namotaja, duž dijela opsega glave do točke sakupljanja s drugim snopovima (Slika 2.b). Kada su svi snopovi oblikovani i skupljeni u željenim točkama, stator se prenosi na sljedeću radnu postaju gdje se snopovi skraćuju na potrebnu duljinu i *spajaju u fazne izlaze i zvjezdišta*. Slika 2.c prikazuje primjer statora s tri fazna izlaza i dva kraja za spajanje u zvjezdište po završetku oblikovanja žičanih snopova. Za redukciju visine glave namotaja, u sljedećem se procesu vrši *oblikovanje* *glave namotaja* pritiskom. Ovaj postupak dodatno učvršćuje zakrivljene dijelove oblikovanih žičanih snopova kao i pregibe u točkama sakupljanja. Jedna od mogućih proizvodnih operacija u proizvodnim linijama ovakvog tipa jest *predoblikovanje glave namotaja* nakon procesa umetanja, a prije procesa oblikovanja snopova (Slika 1.). Ovaj dodatni proces rezultira boljim učvršćivanjem nepomičnih krajeva žičanih snopova u glavi namotaja te time bolje definira relativan položaj nepomičnog kraja snopa u odnosu na širinu i visinu glave.

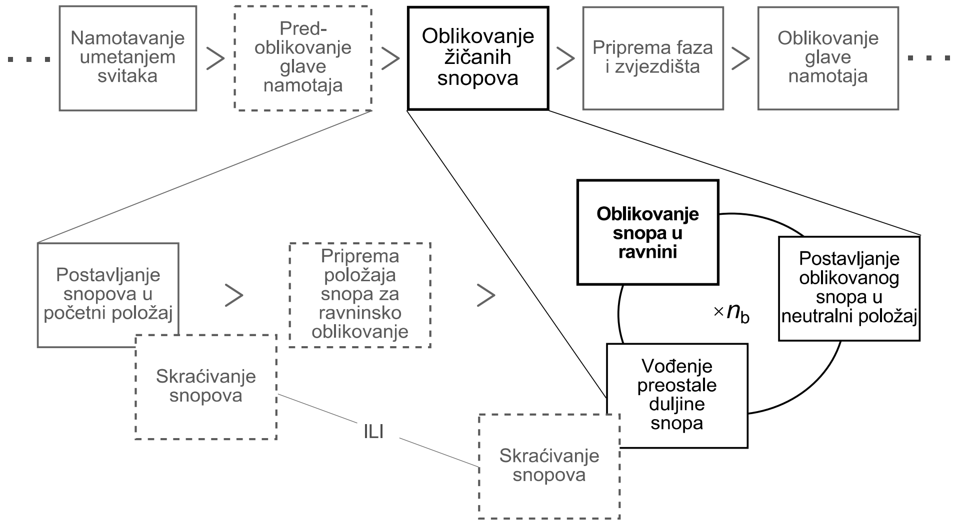


Slika 2. Proces oblikovanja žičanih snopova

Automatizirano rješenje za oblikovanje snopova žica treba pružati mogućnost podešavanja za oblikovanje različitih varijanti statora što podrazumijeva promjenjivost: dimenzija glave namotaja, dimenzija statorskog paketa, dimenzija žičanih snopova u vidu broja i promjera pojedinačnih žica, broja i duljine žičanih snopova kako i broja faznih izlaza i zvjezdišta, što se reflektira u broju i položaju točaka sakupljanja.

2. Analiza problema

Prema sustavnom [39] i inženjerskom [6] pristupu razvoju proizvoda, problem oblikovanja žičanih snopova rastavljen je na manje probleme koji se mogu razmatrati i rješavati zasebno: (a) ravninsko oblikovanje žičanih snopova, (b) vođenje preostale duljine snopa te (c) postavljanje oblikovanog snopa u neutralni položaj. Sljedeća slika ilustrira podjelu sustava za oblikovanje snopova kao i dodatne prilagodbe proizvodne linije koje utječu na rad istog. Ne bi li se osigurala visoka zahtijevana fleksibilnost sustava, rješenje se ograničava na oblikovanje jednog po jednog snopa žica što znači da se navedene tri operacije sustava izvode za svaki stator onoliko puta koliki je broj žičanih snopova n_b. Dok je *Postavljanje snopova u početni položaj* nužan preduvjet za ponovljivost operacija sustava za oblikovanje snopova, *Skraćivanje snopova* na točnu duljinu potrebnu za oblikovanje pomaže pri *Vođenju preostale duljine snopa*. Budući da su nakon procesa umetanja snopovi žica dulji no što je potrebno, operacija skraćivanja može se izvršiti posve neovisno, kombinirano s postavljanjem u početni položaj ili kombinirano s vođenjem duljine snopa. Kod različitih varijanti statora, moguće je da položaji nepomičnih krajeve žičanih snopova variraju u odnosu na glavu namotaja toliko da se, bez redefiniranja nepomičnog kraja snopa, razvijeno rješenje za ravninsko oblikovanje ne može primijeniti. U tom je slučaju potrebno uvesti dodatnu operaciju *Pripreme položaja snopa za ravninsko oblikovanje*.



Slika 3. Prilagođena proizvodna linija

Unatoč opsežnosti cjelokupnog problema oblikovanja žičanih snopova, ovaj se rad koncentrira na traženje rješenja za ravninsko oblikovanje zakrivljenog dijela snopa koji se polaže na glavu namotaja. Sve ostale dodatne operacije trebaju se razviti naknadno uzimajući u obzir specifične zahtjeve pronađenog rješenja za ravninsko oblikovanje. Za oblikovanje svakog snopa žica jednog statora pretpostavlja se poznavanje položaja nepomičnog kraja te položaja točke sakupljanja za taj snop (Slika 2.b). Položaji točaka sakupljanja za svaku fazu elektromotora kao i za svako zvjezdište, prethodno su definirani konstrukcijom elektromotora i shemom polaganja. Istom shemom je definirano i koji se snopovi žica trebaju međusobno spojiti. Iz toga slijedi da se, za svaki pojedinačni snop žica, unaprijed može odrediti kolika je duljina snopa potrebna za oblikovanje zakrivljenog dijela snopa. Pritom se za polaganje snopova koristi uvijek kraći put od nepomičnog kraja snopa do točke sakupljanja, što znači da zakrivljeni dio snopa nikada nije dulji od polovine opsega kružnice sa srednjim polumjerom glave namotaja. Za polaganje snopa žica duž glave namotaja dozvoljeno je koristiti gotovo cijelu širinu glave. Za sigurnost, uzima se da je tolerancijsko polje približno 90% širine glave. Usporedba širina glava namotaja za različite varijante statora, iz zadanog opsega, pokazuje da su varijantne širine dovoljno slične da se tolerancijsko polje za oblikovanje snopa može uzeti jednakim za sve varijante Budući da se tako smanjuje broj parametara sustava, širina tolerancijskog polja *t* uzeta je prema minimalnoj širini glave koja se pojavljuje u različitim varijantama statora te iznos 24 mm za sve varijante statora. Budući da se svaki dio snopa može položiti bilo gdje unutar tolerancijskog polja, moguće je oblikovati snop ne samo u približan oblik kružnog luka već i u oblik dijela mnogokuta čime se područje traženja rješenja proširuje. Kada govorimo o oblikovanju u oblik mnogokuta, moguće je razlučiti dva pristupa: (a) kada odabrani mnogokut ima minimalan broj stranica i (b) kada je duljina stranice mnogokuta konstantna. U slučaju (a) se traži mnogokut s najmanjim mogućim brojem stranica tako da su sve stranice, uzimajući u obzir i debljinu žičanog snopa, unutar tolerancijskog polja za oblikovanje. Za određenu potrebnu duljinu oblikovanja snopa koristi se tada jedan dio mnogokuta čak i u slučaju da se ne koristi cijela stranica. U pristupu (b) predlaže se traženje mnogokuta s takvom duljinom stranice da se za oblikovanje svih žičanih snopova jednog statora može koristiti cijeli broj stranica mnogokuta. Budući da je u tom slučaju moguće da se točka sakupljanja premaši ili ne dostigne, potrebno je odrediti takav broj stranica da je odstupanje od egzaktnog položaja točke sakupljanja unutar dozvoljenog područja. Dodatno je prilikom oblikovanja bilo kojeg od navedenih oblika potrebno obratiti pažnju na promjenjivost poprečnog presjeka snopa žica. Budući da nema elemenata koji bi osiguravali oblik snopa, međusobni položaj žica u snopu nije konstantan cijelom dužinom snopa što rezultira ujedno i nejednolikom vanjskom dimenzijom poprečnog presjeka.

3. Analiza stanja

U prvom koraku analize stanja pretražena su postojeća rješenja za probleme slične oblikovanju žičanih snopova. Kao slični problemi mogu se izdvojiti oblikovanje žica, oblikovanje cijevi te oblikovanje limova. Kao relevantni izvor informacija za navedene probleme pretražene su standardne metode oblikovanja deformiranjem dostupne u normama DIN 8582 i DIN 8587 [7 do 10] te u smjernicama VDI 3430 [11]. Nadalje su pretraženi patenti kao i dostupna komercijalna rješenja.

Pretraga standardnih rješenja za oblikovanje deformiranjem pokazala je da mnoge od metoda nisu prikladne za primjenu na konkretnom problemu jer rezultiraju promjenom poprečnog presjeka što u slučaju oblikovanja žičanih snopova nije dozvoljeno. Također nije dozvoljeno unošenje bilo kakvog naprezanja u nepomični kraj snopa vezan u glavi namotaja kako ne bi došlo do oštećenja bilo snopa bilo umetnutog svitka. Kao zaključak pretrage standardiziranih rješenja izlazi da oblikovanje putem medija kao što su zrak pod visokim tlakom, fluidi ili vakuum nije prikladno za dani problem. Naime spomenuta nejednakost površine snopa kao i relativno male dimenzije snopa otežavaju primjenu danih metoda koje dodatno mogu zahtijevati izradu brtvljenja u kalupima za oblikovanje. Štoviše, primjena fluida može rezultirati naslagama fluida na žičanim snopovima što je nepoželjno za sljedeće proizvodne korake. Iz navedenih se razloga daljnje traženje rješenja za oblikovanje žičanih snopova ograničava na one metode koje podrazumijevaju direktni kontakt između mehaničkog alata za oblikovanje i obratka.

Prilikom pretrage patenata, pronađena rješenja mogu se svrstati u nekoliko kategorija: (a) cjelovita rješenje za oblikovanje snopova žica [12, 13], (b) djelomična rješenja za ostvarivanje prilagodljivosti sustava [14, 15], (c) djelomična rješenja za savijanje u drugu ravninu [16, 17], (d) metoda lokalnog savijanja valjčićima [18, 19] te (e) metode savijanja koje koriste kalup [20, 21]. Patent [13] predstavlja tri metode za sakupljanje snopova, dvije metode za njihovo oblikovanje te dva primjera uređaja za izvođenje operacija. Iako se patent bavi istim problemom sakupljanja snopova žica statora elektromotora, predviđene metode nisu u općem slučaju primjenjive za fleksibilan sustav kakav se zahtjeva u ovom zadatku. Naime, u danom patentu podrazumijeva se sakupljanje uzastopnih snopova u jednoj operaciji sakupljanja. Budući da se u danom zadatku snopovi koji se skupljaju u istim točkama sakupljanja ne nalaze nužno uzastopno jedan za drugim, nije ih moguće skupiti u jednoj operaciji već je potrebno svaki snop oblikovati zasebno.

Budući da je krajnji cilj implementirati sustav za oblikovanje žičanih snopova u serijsku proizvodnju, poželjno je koristiti provjerena rješenja. Iz tog je razloga napravljen pregled metoda savijanja koje se koriste za oblikovanje žica, cijevi i limova kako na ručnim tako i na automatskim, numerički upravljanim komercijalno dostupnim strojevima. Među korištene metode ubrajaju se slobodno savijanje, savijanje u kalupu, preklapanje, savijanje smičnom silom preko ruba držača i slično. Najzastupljenija metoda savijanja na automatskim strojevima za trodimenzionalno savijanje žica jest lokalno savijanje valjčićima slično onome uočenom prilikom pretrage patenata [22]. Međutim, značajke žičanih snopova kao obradaka za savijanje razlikuju se od značajki žica, limova i cijevi u prije svega u konzistenciji oblika, a potom i po mehaničkim svojstvima. Iz tog je razloga primjena navedenih metoda savijanja ograničena.

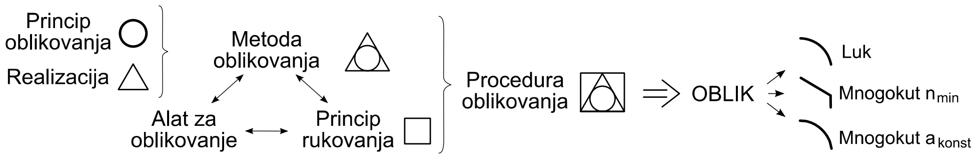
Jedan od glavnih problema koji se javlja prilikom savijanja jest elastični povrat. Elastični povrat je svojstvo materijala da se nakon rasterećenja djelomično vrati u prvobitno stanje.

Prilikom savijanja elastični se povrat očituje u kutu vraćanja koji se definira kao razlika kuta savijanja i kuta savinutog obratka nakon rasterećenja. Najčešće korištena metoda za kompenzaciju elastičnog povrata jest pretjerano savijanje, a okvirne informacije o iznosu kuta elastičnog povrata mogu se iščitati za slične obratke iz tablica [31, 32]. Utjecaj nekoliko parametara na elastični povrat dan je u [33] za slobodno savijanje čeličnog lima oslonjenog duž dvije linije, kada se sila savijanja primijeni primicanjem žiga u sredini lima između oslonaca. Utvrđeno je da se kut elastičnog povrata povećava sa smanjenjem trenja između površine obratka i alata za savijanje. Parametri koji utječu na smanjenje trenja su povećanje debljine izolacijskog filma lima te povećanje brzine žiga. Nadalje se elastični povrat povećava s povećanjem udaljenost između oslonaca te s povećanjem radijusa žiga. Pretpostavlja se da se slični zaključci mogu primijeniti i na savijanje snopova izolirane bakrene žice.

4. Razvoj koncepata

Za ispravan rad sustava uzimaju se u obzir sljedeće pretpostavke (a) postoji jedinstven i unaprijed definiran redoslijed kojim se snopovi žica trebaju oblikovati i (b) postoji jedinstven i unaprijed definiran početni položaj snopova. Pretpostavka (a) dodatno podrazumijeva da se svaki snop žica može oblikovati odjednom, bez potrebe za prekidom oblikovanja kako bi se oblikovao dio drugog snopa. Prema pravilima struke, shema se polaganja projektira tako da se broj uzajamnih križanja snopova svede na minimum, a križanja koja nije moguće izbjeći postavljaju se u slobodan prostor između namotaja. Zahtjev za polaganje jednog po jednog snopa implicira pretpostavku da je moguće ostvariti kompromis između pojednostavljenja operacije sustava za oblikovanje snopova i povećanog broja križanja bez narušavanja pravila struke. Za određivanje početnog položaja žičanih snopova iz pretpostavke (b), analiziran je položaj nepomičnih krajeva snopova po širini i visini glave namotaja u dostupnim primjerima statora. Na temelju analize, za početni je položaj odabran radijalni raspored snopova oko statora, u horizontalnoj ravnini, povrh glave namotaja (Slika 2.a). Za postojeće primjere statora, ovakav početni položaj snopova rezultira minimalnim brojem križanja. Uz spomenute pretpostavke koje se odnose na rad cijelog sustava, prilikom razvoja koncepta uvodi se ograničenje da ravninsko oblikovanje snopova prestaje u točki sakupljanja, nakon oblikovanja zakrivljenog dijela snopa. Također, pretpostavlja se da za vođenje nepotrebne duljine snopa postoji dodatni podsustav razvoj kojega nije predmet ovog rada.

Budući da postojeće metode savijanja nisu direktno primjenjive na oblikovanje žičanih snopova postavlja se pitanje postoji li neka druga metoda koja rješava problem oblikovanja u potpunosti. Postavljeno pitanje sugerira time ne samo potrebu za apstraktizacijom problema već i potrebu za razvojem sustava „bottom-up“ pristupom (Slika 4).



Slika 4. Pristup istraživanju rješenja za oblikovanje žičanih snopova

Kao prvi korak razvoja, istražena su rješenja za osnovnu funkciju podsustava *Snop žica deformirati*. Osnovna je funkcija razložena do razine na kojoj je parcijalna rješenja moguće predočiti fizikalnim i mehaničkim simbolima. Rezultat kombiniranja različitih smjerova sila i momenata te različitih tipova oslonaca je 14 fizikalnih principa oblikovanja koji predstavljaju rješenja za funkciju deformiranja. Kako principi na ovako apstraktnoj razini nisu praktično primjenjivi, u sljedećem su koraku razvijene elementarne tehničke realizacije koje omogućavaju provedbu eksperimenata.

Na temelju fizikalnih principa, osmišljeno je direktno sedam eksperimenata kojima se želi utvrditi primjenjivost pojedinih principa na oblikovanje žičanih snopova. S obzirom na sličnost nekih od principa oblikovanja, zaključci koji proizlaze iz direktno testiranih principa mogu se primijeniti na one srodne, stoga nije potrebno trošiti dodatne resurse. Slično kao prema [33], eksperimentima je utvrđeno da alat za oblikovanje s manjim promjerom, tj. lokalno savijanje rezultira manjim kutom elastičnog povrata. Osim toga, utvrđen je dodatni zahtjev na sustav oblikovanja koji podrazumijeva ravnomjerno oblikovanje kompletnog žičanog snopa, bez ispuštanja pojedinih žica bilo prilikom početnog hvatanja ili kod ponovnog hvatanja. Na temelju eksperimentalnih rezultata moguće je eliminirati neke od metoda oblikovanja, tj. kombinacija principa oblikovanja i njihove realizacije. Budući da je potrebna duljina oblikovanja različita za pojedine snopove istog statora, eliminirane su one metode oblikovanja koje zahtijevaju promjenu kalupa za svaku različitu duljinu oblikovanog snopa. Naime, prilagodljivost duljine oblikovanja pripada prvoj razini prilagodljivosti sustava koja ne zavisi o tipu statora, tj. ne podrazumijeva prilagodbu proizvodne linije. Za daljnju eliminaciju najmanje primjerenih metoda korišteni su kriteriji *Predvidljivosti* i *Ponovljivosti* koji se odnose na krajnji oblik žičanog snopa prilikom formiranja više statora istog tipa.

Upotreba na ovaj način odabranih metoda oblikovanja proširena je principom rukovanja uz odabir veličine alata za oblikovanje. Kombiniranjem različitih rješenja za navedena tri elementa moguće je ustanoviti različite procedure oblikovanja koje određuju krajnji oblik žičanog snopa: luk, mnogokut s minimalnim brojem stranica ili mnogokut sa stranicom konstantne duljine (Slika 4). Pritom se veličina alata za oblikovanje može odabrati tako da radijus alata odgovara približno ili promjeru žičanog snopa ili srednjem polumjeru glave namotaja. Princip rukovanja prvenstveno se odnosi na potreban broj koraka, u kojima se primjenjuje određena metoda oblikovanja, za oblikovanje žičanog snopa u punoj potrebnoj duljini između nepomičnog kraja i točke sakupljanja. Tako razlikujemo tri principa rukovanja: (a) u jednom koraku, (b) u više koraka te (c) u ponovljenim koracima. U slučaju (a) relativno se gibanje između žičanog snopa i alata za oblikovanje ostvaruje samo jednom dok u slučaju (b) postoje barem dva gibanja koja nisu nužno međusobno jednaka. S druge strane, ako su sva gibanja identična, govorimo o slučaju (c). Dodatni utjecaj na proceduru oblikovanja ima točka početka formiranja koja može biti ili pri nepomičnom ili bliže slobodnom kraju žičanog snopa. Ako se formiranje započinje od nepomičnog kraja, zadatak je pomoćnog sustava voditi ravan, neoblikovan dio žičanog snopa. Suprotno, ako se oblikovanje započinje od slobodnog kraja snopa, pomoćni sustav treba, u općem slučaju, voditi žičani snop već određenog oblika te osigurati da se oblikovani dio snopa ne promijeni za cijelo vrijeme oblikovanja i vođenja. Posljednja stavka koja utječe na kreiranje koncepata za ravninsko oblikovanje snopova jest raspodjela stupnjeva slobode između dijelova sustava. Iako postoje tri teorijske mogućnosti raspodijele, samo su dvije izvedive: (a) svi stupnjevi slobode gibanja dodijeljeni su alatu za oblikovanje snopova i (b) stupnjevi slobode gibanja su podijeljeni između alata za oblikovanje i statora. Iako slučaj (b) zahtjeva veću potrošnju energije uslijed veće težine statora usporedno s težinom alata za oblikovanje, raspodjela stupnjeva slobode gibanja omogućava pojednostavljenje osnovnog gibanja alata koje u slučaju (a) može zahtijevati i do šest stupnjeva slobode.

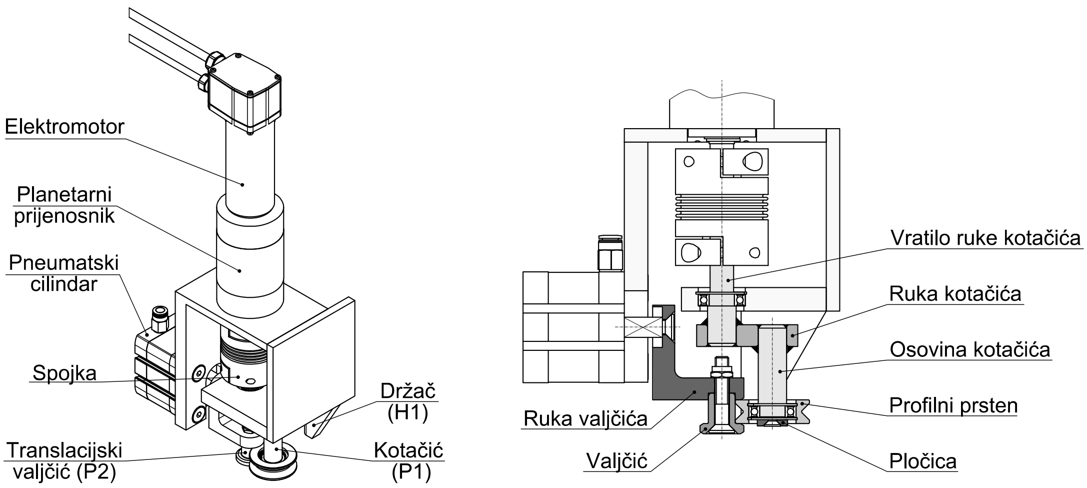
Uzimajući u obzir različite navedene mogućnosti, generirano je ukupno devet koncepata za oblikovanje žičanih snopova u ravnini.

- *koncept A*: oblikovanje robotskom rukom oko kalupa u jednom koraku
- *koncept B*: oblikovanje u više koraka s dvije robotske ruke te pomoćnim elementom za osiguravanje konstantnog radijusa savijanja
- *koncept C*: oblikovanje u više koraka s dvije robotske ruke u izmjeničnom radu

- *koncept D*: oblikovanje u više koraka s dvije robotske ruke u uzastopnom radu
- *koncept E*: oblikovanje većeg radijusa u jednom koraku s podesivim valjcima
- *koncept F*: oblikovanje u brzim ponovljenim koracima s jedinstvenim alatom za hvatanje i savijanje u dvije točke
- *koncept G*: oblikovanje preklapanjem u više koraka pomoću rotirajuće pločice
- *koncept H*: oblikovanje smicanjem translacijskim alatom u više koraka (mnogokut
- *koncept I*: oblikovanje u više koraka okretanjem jednog valjčića oko centra rotacije drugog

Pritom je oblik luka moguće postići konceptima *A* i *E*, oblik mnogokuta s minimalnim brojem stranica konceptima *B*, *C* i *D*, oblik mnogokuta s konstantnom duljinom stranica konceptom *F*, a bilo koji od mnogokuta konceptima *G*, *H* i *I*.

Evaluacija koncepata provedena je korištenjem Pughove metode pri čemu je kao referentni koncept uzet koncept *D*. Kao najmanje prikladan koncept pokazao se koncept *E* budući da zahtjeva ugrađeni pogon žičanog snopa te ne omogućava oblikovanje jednog dijela snopa koji uvijek ostaje ravan. S druge strane, kao najprikladniji se pokazao koncept *I* čija je prednost u odnosu na dobro ocijenjene koncepte *D*, *G* i *H* u tome što osigurava uvijek isti definirani položaj mjesta lokalnog savijanja u odnosu na alat. Iz tog je razloga koncept *I* odabran za detaljniju razradu (Slika 5.).



Slika 5. Alat za oblikovanje prema dabranom konceptu

U konceptu I za hvatanje žičanog snopa koristi se translacija valjčića (P2) prema kotačiću (P1) putem hoda pneumatskog cilindra. Ekscentričnom rotacijom kotačića (P1) oko centra translacijskog valjčića (P2) cilj je lokalno deformirati žičani snop za onoliki kut koliki je kut rotacije kotačića (P1). Kako bi se osiguralo pravilno hvatanje i oblikovanje svih žica u snopu valjčić i kotačić imaju profilni utor pri čemu se, prilikom promjena dimenzija žičanog snopa, mijenja samo profilni prsten kotačića (Slika 5.). Prilagodbe svim drugim promjenama u dimenzijama statora ostvaruju se automatski u kontrolnom programu sustava.

Radi dobivanja dojma o potrebnim dimenzijama elemenata alata za oblikovanje, proračuni su izvedeni okvirno i konzervativno za opći konstrukcijski čelik S235. Preciznijim proračunima i odabirom kvalitetnijeg materijala moguće je dimenzije optimirati.

5. Zaključak

Sustav za oblikovanje žičanih snopova može se podijeliti u tri zasebna podsustava: (a) ravninsko oblikovanje žičanih snopova, (b) vođenje preostale duljine snopa te (c) postavljanje oblikovanog snopa u neutralni položaj. Kao predmet ovog rada, razvijeno je rješenje za podsustav (a), tj. za ravninsko oblikovanje zakrivljenog dijela snopa.

Pregledom standardiziranih metoda za oblikovanje deformiranjem ustanovljeno je da se prikladne metode za primjenu na savijanje žičanih snopova svode na one metode koje podrazumijevaju direktni kontakt između mehaničkog alata za oblikovanje i obratka, prije svega savijanje. Pritom se za kompenzaciju elastičnog povrata predlaže metoda pretjeranog savijanja, gdje je predviđeni potrebni kut savijanja za postizanje željenog rezultantnog kuta potrebno potvrditi testiranjima prije implementacije rješenja u proizvodnu liniju.

Razvoj rješenja vođen je *bottom-up* pristupom od osnovne funkcije sustava koja se može izraziti kao fizikalni princip. Eksperimentalnim putem eliminirane su manje primjerene metode oblikovanja, dok su neke od onih primjerenijih razrađene dodavanjem funkcije rukovanja. Kombiniranjem parcijalnih rješenja za deformiranje i rukovanje žičanim snopovima razvijeno je devet koncepata za ravninsko oblikovanje žičanih snopova. Nakon usporedbe koncepata onaj s najvećom ocjenom odabran je za detaljniju razradu. S obzirom na malen broj ograničenja na sustav te zahtjev na visoku fleksibilnost, smatra se da je primijenjen *bottom-up* pristup primjeren.

Razvijeni koncept potrebno je u sljedećim koracima dalje detaljno razraditi uz potvrdu čvrstoće, krutosti i dinamičke izdržljivosti elemenata prikladnim proračunima. Također je potrebno potvrditi odabir standardnih elemenata kao i prilagoditi dijelove za izradu dostupnim proizvodnim alatima. U nastavku je potrebno razviti dodatne pomoćne podsustave te definirati u potpunosti sve postaje proizvodne linije za serijsku proizvodnju statora.

Ključne riječi: razvoj sustava, razvoj koncepta, odabir koncepta, oblikovanje deformiranjem, elastični povrat, oblikovanje žičanih snopova

1 INTRODUCTION

In serial production of stators for electrical motors, the need for forming of wire bundles arises when stator winding is done by inserting process of pre-winded coils. One example of serial production line targets to produce stators in three minutes per part and one hundred thousand parts per year. The experience gained through example showed that the manual forming of wire bundles is one of the bottlenecks of the production line. For that reason, there is a wish to automate the forming process.

1.1 Production line

Figure 1 represents the main steps of the line where wire bundles are present. Each step is performed on one working station and the work piece carrier transports the stator through the production.

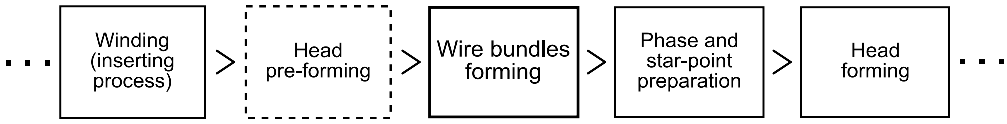


Figure 1 Illustration of the production line

Wire bundles first appear after winding of the stator package by process of inserting coils. Stator package is manufactured out of series of thin lamellas with slots for inserting insulation paper and coils (Figure 2a). Each coil is winded separately out of several wires (Figure 2b) and then mounted on a tool used for inserting the coils in the stator package (Figure 2c and 2d). By relative translation of inserting tool and stator package, several coils are inserted into package slots at the same time (Figure 2e). As a result of the inserting process, coil extensions in form of wire bundles stay not inserted in a stator package (Figure 2f). Depending on the design of the inserting process, additional production step involving a process of pre-forming of winding head can take place before wire bundle forming.

Next step is to form wire bundles, thus prepare them for connecting in phase outputs and star-points. Several wire bundles need to be collected in appropriate collecting points. Each of the bundles needs to, by following the radius of the stator head, is laid on the top of the stator head until it reaches the point of collecting. After all the bundles are placed in the correct collecting points, the stator is forwarded to the next step.

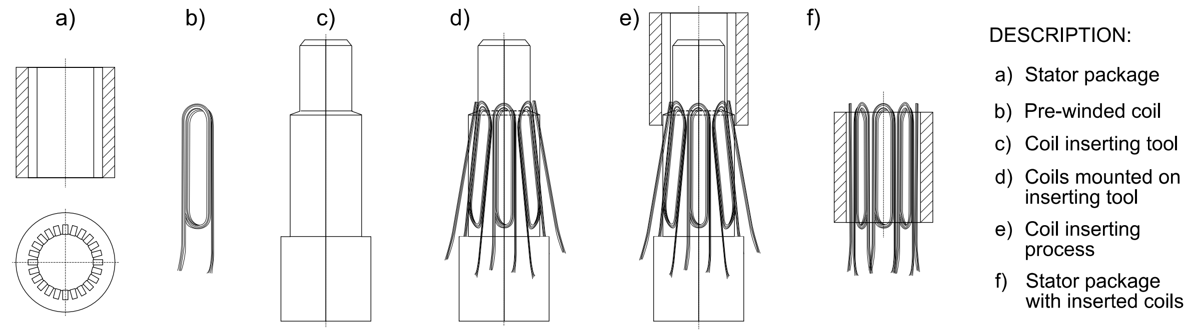


Figure 2 Stator winding by inserting coils

On the following station, the bundles are cut to a desired length and the phase outputs and start-points are formed by placing the insulation tubes and metal connectors on the collected wire bundles. The preceding production step takes place on the station where the head of the stator is fully formed by the compression force. This additionally fixes the position of all laid wire bundles as well as the position of phase outputs and star-points and reduces the height of the stator head.

1.2 Desired wire bundle form

As described in the previous paragraph, to place a wire bundle in a correct collection point, the bundle needs to be placed in the plane on the top of the winding head and formed along the circumference of a head. Depending on the motor design, bundles can be collected to form any number of phase outputs and any number of star-points. One of possible outcomes of the forming process is shown on the Figure 3. In the example, wire bundles are collected to three phase outputs and two ends that are then connected to form one star-point.

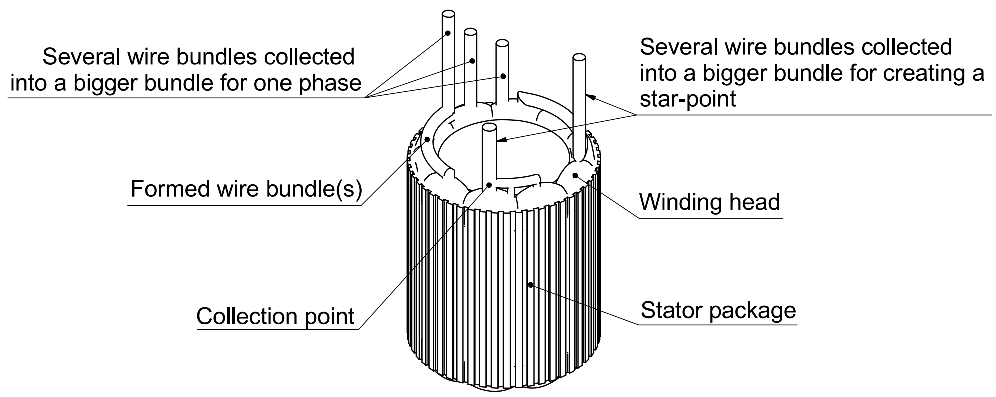


Figure 3 Stator with formed wire bundles

In Figure 4 one formed wire bundle is shown. The formed bundle consists of two parts: (a) part that follows the arc shape and (b) the straight part for which the original form is not changed. According to the Figure 4 in point A the wire bundle is fixed to the stator head. That means that this point at the same time represents a fixed end of the bundle and a start point of curve shaped bundle part. The point B is a collection point for more wire bundles and in that point the curve shaped part of a bundle finishes. Additionally, in the manual forming process, in point B the wire bundle is bended to a plane perpendicular to the plane of the stator head and the rest of the wire bundle remains, without additional forming, in the original straight shape of the bundle. In later process, the straight part of the bundle is cut to the needed length.

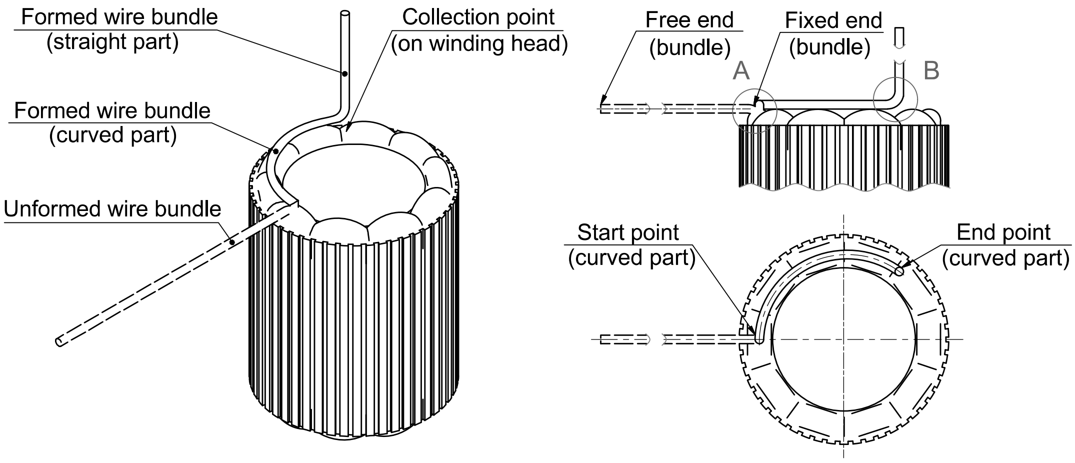


Figure 4 One formed wire bundle

For each wire bundle, the relative position of a fixed end to the winding head is different. The fixed point can lay in the top plane of the winding head or on inner or outer sides of the winding head. That means that the fixed point can be on a bigger or smaller radial distance from the centre of the stator as well as on a different height from the top plane of the winding head. For that reason, exact desired shape in the point A cannot be precisely defined independently from the specific arrangement of the fixed wire bundles' ends in each specific stator type.

On the other hand, the form of a wire bundle in point B, i.e. in the collection point, can be the same for all bundles of all stator types. The exact forming radius and angles around the vertical axes in the point B are not specified from the functional point of view. That means that the final position of a straight part of a bundle can be chosen to fit the needs and limitations of the wire bundle forming system. The bending radius should not be smaller than the minimal allowed bending radius for single wires in a wire bundle, taking in the account as well the insulation of the single wires.

1.3 Task description

According to a philosophy of "Industry 4.0", most of the new solutions developed are trying to be made as flexible as possible [1]. Since the development and production of electrical motors, thus stators, will continue as well in the future, the wish is to find a universal solution that can be used for similar motors of a type with an inserting process for winding a stator. This means that the suggested solution for forming the wire bundles needs to be simple to *adjust* for as wide range of different (dimensional) parameters as possible. Additionally it should be possible to *adapt* the system to overcome new issues that may rise from the new developed motor and stator types, e.g. by attaching some additional modules.

Since it is not possible to find a solution for infinite number of different parameters, limits on the area for a solution search can be drawn by the power range of the electrical motor. Therefore, for practical purposes of an automatic wire bundle forming process, we will limit to the stators of electrical motors with a power range from 20 kW to 100 kW. For better understanding, Figure 5 illustrates some of dimensional inputs needed for the wire bundle forming system, such as diameter of the stator, diameter and a number of single wires in a wire bundle, as well as a wire bundle length.

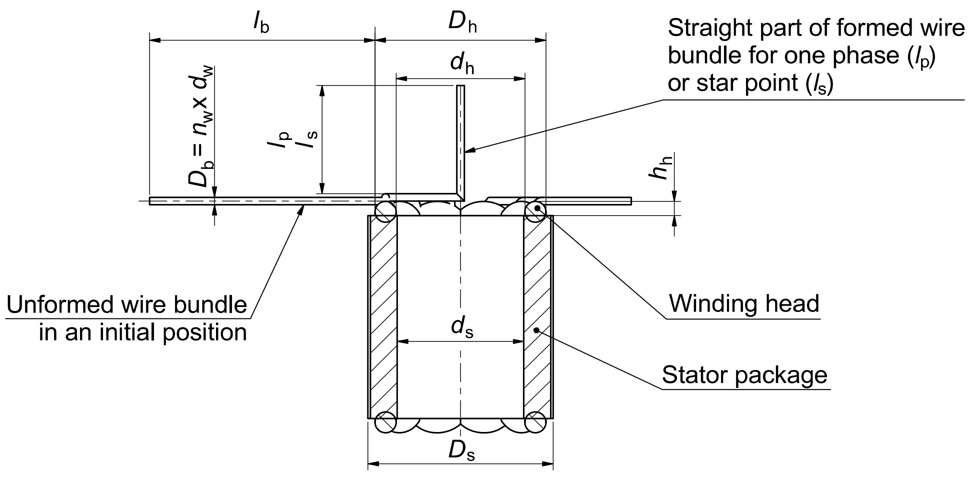


Figure 5 Illustration of dimensional system parameters

While most of the parameters considering the dimensions of the stator are a result of desired electrical properties, the diameter of the wire used for winding is limited also with an inserting technique itself. Due to that limitation, inserting technique is not suitable for the stators that operate on high currents, since for higher currents thicker wires are needed. Ranges of dimensional parameters values, for which the automatic wire bundle forming system should to be suitable, are given in Table 1. The values are based on corporate knowledge, considering the current state of the art of the electrical motors, as well as possible directions of their further development.

Table 1 Range of values of system parameters

Symbol	Min	Max	Description
D_s	166	254	Outer diameter of a stator package, mm
d_s	105	187	Inner diameter of a stator package, mm
D_h	160	248	Outer diameter of a winding head, mm
d_h	106	188	Inner diameter of a winding head, mm
h_{hn}	40	≈50	Height of a winding head (not formed), mm
h_{hp}	n.a.	n.a.	Height of a winding head (preformed)
d_w	0,5	0,95	Diameter of a single wire, mm
n_w	4	18	Number of wires in a wire bundle
l_b	130	580	Length of a wire bundle in initial position, mm
n_b	6	36	Number of wire bundles
l_p	n.a.	n.a.	Length of the straight part of a bundle for phase outputs
n_p	1	4	Number of bundles that need to be collected in one phase
l_s	≈30	≈150	Length of the straight part of a bundle for star-point forming, mm
n_s	1	4	Number of bundles that need to be collected to form one star point

In terms of serial production, for any change in the production line it is an intention to do a *quick change over*. This means that all the changes are done within the cycle time what results in a delay and loss of only one product being manufactured. Deviations from an ideal minimum loss can be allowed in case when bigger changes are needed. Gradual increase in allowed time for stopping the line is then between half an hour and one hour. If that as well is not reachable, the target change time increases to half of the shift, but never longer than for a weekend. Nevertheless that the solution for a wire bundle handling system needs to provide a possibility to stay within the given cycle time of three minutes, during the design of the whole production line, it is possible to reach the cycle time goal by, for example multiplying the number of forming stations. This means that, during the solution search, the cycle time requirement has virtually no influence on *goodness* of a solution.

1.4 Limitations

In addition to the requirements on the system described in previous paragraphs, some limitations as well occur due to the various parameters of the problem.

Used materials Since the wear of material is increased due to the high frequency of the repetitive motions in serial production, rather than adding, e.g. rubber elements, other possibilities to increase the friction coefficient should be considered.

Applied forces The maximum force that can be applied to the fixed point of the bundle in the stator head, represented as point A in Figure 4, is the force used for inserting the winding in the stator package. However, it is preferred not to apply any force, either compression or tension, that may cause stress in the winding of the stator.

Wire forming technology Due to the possibility of changing desired electrical properties, it is not allowed in any way to change the cross section of any of the wires in a wire bundle. Additionally, it is not desirable to bring any additional heat in the production process since that requires great amounts of energy and time. This limits forming technology to cold forming and bending.

Wire insulation A care has to be taken to preserve the insulation of the single wires in the bundle because damage on the insulation can result in a short circuit. This puts limits on the shape of gripping tool and applied gripping and forming forces. However, since the more unpredictable process of forming a winding head is preformed after the forming of wire bundles, this limitation has lower importance.

Tubes Sometimes additional tubes are placed around the wire bundles to ensure better insulation from the winding head. The tube fixes the shape of the bundle and prevents wires going apart from each other, making it easier to handle the bundle. However, this method of fixing the wires in the bundle is not to be used as a regular method since it produces additional cost in material and time needed to perform additional process of placing tubes along the whole wire bundle length.

Other Although the limitations from the previous and following production steps of electrical stator are not known, some limitations arise from the fact that the diameters of wire bundles are rather small. This refers mainly to production technologies used to manufacture certain parts of the system. Especially during the detail design, care has to be taken of manufacturing possibilities and tolerances that might provide limitations on a design of small parts.

2 PROBLEM ANALYSIS

A way to an innovation in engineering design is often full of obstacles placed by one's experience and focus on the first idea that rises in one's mind when hearing about the problem. To clear the obstacles, systematic way of thinking and structured approach to finding a solution can help. In design theory, there are several models that can be used, but as mentioned in [2], none of them is to be followed blindly. According to [3] one of the approaches to solving a problem is to first decompose it to partial problems and in partial problems to find solutions for single smaller and rather specific sub-problems. When the solutions to most of the specific problems are know, it is possible to synthesise them in order to create subsystems and with subsystems to create the complete solution. Figure 6 shows the mentioned approach with two levels of decomposition.

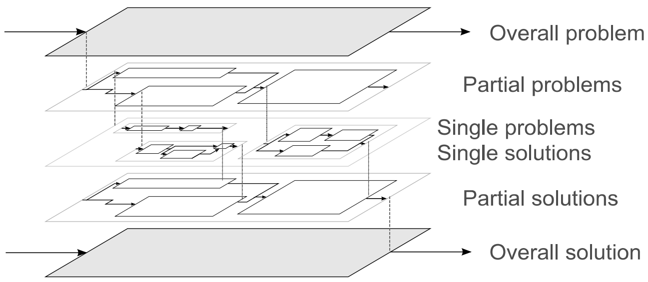


Figure 6 Analysis of a problem and synthesis of an overall solution [3]

However, especially for more complex systems it is appropriate to break them down into even more levels. Furthermore, additional single solutions are often needed to provide the connections between the subsystems in the process of synthesis of the overall solution.

2.1 Problem decomposition

In order to enable systematic solution search, the described problem is analysed and decomposed to smaller issues that can then be observed separately from each other. In that way, it is possible to get a better insight into each of the specific issues, thus to provide more precise and more accurate inspection of possible solutions.

On the highest level of abstraction, only one main function of the wire bundle forming system can be determined:

- *Form a wire bundle.*

However, to support the main function, additional two functions are recognized as the most important ones:

- *Hold the length of a wire bundle and*
- *Place formed bundle into a neutral zone.*

Each of three functions can be analysed separately and several different solutions can be offered independently for each of the functions. Then, in order to create the whole system, it is possible to realise each function as a separate subsystem, or to integrate any combination of functions in a smaller number of system modules [4]. With integration of more functions, modules become more complex from the structural point of view, but a good combination can provide easy-to-use overall system what is the final goal. In these terms, it can be said that the level of complexity is not a measure of *goodness* of a solution.

Required final shape of each wire bundle is a three-dimensional form in space as shown in Figure 4. The 3D form can be achieved by spatial forming of the wire bundle or as a superposition of several planar forming procedures, where each of them is done in a different plane. This suggests that the task can be reduced to finding a solution for forming a wire bundle in one plane (2D forming).

In Figure 7 it is illustrated how to modify the production line to make it fit the wire bundle forming station. Figure highlights three elements of workstation for forming of wire bundles, where each of the elements represents what can be either an additional workstation or a part of a workstation. While element for *Planar forming of one bundle* is the focus point of this thesis, the rest of the operations should be provided additionally to complete the overall wire bundle forming process.

Operation of *Initial positioning of bundles* is a necessary pre-requisite for automatic operation of the wire bundle forming system since it ensures repeatability of the forming process by ensuring always the same position of the bundles. Therefore, this operation should be done before the stator is transferred to the wire bundle forming station. In the case when fixed points of bundles are arranged on different heights in a winding head, it might happen that it is not possible to use the same forming procedure for every wire bundle. Then *Repositioning of a bundle for planar forming* is one more pre-requisite to get the proper initial state for operation of the forming station. This suggests that, although the operations represented with dashed lines are optional, they influence the operation of the forming station.

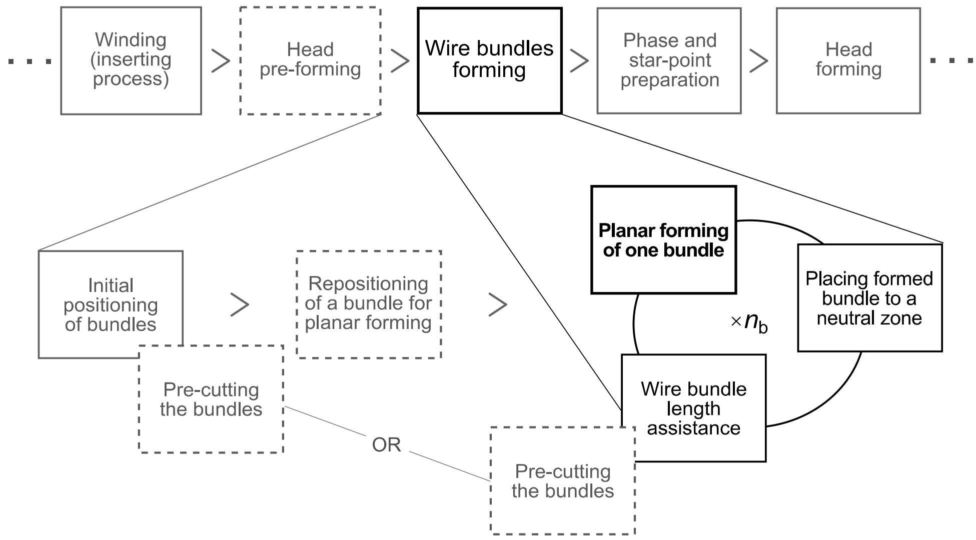


Figure 7 Illustration of the modified production line

Another operation refers to the issue that initial available length of a bundle is longer than needed to create a desired bundle shape. The longer the bundle, the bigger is the deflection, meaning that the deflection of longer bundles might result in collision with the surrounding of the forming system, such as non-formed bundles, station tools, ground, etc. To overcome the problem of extra wire bundle length, operation of *Wire bundle length assistance* can be used. However, to reduce the operating length, thus to simplify handling, operation of *Pre-cutting the bundles* can be used. That operation can be done (a) independently, (b) in a combination with initial positioning of wire bundles or (c) in a combination with gripping of a bundle for forming. Since the length of a bundle or existence of *Pre-cutting* operation cannot be defined in advance, in frame of this thesis task is limited to finding a solution for *Planar forming of a one bundle*, regardless the length of the bundle.

Nevertheless, when a curved part of a bundle is formed in a plane of a winding head, a straight part of a bundle needs to be placed in a neutral zone to avoid same collision problem as the one that might occur with extra wire bundle length. For that, additional operation of *Placing formed bundle to a neutral zone* can be executed as a part of wire bundle forming station. However, that task is not in the focus of this thesis.

Since the forming system is supposed to form one wire bundle at a time, all the operations included in the system need to be executed as many times as the number of wire bundles n_b. The illustration of the system given in Figure 7 shows the circular repeatability of process operations, by at the same time suggesting one of possible physical arrangements of operating elements inside the bundle forming working station.

2.2 Problem clarification

In the next paragraphs, the desired wire bundle form is analysed in order to clarify the task of a wire bundle forming system. From given dimensional parameters, which address desired flexibility of a system, range of wire bundle sizes is calculated together with a tolerance on the result of forming. Additionally a convention to define positions of wire bundles and collection points is proposed as well as the definition of forming path.

2.2.1 Wire bundle size

According to Table 1, it can be determined for which range of sizes of wire bundles the wire bundle forming system needs to be suitable. Since the minimum and the maximum values are provided for number of wires in a bundle as well as for a single wire diameter, the minimum and the maximum wire bundle diameter can be estimated as illustrated in Figure 8. In the ideal radial arrangement of wires in a bundle, the minimum wire bundle diameter occurs in a case when there are a minimum number of wires with a minimum possible wire diameter. The illustration of that case is given the most left in Figure 9 and shows that the wire bundle, that consists of four wires with a diameter of 0,5 mm, has a diameter of 1,21 mm.

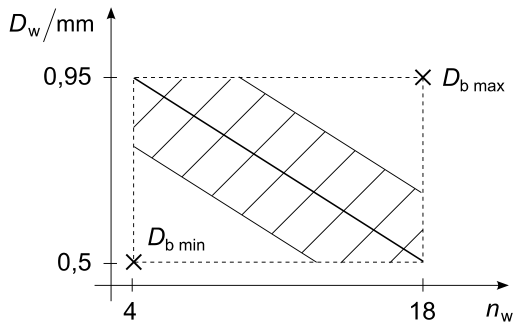


Figure 8 Range of wire bundle sizes

Considering that there are no additional components, which provide the shape of the bundle, the number of possible arrangements of wires in a bundle is infinite and for each wire bundle different. In Figure 9, only five different possible arrangements of wires are shown for a case when there are 18 wires in a bundle. This illustrates also that the size of a bundle varies not only due to the number and size of single wires but also due to their mutual arrangement. The unpredictability of the exact wire bundle size increases even more due to the fact that the shape of the bundle can change within the same bundle. In addition, the same variations occur between different bundles. Maximal wire bundle diameter of an ideal radial arrangement of the wires in the bundle on the other hand occurs for the maximum number of wires with the maximum wire diameter. This case is shown on the second sketch from the left in Figure 9 indicating that 18 wires with a diameter of 0,95 mm create a wire bundle with a diameter of 4,62 mm.

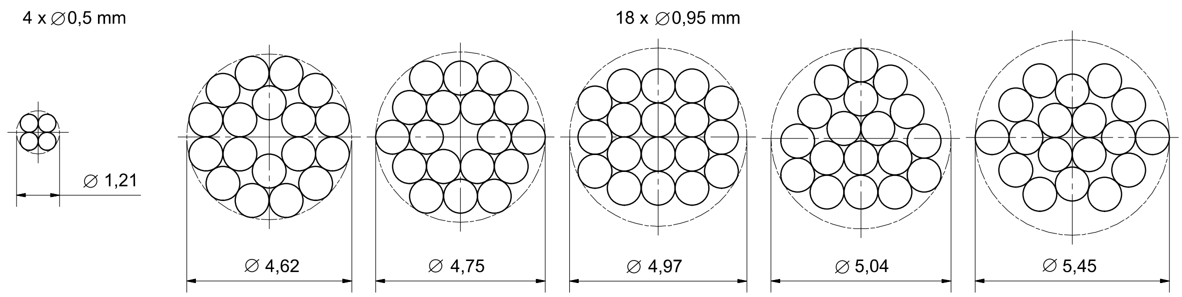


Figure 9 Possible cross-sections of wire bundle

In a specific case when the wires are distributed along the line one next to each other, thus forming a flat bundle, the minimum width of the bundle can be calculated according to the expression:

$$w_{\mathrm{b\,min}} = n_{\mathrm{b\,min}} \times d_{\mathrm{w\,min}} = 4 \times 0,5 = 2 \text{ mm} \quad \textbf{(1)}$$

Accordingly, the maximum flat bundle width is then:

$$w_{\mathrm{b\,max}} = n_{\mathrm{b\,max}} \times d_{\mathrm{w\,max}} = 18 \times 0,95 = 17,1 \text{ mm} \quad \textbf{(2)}$$

All mentioned arises one more requirement on a wire bundle handling system, that is “the ability to perform all the necessary operations regardless the changes which might occur in a wire bundle shape along the wire bundle length”. In this case, the full functionality of the system can be achieved either by fine self-adjustability of the system or with a robust solution.

In addition, the wire bundle forming system initially needs to suit reduced range of wire bundle sizes as illustrated in Figure 8. The reason origins from a production of electrical motors, where constant cross section of a wire bundle is used for coil windings. On the one hand, calculated minimum bundle size might result in too high resistance. On the other hand, stator packages have smaller deviations in slot sizes that represent geometrical limitation for the biggest usable wire bundle size.

2.2.2 Wire bundle shape

From the motor design, it is known which wire bundles need to be collected together to create phase outputs and star-points. This is, together with the position of collection points, defined in the pattern of laying the wire bundles. One collection point is a reference point for more wire bundles therefore its position is defined according to a winding head and not to each wire bundle. If n_c is the number of collection points, the position of a collection point *j,* for every $j \in [1, n_c]$, can be defined by an angle α_{cj} relative to the pre-defined zero-point on the stator as shown in Figure 10. In that case, angle α_{cj} has any positive angle value between 0° and 360° as defined according to a layout pattern.

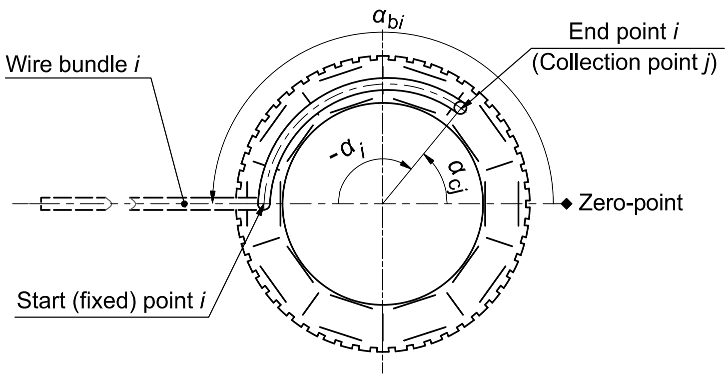


Figure 10 Definition of angular positions of characteristic points

Although the distribution of fixed wire bundle ends is defined by the distribution of slots in a stator package, the position of each fixed end can as well be defined on the winding head relatively to the pre-defined zero-point. For n_b number of wire bundles, in a counter-clockwise direction the position of wire bundle *i,* for every $i \in [1, n_b]$, is a positive angle α_{bi} with a value between 0° and 360°. If it is not specified differently by the design of the winding, the regular distribution of fixed ends can be assumed. In a regular distribution for each wire bundle *i* angular position can be calculated according to the formula:

$$\alpha_{bi} = \alpha_0 + (i-1) \times \frac{360°}{n_b} \quad \textbf{(3)}$$

where α_0 is a displacement of a first wire bundle from the zero-position; $\alpha_0 \in \left[0°, 360/n_b\right\rangle$.

If we define the arc length to be measured from the fixed end of the wire bundle, we can express the forming path for each wire bundle *i* by defining an angle α_i between the fixed (start) point and the end point of the arc (Figure 10). Since the bundle should always be formed along the shortest path, the absolute value of the angle size can be between 0° and 180°. From the point of view from above the stator head, forming the bundle in counter-clockwise direction is marked with a positive angle and forming in the clockwise direction is expressed as a negative angle (Figure 10). Since the arc length angle α_i represents a relative difference between the angular positions of a bundle *i* and associated collection point *j,* it can be expressed as:

$$\alpha_i = \alpha_{\mathrm{c}ji} - \alpha_{\mathrm{b}i} \quad \textbf{(4)}$$

If positive values for a bundle and collection point angular positions are included in the equation (4), the resulting arc length angle α_i has a sign pointing the direction of forming as explained above.

Tolerance field for laying a wire bundle

Since the precision of bundle positioning on the top of the winding head has no influence on motor electrical properties, the bundle of a diameter D_b can be laid anywhere within the winding head width w_h. If we take that R_h is the mean radius of the winding head, that means that the radial position r_i of any point *i* of the wire bundle can be in position:

$$r_i \in \left[R_\mathrm{h} - \frac{(w_\mathrm{h} - D_\mathrm{b})}{2}, R_\mathrm{h} + \frac{(w_\mathrm{h} - D_\mathrm{b})}{2} \right] \quad \textbf{(5)}$$

as shown in Figure 11.

This also implies that the wire bundle does not have to be formed on a constant radius, that is, the position of any point can vary in a given tolerance field. Further implication is that the bundle does not necessarily need to be formed as an arc. The polygonal approximation of an arc shape is good enough as long as all the sides are in the given tolerance field. (Figure 11)

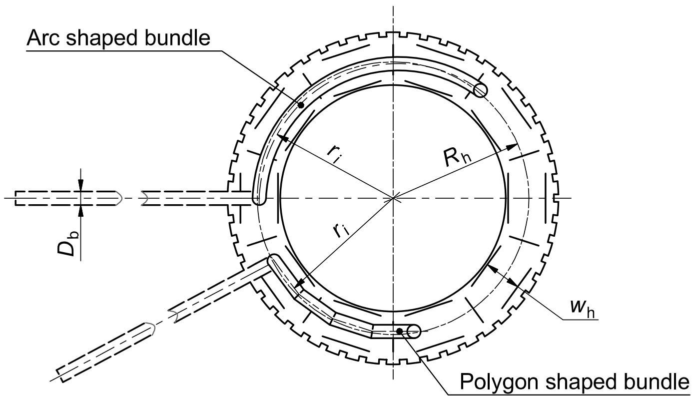


Figure 11 Tolerance on the shape of the curved part of formed bundle

Taking the dimensions from Table 1 into account it is possible to calculate that the mean radius of a winding head is in a range between:

$$R_{\mathrm{h\,max}} = \frac{D_{\mathrm{h\,max}} + d_{\mathrm{h\,max}}}{4} = \frac{248+188}{4} = 109\ \mathrm{mm} \tag{6}$$

and

$$R_{\mathrm{h\,min}} = \frac{D_{\mathrm{h\,min}} + d_{\mathrm{h\,min}}}{4} = \frac{160+106}{4} = 66{,}5 \cong 67\,\mathrm{mm} \tag{7}$$

The range of winding head width is between:

$$w_{\mathrm{h\,max}} = \frac{D_{\mathrm{h\,max}} - d_{\mathrm{h\,max}}}{2} = \frac{248-188}{2} = 30\ \mathrm{mm} \tag{8}$$

and

$$w_{\mathrm{h\,min}} = \frac{D_{\mathrm{h\,min}} - d_{\mathrm{h\,min}}}{2} = \frac{160-106}{2} = 27\ \mathrm{mm} \tag{9}$$

This suggests that the tolerance field for laying the bundles is rather constant for all the stator types so the smaller value can be taken as a general guide. Additionally, in order to provide a certain safety zone, it is chosen to reduce the minimum width of the field by approximately 10% (Figure 12).

In total, it can be concluded that, in a horizontal plane, every wire bundle, for any stator variant, needs to be laid down within a 24 mm wide annulus. The range of the mean radius of the annulus, depending on a specific variant of a stator, is between 67 mm and 109 mm. (Figure 12).

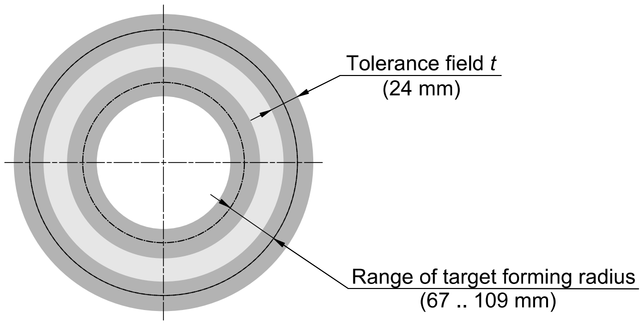


Figure 12 Area of wire bundle forming

Although the tolerance field is unified for all the stator variants, it still needs to be reduced for a size of a specific wire bundle. That means that the borders for a target forming radius are defined by:

$$r_i = R_\mathrm{h} \pm \frac{(t - D_\mathrm{b})}{2} \quad \textbf{(10)}$$

for every point of the centre axis of a bundle.

Polygonal shape

As discussed earlier, the size of a wire bundle varies even along the same wire bundle. Since the diameter or the width of the bundle can be regulated with a shape and a size of a handling tool, the tool shape and the tool size have to be adjusted in a way that the formed bundle still fits the tolerance field t. One of the ways is to form a bundle into a polygonal shape. In that case, several approaches can be applied considering the choice of polygon parameters such as number of sides, side length and a bending angle (weather interior angle or exterior).

First approach is to minimize the number of bends (Figure 13a). This is directly influenced by the number of sides of a polygon. To define the rest of the parameters, the minimum number of sides of a polygon needs to be found using the previously given formulae in a way that the whole polygon fits within the tolerance field t. In addition, minimum number of sides maximizes the bending angle. With this approach, to achieve a specific needed angle α_i for each wire bundle only the needed number of bends is done and the list used side of a polygon is not used with its full length (Figure 13a).

Second approach is to keep the side length of a polygon constant (Figure 13b). Although creating more bends, this approach provides more precise shape of a bundle. Side length can

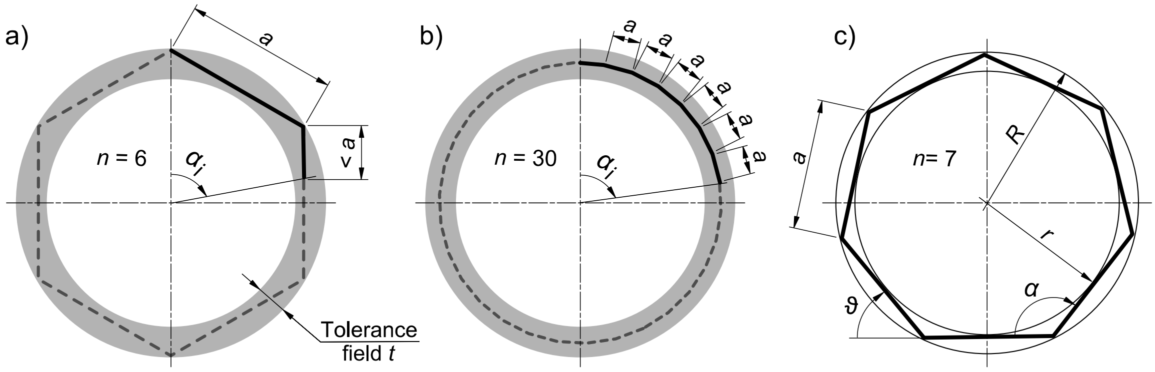


Figure 13 Polygonal wire bundle shape

be chosen in a way that a different length is used for each wire bundle, where the length is calculated to fit the specific needed angle α_i. Another possibility is to choose a unique side length that is used for all the wire bundles of one stator. The length should be chosen in a way that every angle α_i can be reached with an acceptable deviation from exact needed value. Since the unique side length method requires less adjustment between forming two wire bundles of a same stator, that method is preferred.

In following paragraph, formulae and notes on parameters of a regular polygon are given. Illustration of parameters is shown on Figure 13c.

Number of sides n has to be a natural number for a full polygon, however, not all the sides are used nor it is necessary to use the full length of a side.

Interior angle α is a resulting angle after the forming process and can be calculated according to formula [5]:

$$\alpha = \frac{(n-2)\times 180^\circ}{n} \tag{11}$$

Exterior angle ϑ can be observed as a bending angle and calculated according to [5]:

$$\vartheta = 180^\circ - \alpha = \frac{360^\circ}{n} \tag{12}$$

Circumradius R represents the maximum allowed radius and it is limited by the outer border of a tolerance field t as shown in (Figure 13). Circumradius R has to satisfy following condition:

$$R \le R_\mathrm{h} + \frac{(t - D_\mathrm{b})}{2} \tag{13}$$

Inradius r is the minimum allowed radius and it is limited by the inner border of a tolerance field t as shown in (Figure 13). Inradius r has to satisfy following condition:

$$r \geq R_{\mathrm{h}} - \frac{(t - D_{\mathrm{b}})}{2} \quad \textbf{(14)}$$

Side length a is limited by circumradius R and inradius r, i.e by the tolerance field t. Allowed range of values for side length a can be calculated according to [5]:

$$2\,r \tan\left(\frac{180°}{n}\right) \leq a \leq 2\,R \sin\left(\frac{180°}{n}\right) \quad \textbf{(15)}$$

As a side length for forming, mean value can be chosen, or the value can be adjusted in order to achieve a desired bending angle.

2.3 Adjustability and adaptability

Values of all dimensional parameters of the system mentioned in Table 1 are set once at the beginning of the production of a specific stator type. During the production of the same stator type, set values do not change. However, even when the value of only one of the parameters changes for a modified product, the production needs to be newly adjusted. Since the production is serial, the adjustment is allowed to be manual and in discrete steps, especially if that simplifies the solution. If it makes the system more user-friendly, continuous adjustment might be built-in although it is used only when the production needs to be adjusted. For one stator type, the radius, which a curved part of a formed bundle needs to follow, is the same for all wire bundles. However, if several wire bundles need to be formed over the same part of a winding head, the result can be piling of bundles on top of each other. This has several consequences on both forming the preceding bundles as well as on forming the winding head in the following step of production. The problem occurs in increased winding head height what creates uneven wire distribution and asymmetry around the winding head. Additionally, it requires changing the plane for forming the preceding bundles to a higher, parallel plane and it results in instability of the wire bundles.

To enable the more even distribution of the bundles around the winding head, smaller deviations should be allowed between forming every bundle that follows the same part of the stator head. Depending on the forming method, it is possible that already a unique behaviour of each bundle, considering the springback, results in a deviation big enough to place a bundle on the slightly shifted position relative to the previous one.

For adjustability of the system within the production of same stator type, parameters, which are relevant for forming of every bundle, are:

- Position of the fixed point of the bundle on the stator head
- Angle which defines the arc length on which the bundle needs to be formed
- Length of straight part of the bundle

For the known order of wire bundles, the system needs to position to the correct bundle and start the forming procedure.

2.4 Durability and maintenance

As mentioned, the target production is one hundred thousand parts per year with a cycle time of three minutes and a desired working temperature in the factory floor in the range between 18°C and 30°C. Any of the developed concepts has to be adaptable to be used in the given conditions. If there is a need for lubrication, the lubricant needs to be chosen in a way that is active at the given temperature. The lubricated part has to be placed in a way that the maintenance is possible. The service period should be coordinated with other working stations of the production line therefore the lubricant will not be chosen as a part of this thesis. Any materials to be used, as well as any standard elements from different manufacturers and suppliers, which can be implemented in wire bundle forming station, as well need to satisfy given working conditions within the certain service time.

3 STATE ANALYSIS

According to system theory, the problem analysis provided in previous section is only one part of the first phase of systems approach to design and development of products. Additional part is state analysis [6, 39]. For that reason in next paragraphs, analysis is done referring to existing solutions to similar problems as well as to theoretical background considering the material properties and springback effect.

3.1 Existing solutions

Since the given problem is connected to a specific operation of a production line, commercial solutions are not directly available as well as solutions that might be provided in other production lines of a same or similar type. For that reason, research of existing solutions is mostly limited to what can be identified as a similar problem. The closest problem to the given one is bending or 3D forming of single wires. Further ideas with restricted possibility of application can be found in forming of metal sheets, in particular bending. Research with mentioned key topics is done through available normative documents (DIN norm and VDI guidelines), patents and suppliers of metal forming machines.

3.1.1 Metal forming methods

Since the solution being developed should find an application in a serial production, it is preferred to use well know and approved methods. For that reason, DIN norms 8582 to 8587 are inspected for *Forming manufacturing processes* [7 to 10]. Among the rest, norm offers forming methods that use media such as air vacuum, high-pressure air or fluid in a direct contact with a work piece in order to apply the forming force. Nevertheless that a high forming speed can be achieved, it is considered that those methods are not suitable for forming wire bundles due to small dimensions and uneven outer surface of bundles as a result of non-constant cross section. The fluid media is especially not appropriate since it stays on a bundle after forming. Additionally, precise sealing of the mould needs to be established in a great amount of openings and closings. For given reasons, for next solution search steps, the limitation is set to inspect only methods in which forming is done with a mechanical part in a direct contact with a wire bundle.

Out of all offered methods, in Appendix A only those which are considered relevant and in any way applicable to a specific problem of forming wire bundles are presented. In Appendix B, some more methods are added that are found additionally in VDI 3430 guidelines for *Rotary draw bending of profiles* considering the *Categorisation of bending processes* [11].

Although it is given in limitations that bundles should not be stretched, some of the forming methods that use tensile forces are presented because the described realisation of mechanical parts can be adapted and used for forming wire bundles. In general, in order to adapt existing methods, solutions need to be found to how to grip a work piece of a different size and of non-constant cross-section. Similar refers to the forming tool that has to be flexible enough to overcome the same inconsistency problem.

3.1.2 Patents

Investigation of patents is conducted with a focus on bending of wires and wire bundles. Search results can be categorized in several groups, as explained in following paragraphs, depending on how the patent can be used for the purpose of bending wire bundles.

Overall solutions for forming of wire bundles are found in patents [12] and [13]. While [12] deals with 3D forming of a flat wire bundle for use in electrical devices (Figure 14), [13] deals with collecting wire bundles to a same collection point as well as with forming wire bundles between mutually perpendicular planes. As illustrated in images in Appendix C, patent [13] describes three methods for collecting, two methods for forming, as well as two examples of devices for overall operation with wire bundles. Although collecting wire bundles is the goal of the wire bundle forming system, methods provided in this patent are not suitable for the specific task. Methods given in the patent imply collecting bundles with fixed ends placed next to each other in a winding head. In general, in production of stators, not all the bundles in a row need to be collected to form a phase or star-point output. On contrary, as well diagonally distributed bundles need to be collected to the same collection point. Nevertheless, methods in this patent, which consider forming the bundles, especially the one described in Figure 60, can be applied to a wire bundle forming system for example for putting the bundles in a vertical plane.

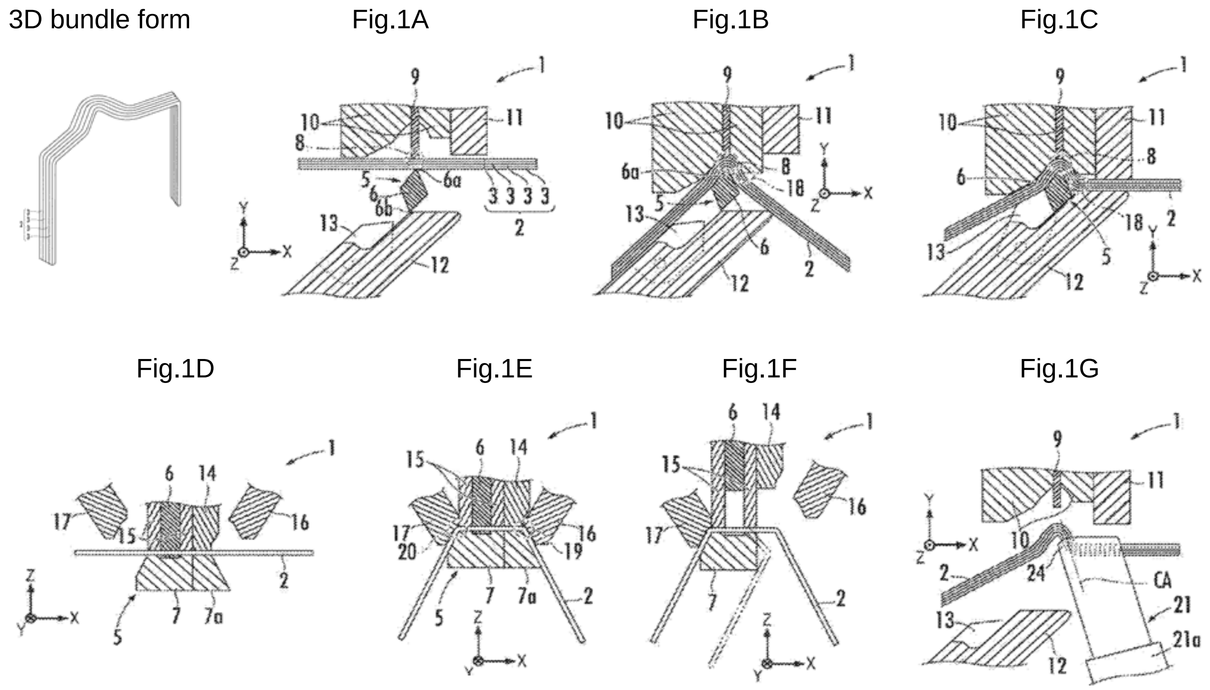


Figure 14 3D bending of a flat wire bundle [12]

Partial solutions for an adjustability function of a system can be seen in patents [14] and [15]. In the next figure on the left, patent [14] offers a possibility of forming wires of different diameter without a need to change a tool. However, this approach limits the possibilities of a system to form only certain number of wire bundle sizes with discrete diameter values. Nevertheless, an idea of using the same forming tool with modifications for different work piece sizes can be as well used for wire bundle forming system. In addition, a part of a machine introduced in patent [15] and shown in Figure 15 on the right can be used as an inspiration for adjusting the forming radius when stator size is changed. With a rotation of a lever (36) either around the point (37) or around the point in upper right corner, it is possible

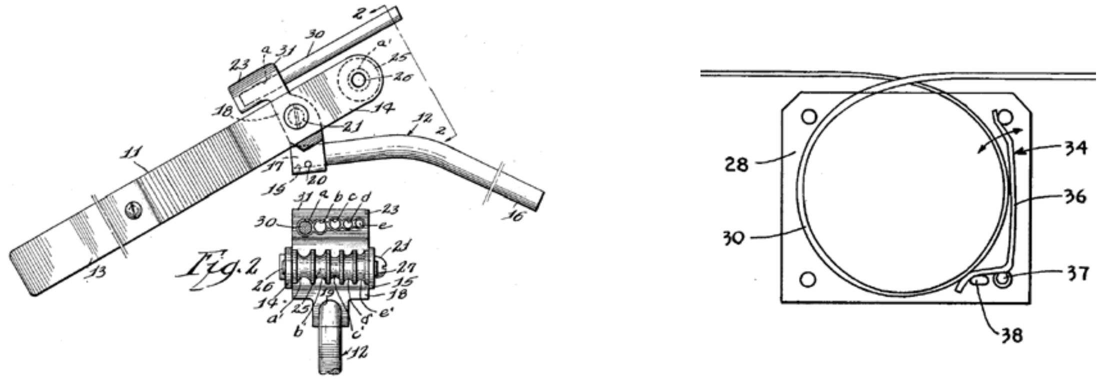


Figure 15 Adjustability for bundle size [14] (left) and stator radius [15] (right)

to create smaller or bigger bending radius of a wire.

Partial solutions for bending into a different plane can be explored from patents [16] and [17]. Patent [16] represents a manual tool that uses a principle of shear force bending as in scissors in order to bend the wire for 90° angle (Figure 16, left). For the same purpose of bending the wire for 90°angle, a flange can be used by following the procedure of bending given in patent [17] (Figure 16, right). Advantage of both solutions is that a bending angle might be regulated by different angle of rotation of lever (2) in patent [16] or of flange (17) in patent [17].

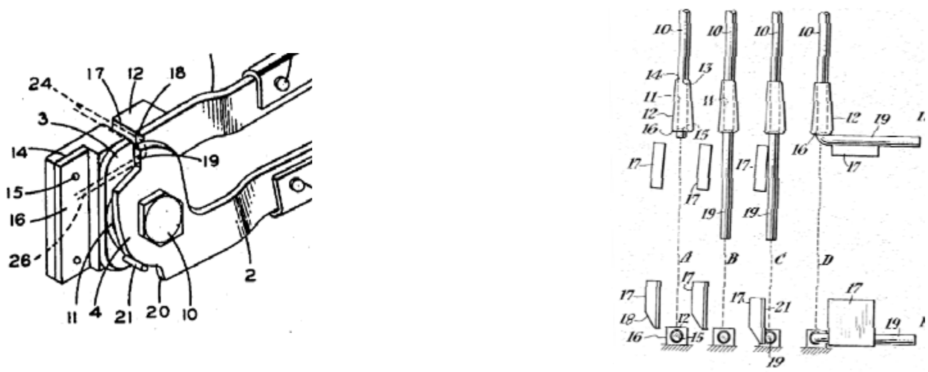


Figure 16 Shear bending [16] (left) and procedure of flange bending [17] (right)

Bending method using rotating pins is presented in patents [18] and [19]. Method used in patent [18] bends a steel spring wire with a pin mounted on a rotary plate. With a rotation of plate, the pin gets into a contact with a wire and produces local deformation (Figure 17). Additionally, in the figure it is shown how springback takes an effect and how to regulate it by over-bending.

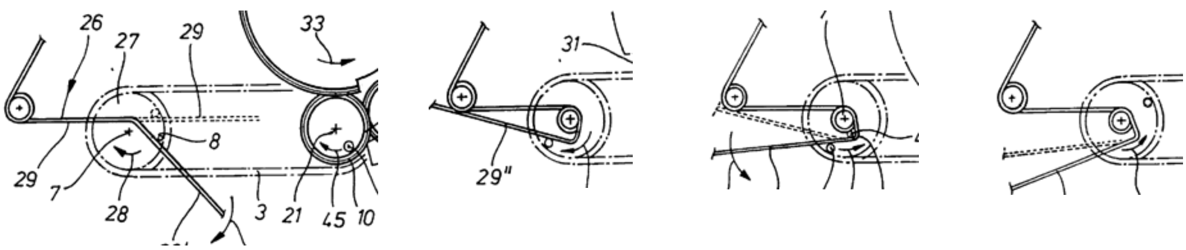


Figure 17 Over-bending of a wire with rotary pin [18]

Another method that can be used for creating a polygonal shape of wire bundle is presented in patent [19]. Bending is done with two pairs of pins where each pair of pins is mounted on a separate rotary plate. By rotation of plates, wire is bent into a desired shape. The parameters that determine the shape are (a) distance between pins in a pair, (b) diameter of a wire and (c) rotation angle. (Figure 18)

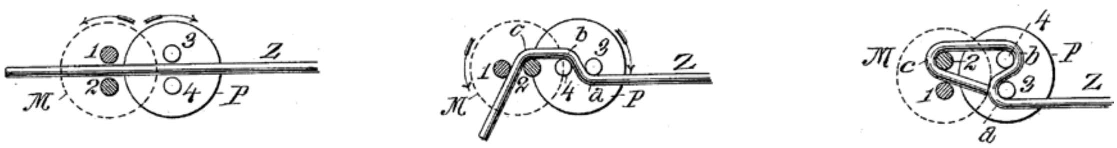


Figure 18 Bending with two rotary pairs of pins [19]

In application of a method from patent [19] for wire bundle bending, it is enough that only one plate rotates while the other pair of pins provides guiding support.

Bending methods using a die are shown in patents [20] and [21]. In patent [20] a die and a punch of a rounded form are used as shown in Figure 19.

Fig.4. Fig.3. Fig.6. Fig.5.

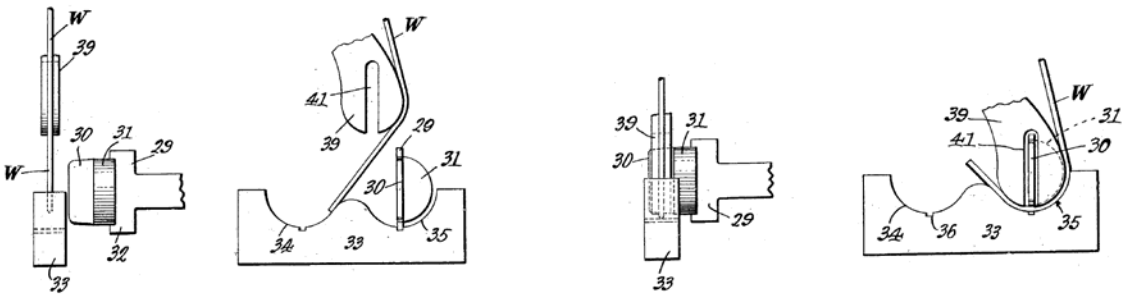


Figure 19 Bending in a die [20]

While in the patent [20] forming of a bundle is done inside the die, in patent [21] forming is done around the die with an angular lever arm that slides over a wire in order to press it against the form as shown in Figure 20.

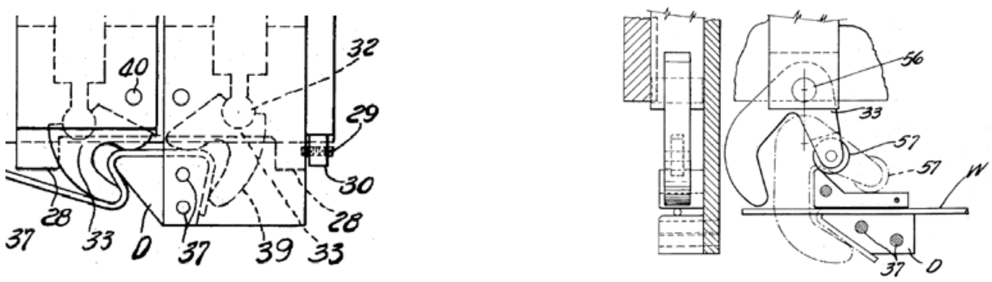


Figure 20 Bending with a lever around a die [21]

If the radius of a die and punch according to patent [20] is increased to a radius of winding head of a stator the method can be applied for forming a wire bundles. On the contrary, the method from the patent [21] can be applied for forming of polygonal shape if the lever arm and a die are manufactured with smaller forming radius.

3.1.3 Commercially available solutions

As commercially available solutions for problems similar to forming of a wire bundle, automatic bending machines for bending of single wires, pipes and sheet metal are detected as the most similar. Machines for bending pipes and sheet metal use forming methods such as bending in die (both symmetrical and non-symmetrical), folding and free bending with a shear force over the edge of holding tool. Although the work piece is different, those forming methods can as well be adjusted for forming of wire bundles.

Through the search for commercially available automatic bending machines for bending of wire, it is observed that most of them work on a similar principle of forming a wire by rotary pins or by shear force. In Figure 21, one of typical machines is shown. The machine is presented in a patent [22], that describes devices, systems and methods for automated wire bending.

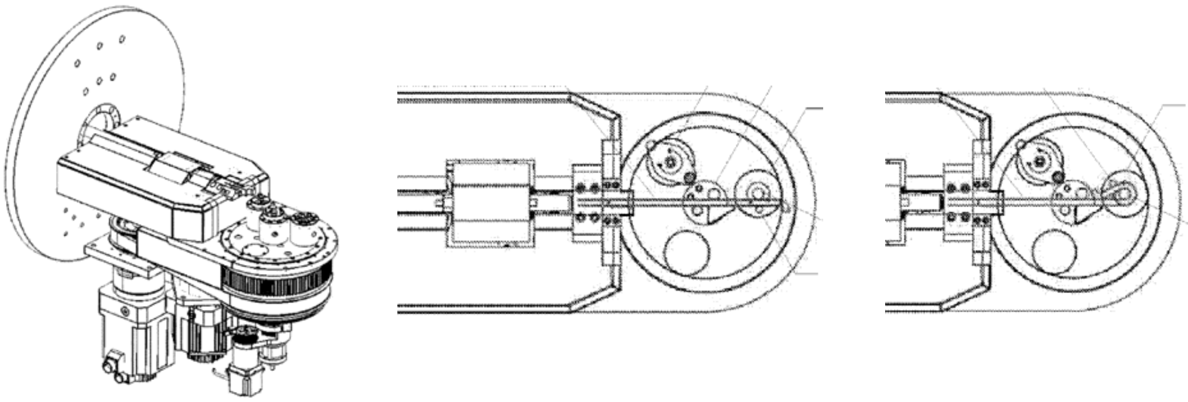


Figure 21 Automatic wire bending machine [22]

One of significant differences between commercially available automatic wire bending machines and the given problem of forming wire bundles is the fact that the wire forming machines use a wire feeder and the infinite wire length. Wire feeder at the same time holds the wire firmly and drives the wire through the bending pins. Since in the given problem wire bundles have a definite length, motion of a bundle during the forming has to be established relatively to the forming tool. This can be done by either moving the whole stator while forming tool remains static or by moving the forming tool along the bundle. Additionally, wire bundles have a non-constant cross section and at the free end of a bundle, wires are twisted in order to remain together in a bundle. Due to those reasons, it is not applicable for a wire bundle to only slide between the forming pins as is the case with a wire on a wire bending machine. In order for wire bundle to come into a contact with a wire bundle holder, bundle needs to be gripped, Unlike for the fixed positions of the pins in a wire bending machines, for gripping the wire bundle, relative motion between gripper fingers needs to be enabled.

3.2 Mechanical properties of a copper wire

Wires used in the production of stators of electrical motors are enamelled round copper wires with an amount of copper, oxygenic, over 99% and polymer insulation coating. For the production of wires, wire rods of annealed bright copper Cu-ETP1-A..-P (CW003A) is used as per DIN EN 13602 (2013-09). The most commonly used enamel film insulation is based on polyvinyl acetals, epoxy resin and polyesters [23]. Often dual coatings are provided to increase the properties of enamelled wires. The thickness of the coating defines the wire grade and the thermal resistance defines the wire class.

Although the specific material properties of a wire are defined by the manufacturer, required properties are defined by both international and internal company norms. Mechanical properties of the wire that need to comply with normative requirements are:

- *tensile strength* of 200 N/mm^2 or over 250 N/mm^2, depending on the required delivery conditions [24]
- *elongation after fracture*, for wires of diameter between 0,5 mm and 1 mm, needs to be minimally 24% [24]
- *adhesion* of coating to the wire needs to stand, for wires of diameter between 0,63 and 1,4 mm, 10 revolutions around the winding mandrel of a size of one nominal diameter of a wire and with pre-elongation of 10% [25]
- *frictional coefficient* maximally 0,14 [25]
- *flexibility* in terms of cracking of the coating requires no cracks after 32% of elongation [26]

Additional properties provided by the manufacturer consider:

- *hardness of the coating* expressed as pencil hardness of 5H [27]

General mechanical properties of annealed copper:

- *yield strength* of 80 N/mm^2 [28] and [23]
- *modulus of elasticity* of 125 000 N/mm^2 [29]

Other specific properties such as resistance and conductivity are considered as not relevant for the problem of wire bundle forming, thus they are not mentioned in this paragraph.

Mechanical properties of wire bundles

Additional not-fixed parameter addresses the mechanical properties of the wire bundles. Mechanical properties of wires depend on the source of the material, manufacturing process and the operations through which the wires have passed before they arrived to wire bundle forming station [30]. Although the manufacturers produce wires according to given standards, the deviations in mechanical properties still exist from batch to batch and from manufacturer to manufacturer. Moreover, any further change of the wire shape, as, for example, during the inserting process of winding, results in dislocations of the atoms in a structure of the wire, thus changing the material properties [31]. Due to uncertainties of each of the processes, the amount of change in properties cannot be predicted easily. Additionally, the forming process deals with bundles of wires instead of with only one wire. That means that the mechanical properties of a wire bundle are a combination of mechanical properties of all the single wires in a bundle. Taken that the probability that the mechanical properties of each single wire in a bundle are modified in a same way is low, it is even more difficult to predict overall mechanical properties of a wire bundle.

3.3 Springback

Springback is an elastic recovery of a material that happens at the end of the deformation operation. After the bending pressure is removed, stored elastic energy causes the material to partially recover towards the original shape, leaving only the plastic deformation visible. In bending operations, springback is measurable as a difference between included bending angle of the forming tool or the forming operation and the resulting angle of the metal part. The bigger the modulus of elasticity and the yield strength of the material, the bigger is the springback. [32]

There are several known methods for compensation of springback, most common of them being bottoming and overbending. *Bottoming* consists of plastically deforming the part in the region of the bend by squeezing it at the end of the stroke [32]. This implies the use of punch and a die as a forming method, suggesting that the method is not suitable for any forming process. On the contrary, *overbending* is bending to an angle smaller than the needed one, with an intention of achieving the target bending angle after the elastic recovery. As such, *overbending* is an applicable method for different forming processes and it is recommended for purposes of this thesis.

Influence of process parameters on springback

According to [33], several parameters are detected as influential for the process of bending of steel sheet: (a) coating thickness, (b) orientation of a work piece, (c) punch radius, (d) die opening, (e) die radius and (f) punch velocity.

For conducting an experiment, [33] used a method of free bending as shown in Appendix A, Table 8. For forming, work piece is supported with a die in two points with a certain radius and a force is applied to a work piece, via punch, in the middle of a die opening. A springback angle is defined as the difference between bending angle during the loading and an angle of the bended work piece after unloading. This means that, the bigger the springback angle, the bigger is the elastic recovery of a material.

Gained results showed that friction coefficient plays significant role in the bending process. When friction is decreased, the springback angle increases. Parameters that reduce friction are increasing coating thickness as well as increasing velocity of a punch. Further, value of die radius can be joined with a die opening in a way that increasing the radius at the same time increases the distance between supporting points. In the case when supporting points are further away, the deflection can be considered to be bigger and plastic deformation smaller, therefore, the springback angle increases with increasing die opening. Considering the radius of a punch it can be noticed that the smaller the radius the higher is local strain what results in larger plastic deformation, thus smaller springback angle. [33]

It is assumed that all of the results, apart from the one considering orientation of a work piece, can be applied to forming of a wire bundle as well.

4 PLANAR FORMING CONCEPTS

To a concept development, it is possible to approach from several sides. One of the approaches, which is closely connected to developing an automatic manufacturing process, is (a) copying the manual process as it is. Other approaches are (b) copying concepts that already exist either in a particular industrial branch or in a neighbouring branch, and (c) deriving a concept from results of scientific or engineering research. [34]

Nevertheless, that the first approach, that is to imitate directly the manual process with a machine, seems to be logical and intuitive, it most often does not provide a solution that is well suitable for the industrial application. One of the reasons is the fact that in a manual process, human worker does not only use his hands but also combines hand motions with other senses he has on a disposal, e.g. vision, touch, hear or simply a feel. Moreover, human arms, hands and fingers have much more degrees of freedom than any existing mechanism [34]. In addition, they have more degrees of freedom than it is necessary to have in order to perform most of the operations that can be automated. However, observing the manual manufacturing process helps the designer to understand the task and the problem better and enables him to look at the problem from another side, noticing different possible approaches to the same task.

According to the second approach of copying the existing solutions in a neighbouring industrial branch, many possible forming methods are already detected during the *State analysis*. However, detected solutions are not directly applicable to a given problem due to the different nature of a work piece. Unlike wires, pipes and sheet metals, wire bundles are not consistent in their form nor in their mechanical properties. For that reason, as a next step of completing the given task, the third approach is chosen, that is to generate concepts from an engineering research. To bring the following step of a solution search to a research level, level of abstraction is chosen to be higher than the one of forming methods given in *State analysis*. Setting the level to observe the problem with a higher abstraction should increase the creativity in looking for new forming methods that should suit the specific problem better than the existing ones.

At the beginning of a concept generation, assumptions are made to reduce the number of open points, thus to reduce the space of solution search by dealing with less flexibility and focusing on a real problem that needs to be solved, that is the planar forming of a wire bundle.

4.1 Assumptions

Since the demand on a high flexibility of a system does not allow full definition of all of the needed parameters for a system development, some of the open points from task description need to be fixed through making assumptions. Points are observed which have an influence on functions of the system in a way that they require additional or change specific existing functions:

- order of laying wire bundles
- initial position of each of the wire bundles

Meeting the given assumptions will ensure usability of the system concept for more use cases depending on specific requirements of each individual stator type. If the assumptions cannot be met in the implementation of the system, it may be possible that some parts of the concept or even the complete concept needs to be revised and adapted to new conditions.

4.1.1 Wire bundles laying order

The main principle of laying the bundles is to make as less crossings of bundles as possible, and when they are unavoidable, to place them where there is enough space, for example in a place between two winding coils where there is a gap. In addition, the intention is to use the shortest way for each bundle when forming it from fixed point to the collection point. For the wire bundle forming system, it is desirable that each bundle can be formed at once without a need for temporary, intermediate positioning of partially formed bundle. If it occurs that one bundle should stay in a way for full forming of the other bundle at once, it is assumed that it is possible to find a compromise between additional crossings and good practice in creating the layout pattern. Therefore, it is expected that the layout pattern provide following information, which are necessary for a wire bundle forming system to have a clearly defined operation task:

- Unique order of laying the bundles in a way that every bundle can be fully formed at once – for example, if the wire bundles are counted from 1 to n_b from the pre-defined zero-position on the stator, the exact order can be defined as ($n_b - 1$)–1–n_b–...

- Exact positions of all the wire bundles – for example with an angular position α_{bi} measured from the pre-defined zero-position on the stator
- Exact positions of all the collecting point bundle – for example with an angular position α_{cj} measured from the pre-defined zero-position on the stator
- Definition of which wire bundle should be associated to which collection point
- The direction in which each bundle should be formed to reach the collection point in the shortest way, when that direction is different from the one which can be calculated using the equation (4) – for example with "+" or "-" according to the sign convention proposed above

For illustration of listed parameters, refer to Figure 10 in this thesis.

4.1.2 Wire bundles initial arrangement

In addition to the known position of the fixed point of the wire bundle, knowing the exact position of the whole bundle makes it easier to adjust the system to operate automatically. The way wire bundles are arranged around the stator when it is delivered to the wire bundle forming station defines not only the position of each of the bundles but it also influences handling strategy and geometrical arrangement of the elements of the workstation. Defining the way of initial positioning of bundles ensures the repeatability of the process even when some of the parameters are changed.

Generally, three possible wire bundles arrangements, which might be suitable for the purpose, are recognized: (a) horizontal tangential distribution, (b) vertical radial distribution and (c) horizontal radial distribution. In the same order, the possible initial arrangements are illustrated in Figure 22. Additionally one formed bundle is shown to better illustrate the consequences of each possible arrangement.

Horizontal tangential distribution (a) takes less space than the radial distribution and provides better initial position for forming in the fixed start point of an arc shaped part of the bundle. Since not all the bundles are formed in the same direction, it is required to lay each bundle in

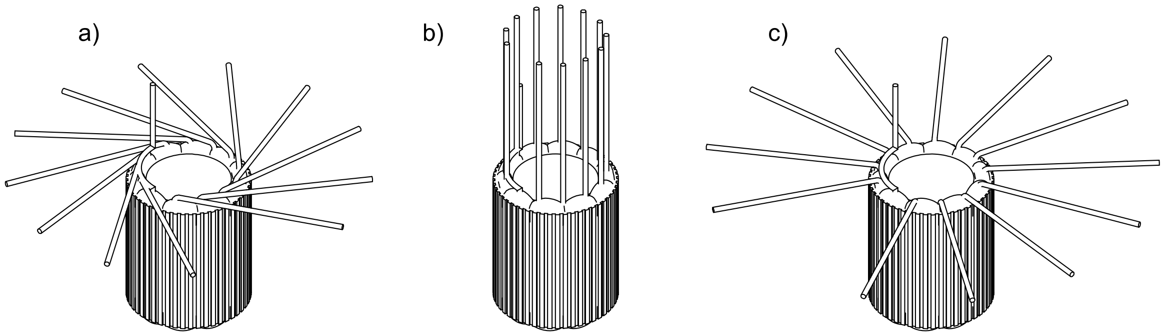


Figure 22 Possible initial arrangements of wire bundles
a) horizontal tangential, b) vertical radial and c) horizontal radial distribution

the correct tangential direction in advance. Nevertheless, in that case, bundles are crossing each other. That means that, to provide an accessibility to each bundle, it is necessary to place the bundles initially in the order opposite to the order of forming. For example, if the laying order is defined as ($n_b - 1$)–1–n_b–($n_b - 2$), then the wire bundle placed on the top of arranged bundles should be ($n_b - 2$), with wire bundle n_b underneath and bundles 1 and ($n_b - 1$) even lower. When this kind of an arrangement is ensured, each bundle can be taken and formed without interfering with other bundles. However, in this way bundle crossings are inevitable, what makes it more difficult to generalize the bundle gripping procedure at exact point. Since it can happen that the crossing is exactly on the position where the bundle should be gripped, this is considered as main disadvantage and as an argument to *reject* this possible arrangement.

Radial arrangements solve the main issue of tangential arrangement, meaning that they provide a good accessibility to each wire bundle at any time and they do not require special order of piling the bundles. However, both vertical (b) and horizontal (c) radial arrangements require more space. While vertical arrangement requires bigger height of the station, the horizontal one requires bigger ground area. In the existing examples of stators, most of the fixed wire bundle ends are positioned either on the top of the winding head or on the outer side. For that reason, it is assumed that putting the wire bundles in the horizontal initial arrangement will result in fewer crossings then if the wire bundles are initially put vertically.

In order to ensure clear path for forming every wire bundle, it is necessary to put a formed bundle in a position in which it will not interrupt further forming process. If wire bundles are initially arranged in a horizontal plane and extra length of a bundle that is not formed is left in a plane of forming, it can happen that it overlaps non-formed wire bundles in a way that it is not possible to grip them. Latter can happen regardless the position in which the extra length of the bundle is left. This means that neither tangential nor radial orientation of extra bundle length is suitable. To avoid the possibility of crossing the extra bundle length and non-formed bundle, the rest of the bundle after forming can be put in the plane vertical to the plane where the wire bundles are initially arranged.

Similar applies to a distraction of laying and forming the bundle on the winding head. If possible, any additional crossing should be avoided between formed bundle and/or its extra length and the bundle that is being formed. Since bundles are formed in a horizontal plane of a winding head, possible solution to prevent crossing is to always keep the rest of the bundle in a plane vertical to the plane of forming. When reasoning about positions of desired planes for the extra bundle length are summed up, we can say that the horizontal radial initial arrangement is a better choice than the vertical arrangement.

However, it can occur that on the specific stator type, more of fixed wire bundle ends are positioned on the inner part of winding head than on the top or on the outer side. Putting bundles to initial position radially out of the winding head can then produce too big amount of additional crossings. In that case, the vertical initial arrangement of wire bundles should be considered. Accordingly, extra bundle length should then be formed in the horizontal plane. Since the main forming of the bundle is anyhow done in the horizontal plane, forming of the extra bundle length can be done using the same method with different parameters. Since in the existing examples of stator types, only the minority of bundles start from the inside of the stator head, in this thesis the horizontal radial distribution will be taken as relevant.

Fixing the initial position

To ensure the repeatability of the process, the position of each of the wire bundles needs to be strictly defined. Additionally, no movement of the bundles is allowed while the stator is transported from one workstation to another. One of the possibilities to keep the position of each bundle is to use clamps on a work piece carrier that enables the stator to advance on a conveyer through a production line. Used clamps can be active or passive. Active clamps have an actuator that controls opening and closing of the clamp. However, since clamps are placed on a work piece carrier it is preferred to avoid a need for electrical power, thus it is preferred to use non-active clamps. The passive clamp for this use has to be designed in a way that it ensures that all the wires in a bundle are fixed on an exact position and that they cannot move while the work piece carrier moves along the conveyor. At the same time, it has to be possible to take all of the wires in a bundle out of the clamp in a way that the clamp produces no resistance to the motion of the bundle. In other words, the bundle should not be exposed to any tension, compression, torsion, shear or bending while being taken out of the clamp.

Ensuring the correct start position for forming

With different stator types and different design of the winding it can happen that the position of the wire bundles in the winding head varies along the height of the head. The difference in the position of a bundle can occur also between pre-formed and non-pre-formed head. When winding head is pre-formed the position of each wire bundle in the winding head is better defined, that means that the possible movement of the bundle is reduced. In case if a more precise forming of the wire bundle next to the point fixed in the head is needed, the wire bundle has to be brought above the head level in order to start the forming process with a current wire bundle forming system. When this motion cannot be done with the current system, an additional module is needed which will ensure the position of a bundle assumed for the current system. The care should be taken that it is possible with the forming system to overtake the wire bundle from the additional module. This means that the suggested approach to changing the initial position of the wire bundle is to keep the bundle radially distributed around the stator and move it in the parallel plane that lays over the top of the winding head.

4.1.3 End of planar forming

Planar forming system deals with forming the curved part of the wire bundle, which is defined as a part of the formed bundle between predefined start point of the bundle and the collection point for that specific bundle. Forming in the collection point is in general covered by an additional *System for placing a bundle into neutral zone*. Although the development of the additional system is not part of this thesis, with each planar forming concept, the suitability of forming method for this operation is discussed as well.

Processes that follow forming the wire bundles are the processes of phase and star-point preparation as well as final head forming. It is assumed that the following processes additionally fix the position and the form of wire bundles. That means that a formed wire bundle does not have to be self-reliant after forming. Shape of formed wire bundles, however, needs to be preserved while being transferred to the location of next process. Therefore, it is suggested to fix the bundles in a plane vertical to the plane of winding head. When fixing is done with clamps, the same rule applies as for fixing in initial position, that the bundle should not be exposed to any tension, compression, torsion, shear or bending which might jeopardise the produced form. A similar type of a clamp can be used as in initial position, but with taking care that some of the wire bundles, which are already placed in a clamp, cannot fall out when adding other bundles. The problem can be solved as well with clamping each bundle in a separate clamp where clamps for one phase or one star-point are placed closed to each other so that there is no confusion to which bundle group which bundle belongs.

4.2 Planar forming of wire bundles

Functional decomposition of a subsystem for planar forming of wire bundles is shown in Figure 23. In order to keep the level of abstraction of functional decomposition corresponding to the level of task definition, and at the same time to stay solution independent, low level of detail is involved in the structure. As mentioned already in a decomposition of an overall problem, the main function of a wire bundle forming system, accordingly of a planar forming subsystem, is to *Form a wire bundle*. Nevertheless, when concentrating only on planar forming of the curved part of a wire bundle and taking possible shapes of arc or polygon into account, we can say that there are two sub-functions needed to fulfil the task:

- *Deform the wire bundle* and
- *Handle the bundle until collection point is reached*.

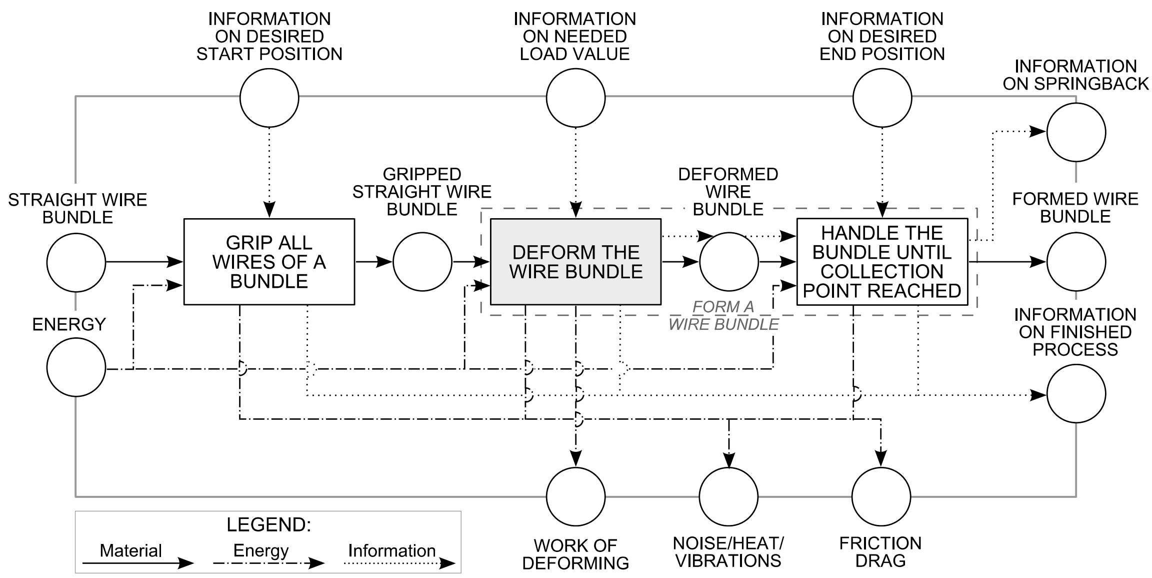


Figure 23 Functional decomposition of a subsystem for planar forming of wire bundles

First function deals in general with changing the shape of a straight bundle while the other function ensures that the shaping is done for the complete length of a desired curved part of a formed bundle. Hereby it is important to notice that requirements which handling function needs to meet come as well from the method chosen for deforming the bundle. Similar applies as well to a gripping function that is only the auxiliary function to support the forming process. For that reason, problem-solving starts with finding, in a frame of *Form a wire bundle* function, a suitable procedure for planar forming of a wire bundle along the winding head. In addition, partial solutions are offered which address the auxiliary gripping function.

Approach

To enable observing the problem more clearly, in a first step level of abstraction is set on a level of physical principles. Possible solutions are inspected by looking at simplified mathematical models and illustrated by mechanical symbols. For mechanical *Realisation* of physical *Forming principles*, ideas gathered from state analysis are used to define *Forming methods* suitable for laboratory testing (Figure 24). Analysis of experimental results pointed to advantages and disadvantages of certain methods. Based on those observations, evaluation of *Forming methods* is done in order to eliminate those methods that are less appropriate for application to a specific problem of forming a wire bundle. Moreover, adaptations of methods are done with respect to experimental results.

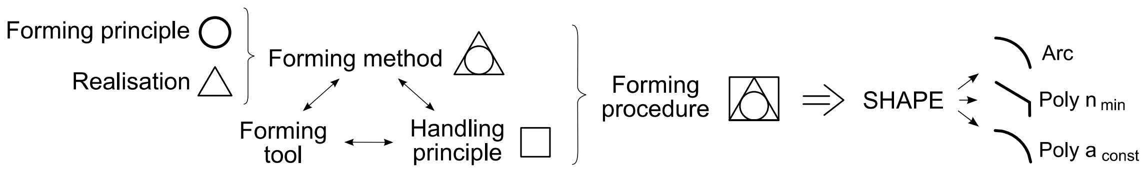


Figure 24 Development of forming procedure

Nevertheless, *Forming methods* themselves are not sufficient to get an exact desired *Shape* of a wire bundle. For a *Shape* that can be realised in several forms (Figure 24), a certain *Handling principle* needs to be applied together with a *Forming method* to complete forming along the full forming length of a bundle. In order to fully define a *Forming procedure* that combines *Forming method* and *Handling principle*, some of parameters of *Forming tool*, especially the size, need to be given in advance (Figure 24). Analysis of *Forming procedures* defined in this way, gives then a possibility to evaluate the suitability of each procedure and choose the most appropriate ones for developing them into *Concepts* for a planar wire bundle forming system.

4.2.1 Forming principles

Although to *Deform the wire bundle* is an essential function itself, it can still be decomposed into two basic functions that need to be performed one after each other in order to achieve the main goal:

- *Support the wire bundle and*
- *Apply the load.*

In order to simplify the approach to solution search, following functional decomposition represents only base level of creating a form. This enables to keep the solution search on a level of abstraction that is appropriate for a level of task definition.

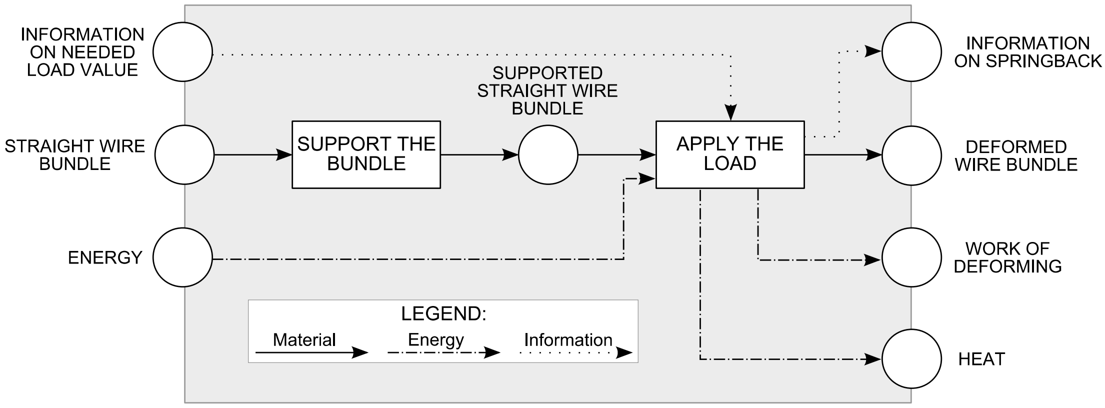


Figure 25 Functional decomposition of "Deform the wire bundle" function

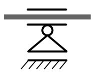
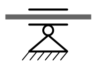
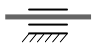
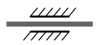
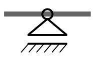
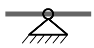
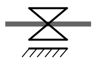
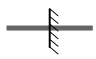
Due to small number of partial functions and relatively big amount of options for fulfilling the functions, it is considered that a morphological chart is not a suitable tool for their representation. Therefore, possible solutions to each of the partial functions are described and discussed in next paragraphs. Afterwards, they are combined in a form of physical forming principles.

Support points

Support point is a point in which a wire bundle and a wire bundle forming system directly interact. On one side, the intention of a support point is to reduce degrees of freedom of a wire bundle relatively to the system. When the motion of the bundle in support point is limited only to translation along the wire bundle length, we will consider the wire bundle to be "free". When the translation is disabled as well, there are no degrees of freedom of the wire bundle in a supporting point. In that case, we consider the wire bundle to be "fixed". Depending on the physical realisation of a support point, it is possible that a rotation around the longitudinal axis of a wire bundle occurs, however that is not the target motion. On the other side, the support point is a part of the system and interacts with the system surrounding. Relative to the surrounding, either the point can move in any direction or the motion of the point can be restricted. Hereby the degrees of freedom of the point are independent from physical realisation of the point as well as it's specific position or function.

When all the motions in space are allowed, we consider the point to be "free" from the surrounding. If the point lays in a certain plane, we consider the point to be "fixed" to the surrounding. Although not necessary, nevertheless if the point is fixed to one plane, either a translation or a rotation in that plane can be enabled.When the described options are combined, there are in total ten possibilities on how to establish the interaction between the wire bundle and a wire bundle system together with the system surrounding. Possible support points are illustrated in Table 2.

Table 2 Possible support points

	Respective to surrounding				
	Free	**Rotatable and translatory**	**Rotatable**	**Translatory**	**Fixed**
Free wire bundle					
Fixed wire bundle					

For the application purposes, the support point is a holder of a wire bundle, whether realised as a clamp, a gripper or other mechanical part. The surrounding system area to which the support point can be fixed could, for example, be the top of the stator head, the work piece carrier or similar. However, the physical realisation of the support points highly depends on the overall handling process. Therefore, it will not be further discussed in this section.

Loads

In general, a load can be a force, a moment or a combination of both. In a space, there are six general loads that can act in a point: normal force, transversal force in vertical plane, transversal force in horizontal plane, bending moment in vertical plane, bending moment in horizontal plane and a torque (Figure 26, left).

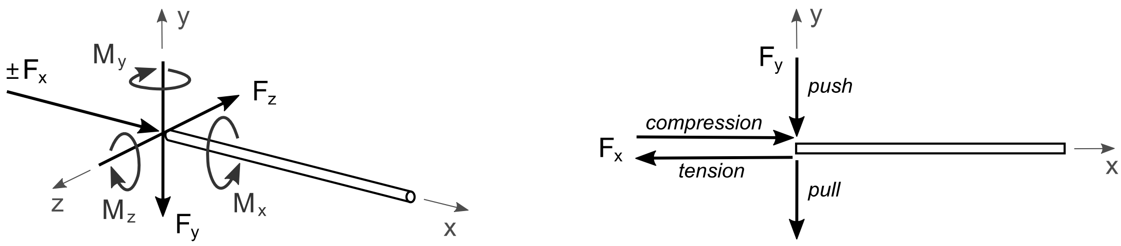


Figure 26 Possible loads

Whereas the transversal forces always produce bending or shear load regardless the direction in a coordinate system, the direction of the normal force has a significant influence on possible forming methods. Considering the direction of the normal force, we distinguish between compression and tension (Figure 26, right). However, when we consider the possible point of application of transversal forces, every transversal force can be realised as either a push or a pull force (Figure 26, right). Although the pull and push force are physically the same, differentiation between them provides wider spectrum of possible forming methods. However, this differentiation is not used for generating forming principles since it suggests which technical realisation should be used. Nevertheless, it can help in following steps of further development

Forming principles

To change the form of a straight wire bundle by applying a load, the wire bundle has to be supported in at least two points. Moreover, the active load needs to move along a certain path to complete the forming process. Forming principles are created by varying different load possibilities as well as type and number of support points. For load cases, only active loads are considered. On the illustrations of the principles given in Table 3, the resulting shape of the wire bundle is illustrated with dashed line. Additionally, for full definition of the principle, dashed arrows indicate the direction and a path of motion of active loads. However, for a realisation of the principle, the indicated motion can be done either by moving a tool producing a load or by moving a wire bundle.

Table 3 Forming principles (systematic search)

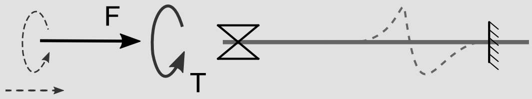
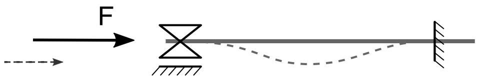
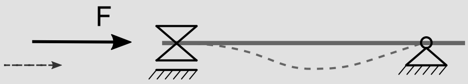
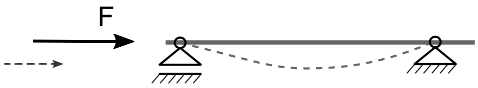
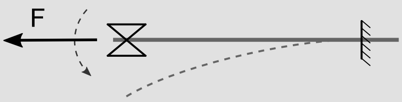
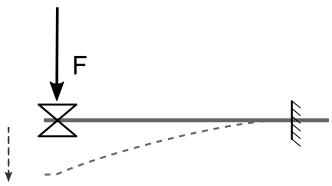
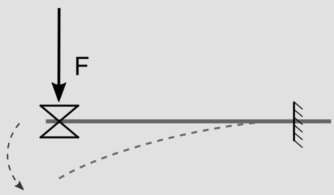
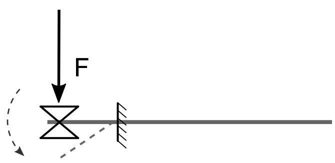
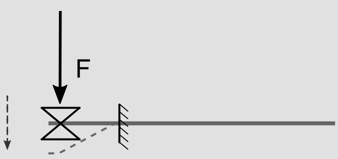
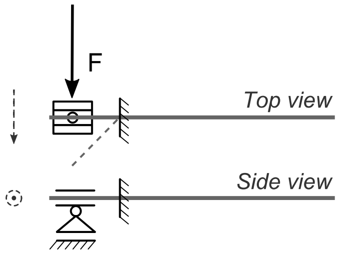
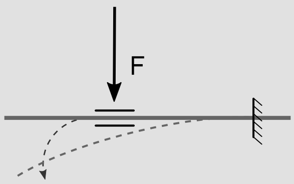
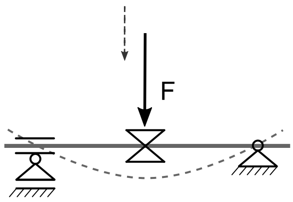
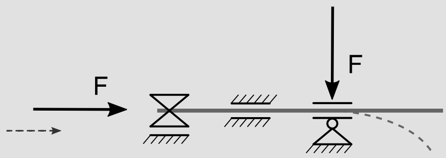
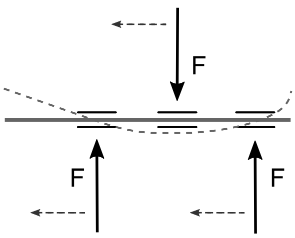
No.	Forming principle	Comment
a		3D forming of both curved and straight part of a wire bundle at the same time
b		2D forming
c		2D forming
d		2D forming
e		2D forming; force remains as a continuous tension during the motion
f		2D forming
g		2D forming; during the motion force stays perpendicular to the wire bundle
h		2D forming; during the motion force stays perpendicular to the wire bundle
i		2D forming

Table 4 Forming principles (systematic search) - continue

No.	Forming principle	Comment
j		2D forming
k		2D forming; during the motion force stays perpendicular to the wire bundle
l		2D forming
m		2D forming; wire bundle moves due to parallelly applied compression force
n		2D forming; all the forces move simultaneously

NOTE: "2D forming" refers to forming of a curved part of a wire bundle in one plane. This means that a wire bundle needs to be kept in a plane of forming and that any possibility for a wire bundle to leave the plane of forming needs to be prevented. On the sketch, the plane of forming is aligned with a plane of paper.

4.2.2 Realisation through experiments

In total seven experiments were designed according to suggested forming principles. The aim of experiments is to inspect the behaviour of wire bundles and observe the suitability of different forming methods for producing a desired wire bundle shape. Additionally, experiments help to detect advantages and disadvantages of certain forming method as well as specific requirements and additional problems that need to be solved in order to fully apply the method. Next figure shows which forming principles are transferred to which experimental settings. To save resources for conducting experiments, forming principles were not directly tested if conclusions for those principles could have been drawn on basis of other experimental results.

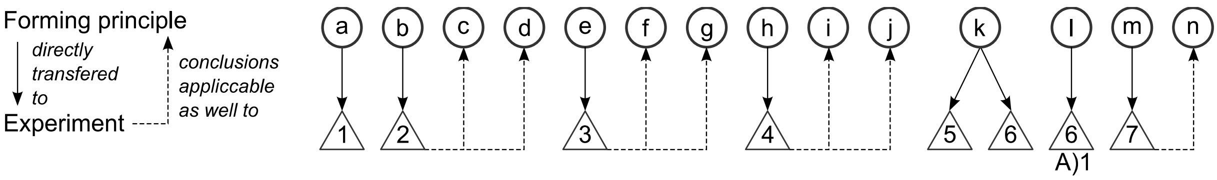


Figure 27 Relations between forming principles and conducted experiments

Whenever possible, the common tools were used in experiments in order to enable better comparability of the results. Such a common tools are:

- 6-axis robot
- Pneumatic parallel 2-finger grippers
- Cylindrical punch with a diameter of 100 mm
- Die in a form of part of an annulus with outer radius of approx. 150 mm and inner radius approx. 120 mm

Additionally, all the experiments are done with wire bundle testing samples of a same type. Testing sample consists of eleven single copper wires with a diameter of 0,56 mm and length of approx. 500 mm. On all the testing samples, bundle ends are twisted, as in the production of stators, along approx. 15 mm length to prevent single wires to go apart from each other, thus to keep the consistency of the bundle.

Experiment 1

First experiment tests the forming principle *a* when moment of torsion is applied to a bundle and at the same time the compressive force is added to produce the motion of a bundle along the longitudinal axis. Experimental setting is chosen as twisting between fixed point and point in motion.

Description

First, each of two ends of straight wire bundle testing sample (WB) is placed in the grippers (G1) and (G2) respectively (step 1). Gripper (G1) is moveable and mounted on a 6-axis robot, while the gripper (G2) is fixed on a table. Using a robot program the torque is applied to the bundle by rotating the gripper (G1) around the longitudinal axis of the bundle. At the same time, the robot provides translatory motion of gripper (G1) along the defined path (step 2). Described steps are shown in Figure 28.

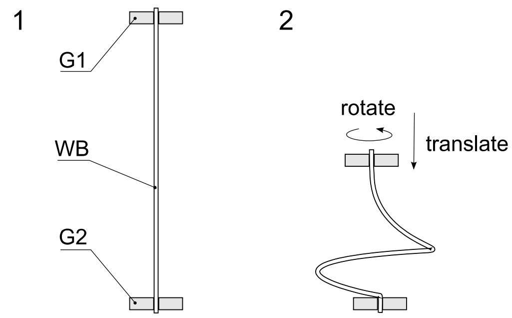


Figure 28 Experiment 1 – steps

In this experiment, several paths as well as several rotating angles of gripper (G1) are tested in order to observe the influence of those parameters on the final shape. Hereby, path is defined by starting and ending point, where each of the points is defined with six coordinates in space: three linear dimensions *x*, *y* and *z* along axes of "world coordinate system" and three angles of rotation *r*, *p* and *w* respectively around axes of the same system. The robot moves the gripper coordinate system linearly between defined points of the path. Accordingly, the difference between starting and ending defined angle, around vertical axis, represents the angle of twisting the bundle.

Results and analysis

Experiment showed that it is possible to use the described method in order to produce the complete required three-dimensional shape of a wire bundle in just one step of forming. However, the angle of rotation of gripper (G1) is a key parameter to achieve a certain shape of a bundle and multiple experimental trials are needed to roughly adjust it. If taken that for each wire bundle of a same stator type it is necessary to adjust the length of forming, the number of trials that need to be done, in order to set an acceptable shape for each bundle, significantly increases. Further observation is that the rotation of the gripper (G1) has to be performed in the same direction in which single wires are twisted to form a bundle. Otherwise, wires can go apart from each other resulting in the loss of the form of bundle itself. In that case there is no control over which wire will be formed in which way and the used method does not result in desired wire bundle shape. In addition, the resulting shape around the points where the bundle is gripped is difficult to predict. The reason for that is that a bigger force is needed to do forming on a smaller bundle length and in the described setting, it is difficult to adjust parameters of the process to use different load.

Possible adaptations

To avoid pressing the formed bundle against the winding head, and still increase the repeatability of the shape of a bundle around the gripping points, additional supporting points should be added. This is possible to achieve with, e.g. additional parts in a form of a die, mounted on a fixed surrounding or on additional robots.

Experiment 2

Second experiment tests forming principles where the axial compression force is used to create a desired wire bundle shape by means of buckling. Experimental setting is chosen as a realisation of forming principle *b* where both ends of the testing wire bundle are fixed. As additional elements for controlling the forming process, a die and a holder are set. Out of three buckling principles, principle *b* is chosen since it requires the biggest compression force. However, observations can directly be applied to principles *c* and *d*.

Description

Straight wire bundle (WB) is initially positioned in a way that it leans on a forming die. Each end of a wire bundle testing sample is hold tight with holders (H1) and (H2). Holder (H3) is added centred to the die as a direction pointer to ensure that buckling occurs to the correct side (step 1). Next, holder (H1) is used to bring the axial force to the bundle by translation along the wire bundle longitudinal axis. The force is applied until the wire bundle fills completely the forming die (step 2). Described steps are shown in Figure 29.

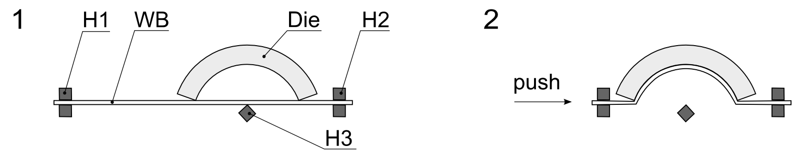


Figure 29 Experiment 2 – steps

The experiment is conducted in a horizontal plane and all the elements, apart from translatable holder (H1), are fixed on a working table to provide proper support for the wire bundle (WB) being formed.

Results and analysis

Although holder (H3) and the surface of a working table represent direction pointers for buckling, experiment showed that an additional plate is needed to ensure that the buckling occurs completely in the horizontal plane. Moreover, a non-constant axial force is needed during the forming in order to ensure full filling of the die. Furthermore, the needed force value differs from one bundle to another due to a different bundle forming length.

In the experiment, shape of the used die is a part of an annulus with both inner and outer arc of approx. 130°. However, the inner part of a die for the production needs to be in a form of a half circle, meaning that the inner arc needs to be defined with an angle of 180°. This is necessary to enable as well the forming of the longest needed bundle arc. In order to enable control of resulting arc length of a formed bundle, the die needs to be flexible. Adjustment of the die should then be made for every wire bundle of the same stator type.

Possible adaptations

When adding one more horizontal plate in order to limit all the possible directions of bundle buckling to only one desired one, realisation of buckling forming principle is rather difficult to implement as a system solution since it requires lot of separate parts. Adaptation could be done in a way that all the direction pointers, i.e. holder (H3) as well as two additional horizontal plates, are integrated with a die. For even bigger reduction of separate parts, holder (H2) could as well be integrated with a die in form of a parallel gripper. However, the problem of flexibility of a die still stays.

Experiment 3

Third experiment tests the forming principle *e*. Experimental setting is chosen as forming around the die. Since principles *f* and *g* differ from the principle *e* only in the direction of action and motion of the applied force, the same testing setting could be used to test those principles as well. For that reason, logical conclusions are drawn from one testing for all three principles.

Description

First, one end of the straight wire bundle sample (WB) is placed tangentially to the left most outer corner of a die. At the point of a contact, the wire bundle is pressed to the die with holder (H1). The free end of the bundle is held with holder (2) (step 1). Holder (H2) is then moved along the curved path by applying tension force to the bundle until the wire bundle lays along the full length of outer surface of a die (step 2). Described steps are shown in Figure 30.

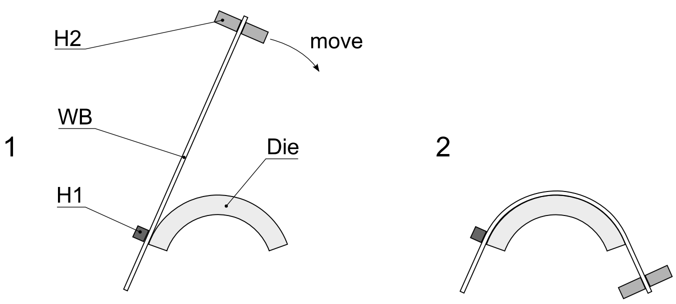


Figure 30 Experiment 3 – steps

As well as the experiment 2, the experiment 3 is done in a horizontal plane and all the elements, apart from moveable holder (H2), are fixed on a working table.

Results and analysis

The experiment showed that, with a use of only tension force in a bundle, it is difficult to both predict and overcome a springback of a wire bundle. Through several trials, it is observed that the resulting shape is less reliable, the shorter the length of forming. Additionally, the most correct form, that is the smallest springback, is gained when the bundle is bended over an edge of a die suggesting that the smaller radius of a die is more appropriate to be used with a given method. Overall conclusion from described observations is that, although this forming method cannot ensure self-reliant shape of a formed wire bundle, it can still be used if shape is fixed in some other way.

Possible adaptations

Apart from possibility to change the type of force and its motion, the forming method can be adapted by using a die of a different size. To make the method suitable for different forming radii, it is possible to use a die consisting of pins that can be radially adjusted (Figure 31). Herby, the radial adjustment needs to cover the radii between maximum and minimum mean head radius, where the minimum radius of adjustment needs to be even smaller in order to enable overcoming springback. The tool showed in Figure 31 can be realised either as a full circle or as a half circle. When realised as a half circle, then additional degree of freedom is needed in a system to enable relative rotation of a tool to a stator so that any bundle can be formed regardless its start position.

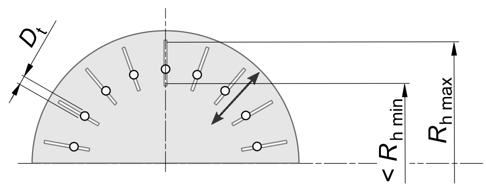


Figure 31 Die variant for forming principles *e*, *f* and *g*

The number of pins should be chosen to be the smallest possible, by taking care that the resulting wire bundle shape is still in the tolerance field *t* for all the mean winding head diameters. The size of the pin D_t has to be bigger than minimum allowed bending radius for wires in a bundle. Additionally, the same forming principle can be used with a die of a smaller outer radius in order to deform a bundle only locally.

Experiment 4

Fourth experiment tests the forming principle *h* where the bending force, along the motion, acts always perpendicularly to the bundle. The main distinction between this principle and principle *g* is in the distance of the active force relatively to the fixed point on the bundle. When moment arm is shorter like in the principle *h*, the influence of low wire bundle stiffness is negligible. Therefore, there is no need for additional support like a die in order to perform a bend. Experimental setting is chosen as bending between two gripping points.

Description

First, straight wire bundle (WB) is placed in a pneumatic gripper (G1) and afterwards gripped with pneumatic gripper (G2) mounted on a 6-axis robot (step 1). While gripper (G1) holds the wire bundle in place, robot performs rotation of gripper (G2) around an eccentric point in order to create a bend in the bundle (step 2). Described steps are shown in Figure 32.

Figure 32 Experiment 4 – steps

Experiment is done in a horizontal plane, with gripper (G1) being fixed on the working table. In multiple trials, different bending angles were used to inspect the springback of testing wire bundle sample. In addition, the experiment was conducted in several repetitive steps in order to form a polygonal shape of a bundle.

Results and analysis

Experiment showed good quality of an achieved bend as well as simplicity of adjusting process parameters. With unregulated bending force applied by a robot, the springback is possible to overcome by increasing or decreasing the bending angle in several trials before the correct angle is accomplished. On such a small moment arm for bending the bundle, it is assumed that forming principles *i* and *j* would provide equally good result. Especially principle *i* would be suitable for the last part of a polygonal shape since it leaves the left part of the bundle, according to a sketch in Table 3, in any desired direction.

Additionally, while conducting the experiment, several general issues are observed. First issue addresses gripping all the wires of a bundle. Due to non-constant shape of a bundle, it can happen that some of the single wires are not collected with the gripper fingers; consequently, they are not formed and the coherence of a bundle is interrupted [35]. Second issue concerns the preservation of a formed bundle. When the forming step is repeated several times, the length of a formed bundle increases what results in bundle tilting downwards, exiting the plane of forming [35, 36]. This effect can cause los of formed shape, but as well collision with other parts of a system or other wire bundles. Since both negative effects can produce unwanted results and even interrupt the forming process they have to be prevented. Preventive measures also need to be taken in combination with any other forming principle with which the same problems could occur.

Possible adaptations

To more clearly define the bend and ensure full repeatability when the same method is applied to other type of wire bundle, additional holder (H1) can be added in front of the gripper (G1) as shown in Figure 33, left. This way, gripper (G2) bends the wire around the holder (H1) making sure that the bending radius and relative position of the bend to grippers are always the same.

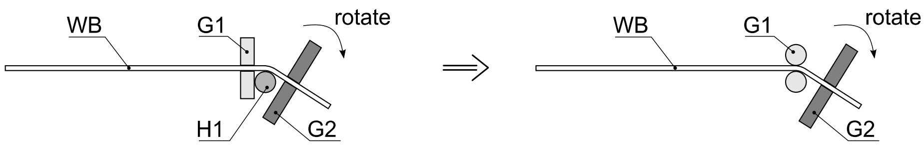


Figure 33 Possible realisation improvements for forming principle *h*

Further adaptation considers the fact that, for the better performance, additional part is added to the system. Since the only function of a gripper (G1) is to ensure that there is no movement of the wire bundle, the function to control the bending radius can be integrated by simply changing the shape of gripper fingers to be cylindrical. This change is shown in Figure 33 on the left and represents improved realisation of the forming principle *h*. When analyzed, this improvement corresponds to a suggested adaptation of a forming principle *e* given in the experiment 3.

Experiment 5

Fifth experiment tests the forming principle *k* when compressive force is applied as sketched. Experimental setting is chosen as a rolling around the die from outer side.

Description

First, the straight wire bundle (WB) is placed between a punch and a die at the left most part of a die, tangentially to outer surface of a die (step 1). Punch is then rolled along the outer side of the die by at the same time applying the compression force in the direction of a normal line to the surface of the die (step 2). Described steps are shown in Figure 34.

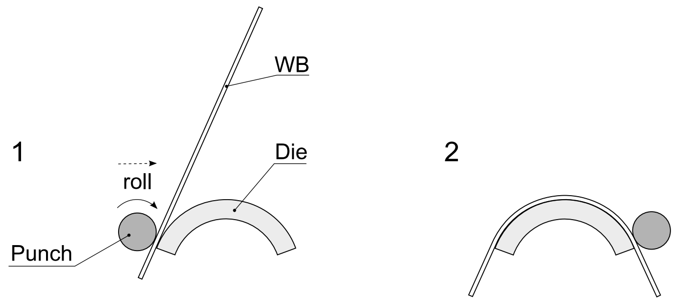


Figure 34 Experiment 5 – steps

In several trials, the punch was rolled along different arc lengths of a die to inspect the possibility of achieving different required end positions for each single wire bundle.

Results and analysis

The resulting form of a bundle depends on a used compression force as well as on the possibility to maintain the force and the punch motion constant. Due to the springback, the resulting radius of a formed bundle is bigger than the outer radius of a die. Unlike in the conducted experiment, to ensure more precise forming, wire bundle should be hold in place. The holding point should be on part of a bundle that is not going to be formed; outside of the area where a contact between the punch and the die can be established. In Figure 34, step 1, the straight part of the bundle under the level of the die needs to be held with an additional holder. Otherwise, when a bundle has a possibility to translate along the die, it is difficult to predict the effect of used process parameters and the forming can be disrupted. Without holding the bundle, the resulting bundle shape can even have a radius smaller than an outer radius of a die.

Possible adaptations

Single wires used in winding with inserting process have a low friction coefficient in order to ease the inserting process. For that reason, it is possible to slide the punch instead of rolling. To create smaller or bigger formed length of a bundle, punch is moved along the die only as much as necessary to achieve the desired length. In this process, the die should have outer radius of a size similar to the desired forming radius for a bundle. When the size of the die is smaller, with this method it is as well possible to produce polygonal shape of the wire bundle.

Experiment 6

Sixth experiment tests the forming principle *k* when compressive force is applied in opposite direction of the sketched one. Experimental setting is chosen as a rolling around the die from inner side. Additionally, with step 1 of test A of the sixth experiment, forming principle *l* is tested as bending between two supporting points.

Description

First, a straight wire bundle (WB) is placed between the punch and the die in a way that the punch is placed centred between two support points in which the wire bundle is leaned on the die (step 1). In order to create initial bend of a wire bundle, punch is translated until it comes in contact with the die (step 2). Following, the punch is rolled along the inner surface of the die by at the same time applying a push force (steps 3 and 4). Described steps are shown in Figure 35.

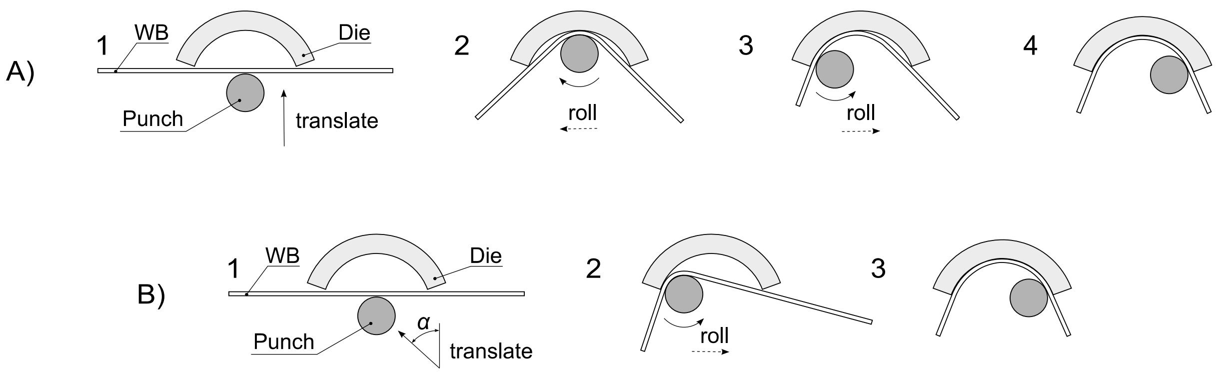


Figure 35 Experiment 6 – steps

In test A) the punch is translated to the centre of a die. This results in symmetrical initial bend, however it requires rolling of the die firstly in one and then in the opposite direction. To keep rolling of the punch as one continuous motion, in test B) the punch is translated under an angle to reach the most left corner of a die and then rolled only to one side.

Results and analysis

Equally as in the experiment 5, the resulting form of the bundle depends on the used push force force as well as on the possibility to maintain the force and the punch motion constant. Due to the springback, the resulting radius of the formed bundle is bigger than the inner radius of the die. However, depending on the applied force and relative motion between the bundle and the die, it is even possible to get smaller radius of the formed bundle. This again indicates that the wire bundle should be hold fixed to the die in at least one point.

When the bundle is being formed from the middle as in test A), there is no possibility to establish a fixed point in end points of the die since both ends of the bundle need to have freedom to move in order to fill the form of the die. Nevertheless that the middle point of initially bended bundle in step 2 is logically a good choice for a fixed point, the solution is difficult to achieve since the punch needs to pass that point twice.

In addition to smaller number of steps, described issues with fixing point suggest that the arrangement from test B) is a better solution. However, it is difficult to ensure that every needed arc length of a wire bundle can be formed. Same as in experiment 2, the inner part of the die for the production needs to be in a form of a half circle. When initial bend is created, the end points of the die keep supporting the wire bundle through the whole forming process, regardless to how long arc length is used. This puts a limitation to the final shape in a way that, for shorter arc lengths, the wire bundle is over-formed, in undesired way, due to end support point. In order to have a better and easier control on resulting arc length of a formed bundle, this method, as well as the method in the experiment 2, require the die to be flexible and adjustable for every wire bundle.

Forming principle *l* was tested in a step 1 of test A) in a way that in both support points the wire bundle was free. The results confirmed that, in order to get better control over the bending process, at least in one point the wire bundle needs to be fixed. In the other support point it is preferred to have guidelines in order not to lose the shape. From geometrical setting it is then easy to calculate the exact length of the wire bundle needed or used for the bend.

Possible adaptations

Considering the results of only step 1 of test A) it can be seen that it is possible to get the full form of a wire bundle with only one translatory motion of a punch. In that case, the outer radius of a punch needs to be equal as the inner radius of the die. The forming load is then equally distributed along the whole wire bundle length providing a smooth arc shape. Additionally, there is no possibility of relative translation of the bundle along the die. However, the length of an arc is defined by shape of the punch, meaning that the die needs to be changed for every different bundle length. When the size of the punch is smaller, with the method in step 1 of test A) it is as well possible to produce polygonal shape of the wire bundle. In that case, the shape of the die can be chosen in any way that is suitable for support the bundle in two points.

Experiment 7

Seventh experiment tests the forming principle *m* when the left most support point moves together with a wire bundle, in the direction of the axial force, while other support points are fixed to the surrounding. Experimental setting is chosen as a bending with three rollers where two rollers are used as a guiding rollers and the third, adjustable roller provides the bending force.

Description

In a first step, adjustable roller (R2) is in a neutral position. Straight wire bundle (WB) is gripped firmly with a holder (H1) and placed between fixed rollers (R1) in a way that the end of a bundle exceeds the adjustable roller (R2). To perform initial bend, adjustable roller (R2) is translated under an angle to the desired position (step 2). Forming of the bundle in the curved shape is realised by pushing the bundle via holder (H1) in the bundle direction (step 3). Described steps are shown in Figure 36.

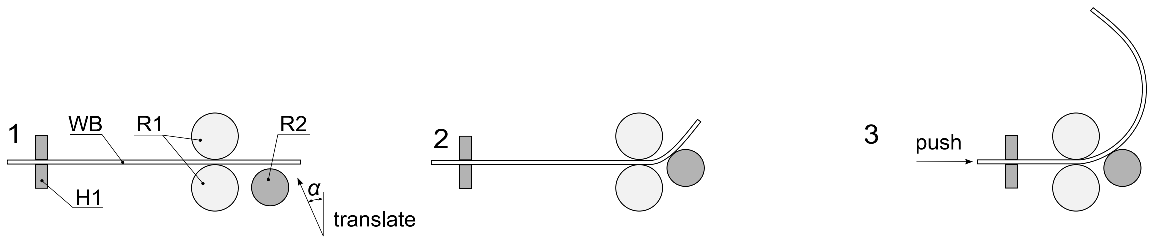


Figure 36 Experiment 7 – steps

The position of the adjustable roller (R2) in second step defines the bending radius of the bundle. The needed position in order to get the desired bending radius after springback is predicted by the formula given in the Appendix D according to [37] and [38]

Results and analysis

The experiment showed that the resulting shape of the wire bundle is a regular arc for which the resulting radius can be well predicted by the formulae given in Appendix D. Depending on the initial distance between holder (H1) and guiding rollers (R1) it is possible that buckling occurs if the distance is too big. This means that the maximum distance needs to be chosen in a way that only normal compressive stress can occur in the wire bundle. As in experiment 2 where buckling is a forming principle itself, buckling length changes respectively to the cross-section of a wire bundle so it can happen that, for smaller bundles, the length of the bundle that needs to be formed exceeds the maximum allowed length to avoid buckling.

Additional observation is that, when pushing a wire bundle through the guiding rollers (R1) in the first step, it can happen that not all of the single wires are caught in a gap between the rollers nevertheless there is a twist that holds all the wires together at the end of the bundle.

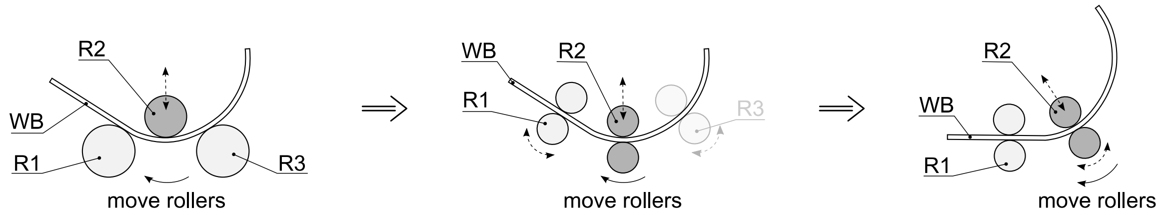


Figure 37 Realisation of principle *n* (left) and adaptations (middle and right)

The forming principle *n* can be realised with three rollers in a way that the middle roller (R2) is adjustable perpendicularly as shown in the Figure 37 on the left. In this case forming is done in a similar way as in experiment 7 conducted according to forming principle *m*. To produce a curved shape, a relative motion between rollers (R1), (R2) and (R3) and the wire bundle (WB) needs to be established. As discussed earlier, axial force applied to the bundle in form of a push force could result in buckling. On the contrary, axial pull force would destroy already formed shape. Therefore the motion should be put on the rollers as originally sketched in the forming principle *n*. Since the middle roller (R2) has a degree of freedom to move up and down, it is technically easier to realise a drive of rollers (R1) and (R3).

Possible adaptations

To eliminate the buckling issue, the drive for moving a wire bundle should be, for the forming principle *m,* integrated in guiding rollers (R1). Since guiding rollers act then at the same time as a gripper, it is necessary to ensure that all the single wires of a bundle are gripped. This means that additional degree of freedom should be added to at least one of the rollers in the pair, which will enable opening and closing a gripper. In general, to make sure that all of the wires of a bundle are being formed equally, every used roller, which does not have a pair, in both forming principles, can be replaced with a pair of rollers. When this adaptation is applied to principle *n*, pairs (R1) and (R3) of rollers need to get an additional degree of freedom in a form of free rotation around the centre of the pair (Figure 37, middle). That ensures that position of added rollers does not interfere with a desired forming shape. However, this way the drive of the bundle can be established as well only with a roller pair (R1) what results with a redundant pair of rollers (R3) as shown in Figure 37, middle. When now the redundant pair (R3) of rollers is removed from adaptation of realisation of principle *n*, we get the same adapted solution as when a roller is added to a realisation of principle *m*. The end result of adaptation for both of the principles is shown in Figure 37, right.

General conclusions from conducted experiments

From all conducted experiments, some conclusions can be drawn that refer to a problem of forming a wire bundle in general. These conclusions should be taken into account for further development as they represent an important input for system operation.

Gripping

It is noticed that single wires are not necessarily closely connected along the whole wire bundle length. The resulting issue is a high probability of incorrect gripping in terms of missing one or even several wires. In order to ensure correct forming of a wire bundle, it is crucial to collect all single wires of a wire bundle in initial as well as in every following gripping, if there is one.

Forming die

The experiments showed that using a die of bigger outer diameter in general provides less reliable end shape of the bundle. This refers mainly to the achieved radius of the curved part of a formed wire bundle, which depends on the size of the forming tool, applied forming force and the springback of a wire bundle. This result conforms with conclusions from [33] considering the influence of punch radius on springback where it is claimed that the smaller the radius of the punch, smaller the springback. To get the desired forming radius and overcome springback of a wire bundle, outer radius of the die needs to be smaller than the mean radius of the winding head. This requires a different die size for any change in a motor type, which results in a need for a different forming radius, as well as when the springback is changed.

Overcoming springback

Due to unpredictability of overall wire bundle mechanical properties, it can be concluded that, nevertheless the methods to predict springback exist, they are not fully reliable for the application in wire bundle forming process for every forming method. The existing springback prediction methods can be used as a starting point for setting the system parameters, however, the resulting shape still has to be verified through several experimental trials before implemented in a production. This means that the importance of springback predictability is set to a lower level for a solution search. Still, for evaluation of solutions, springback predictability can be used as one of the comparison criteria where the solution with a possibility to predict springback has an advantage to a solution with no springback prediction.

Collision and shape preservation

As observed in experiment 4, when forming steps are repeated, due to its weight, the formed bundle cannot stay in the plane of forming without additional support. The resulting issues are a possibility of collision with other parts of a system or stator itself and consequently los of formed shape. This adds one more required function of a wire bundle forming system: *Maintain the wire bundle in the plane of forming*. However, it is assumed that this function can be fulfilled with the same or similar subsystem that provides assistance with extra wire bundle length. For that reason, this issue is not further addressed as a part this thesis.

4.2.3 Elimination of forming methods

Although presented forming methods do not yet fully solve the problem of planar forming of wire bundles, they are the basis for building up the overall forming concepts. As seen through experiments, some of the forming methods have limitations on fulfilling the basic requirements set on a system. For that reason, elimination of some of the methods can be done already as a part of a solution search [39]. This step is necessary in order to keep the focus of further development on those forming methods that showed to have the biggest potential. The method for guiding the concept selection process from [2] is developed with a similar reasoning: “Concept selection is an iterative process closely related to concept generation and testing” [2, p.128]. With two stages of concept selection, that is *concept screening* and *concept scoring*, method is especially suitable for early phase of development process because it enables both narrowing and temporary widening of a solution search space [2]. The possibility to both eliminate and further develop ideas with greater potential is necessary when concepts are on a high level of abstraction as in this task. Therefore, the method is adapted in order to fit the specificities of a task given in this thesis.

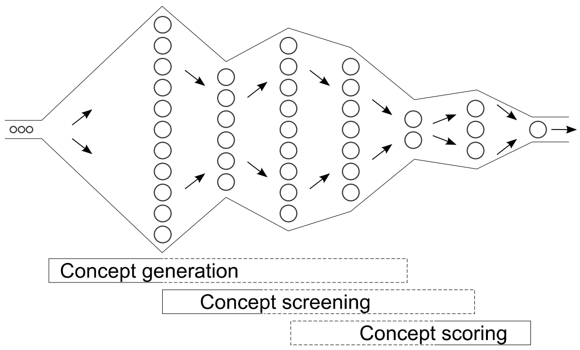


Figure 38 Concept selection method [2]

Suggested first phase of concept selection is *concept screening*, that is narrowing down the number of rough initial concepts by quick evaluation. Further, during *concept scoring*, more careful analysis of more detailed concepts is used in order to choose only one concept that is most appropriate for further application [2]. Although the *screening matrix* from suggested method is not used directly, the elimination of forming methods can be considered to represent first *screening* in overall process of concept selection. While *evaluation* implies giving an overall grade to a solution by comparing it with other solution variants, *elimination* is based only on the analysis of each solution separately [39]. However, the elimination of certain solutions should still be done by common criteria of high importance, but still suitable for given low level of details in solution variants.

Firstly, some of the forming methods are eliminated by the key discriminating criteria considering the *first level of adjustability* of the solution. First adjustability level refers to a possibility of creating a different length of a curved part of a bundle for every bundle, also within the production of a same stator type. *Second adjustability level* takes place when dimensional parameters are changed such as number of single wires, diameter of winding head, number of wire bundles. As such, second adjustability level has lower importance as it does not appear in every single step of a process, but only when the whole production is adjusted for a different stator type.

As illustrated in Figure 39, by the *First level adjustability* criteria, forming principles *b* to *d* , which are realised through second experiment, as well as the realisation of principle *k* in experiment 6 are eliminated. The reason behind is a need for change in a die in every forming step what is considered to be unnecessary additional action when compared to other methods.

For further elimination, considered very important and important criteria are *Repeatability* and *Predictability*. Hereby, *Repeatability* refers to if the forming procedure is precise enough so that the resulting shape of a bundle does not significantly differ from one stator to another within the production of the same stator type. Additionaly, *Predictability* refers to if it is easy to predict the resulting shape (also considering springback) when setting certain process parameters. For both criteria, the solution should give a positive answer to raised questions in order to pass the elimination test. However, in order not to exclude potentially applicable forming principle just on basis of a realisation given through the experiments, criteria are applied also to *Possible adaptations* of realisations described for each experiment.

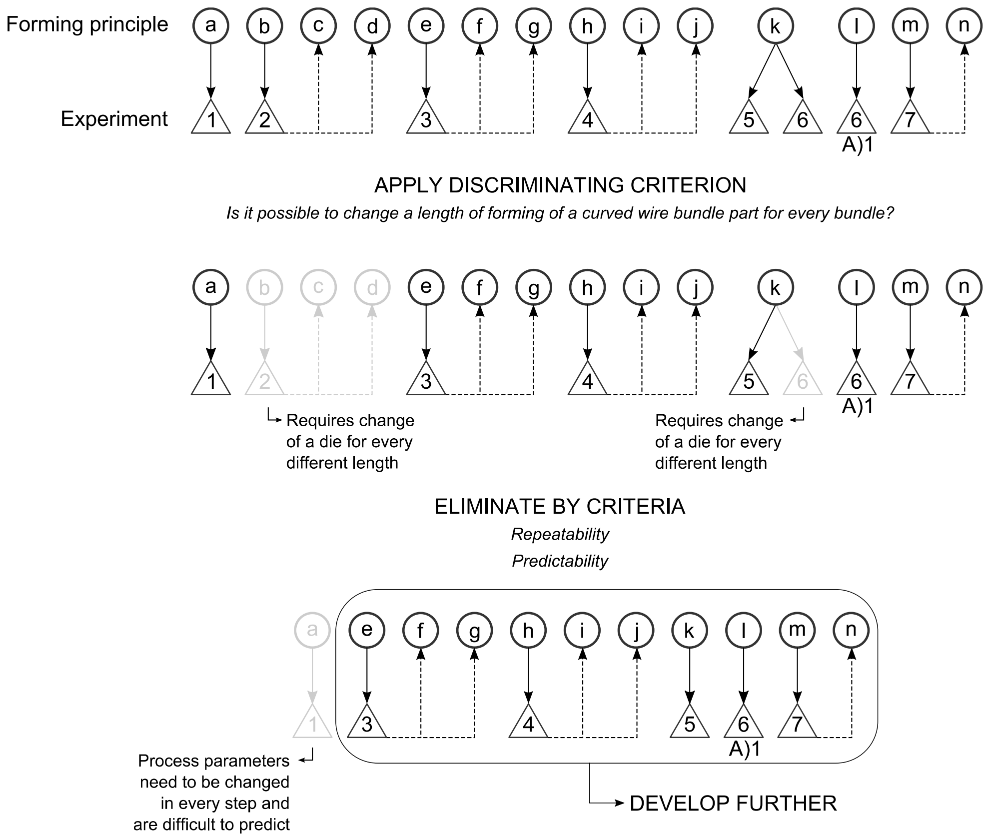


Figure 39 Elimination of forming methods

After the analysis, it is concluded that only forming method *a*, realised through experiment 1, has no possible adaptations which would satisfy given elimination criteria. This means that all forming principles from *e* to *n*, with realisations through experiments 3 to 7 and possible adaptations, are suitable to be further developed. (Figure 39)

4.2.4 Forming tool

For most of the shown principles, it is necessary to use a certain additional part to ensure the correct resulting shape of the wire bundle. The additional part, as well as the supporting points in a certain realisation, can be considered as a forming tool.

With further analysis of possible load cases, it can be seen that, depending on the used tool, each force or moment can be applied either locally, as a concentrated load, or over a longer length of a bundle, as a continuous load. If R_t is a radius of a forming tool, D_b is a mean diameter of a wire bundle and R_h is a mean radius of a winding head, i.e. the target radius for forming a curved part of a wire bundle, we can say that the load is concentrated if

$$2\,D_b \approx R_t << R_h \tag{16}$$

Otherwise, when

$$2\,D_b << R_t \approx R_h \tag{17}$$

we can say that the forming is done by a continuous load distribution.

When the radius of a forming tool is smaller and a tool acts as a concentrated force, the deformation process of the wire bundle can be considered to be bending. In that case, the radius of a tool has to be bigger than the allowed bending radius for a single wire. According to the norm requirement, which refers to testing of film adhesion and wire flexibility, single wires with a diameter up to 2 mm have to stand the bending radius of one nominal diameter of a wire [25]. Conservatively, it can be taken that the minimum bending radius for a wire bundle needs to be double the diameter of the bundle.

The size of the tool, although it affects the resulting shape, is not a governing parameter. When a polygonal shape is desired, a tool with a smaller radius needs to be used, however, arc shape is possible to achieve as well with a tool that has a radius smaller than the forming radius, for example by using roller forming method. This means that the end shape is a result of combination of all three elements of forming procedure: of forming method, forming tool and handling principle.

4.2.5 Handling principle

Since handling principles serve as an extension of forming methods, they originate from the fact that forming needs to be done in one or more steps in order to get a complete shape of a formed wire bundle. Here, the *complete shape* refers to the curved part of a bundle, from fixed point to a collection point, where the relative distance between points is defined by angle α_i

as described in Figure 10. Alternative shapes, which fit the requirements on bundle forming system, are shown in Figure 40.

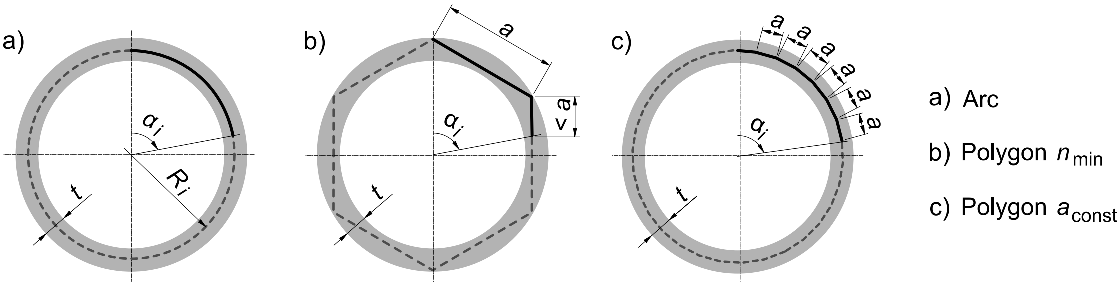


Figure 40 Shape alternatives of curved part of a formed bundle

Considering found forming principles, realizable forming tools as well as shape alternatives, it is possible to distinguish between three main principles of handling:

- *One step*,
- *Multiple steps* and
- *Repetitive steps*.

Here, the term *Step* corresponds to an operation of deforming the bundle in a way that *One step* represents one deformation of a bundle. Accordingly, *Multiple steps* mean that the deforming operation needs to be done two or more times. Similarly, *Repetitive steps* imply minimum of two deforming operations, but, unlike the *Multiple steps*, all of the *Repetitive steps* are exactly the same for each of the deformation points along the length of the bundle that needs to be formed.

Compared with shape alternatives and inspected forming methods, it can be seen that an arc shape can be done in *One step*. Polygon with minimum number of sides in general requires *Multiple steps* since in general the needed side length of a polygon varies for different angles α_i. Even when for some specific angles α_i only one side of a polygon is needed, thus only one deformation operation takes place, it is considered that *Multiple steps* forming is done as a part of a whole used forming procedure. Similar applies as well to polygon with a constant side length. However, since the side length is constant, it is possible to use exactly the same set of operations for deforming each of polygon vertices, thus to use *Repetitive steps*.

Nevertheless, direct application of *Handling principles* to resulting bundle *Shape* can be extended when different design of a *Forming tool* is taken into account together with *Forming principles*. For example, if tool illustrated in Figure 31 is used in combination with any of forming principles *e*, *f*, *g* or *l*, it is possible to form the bundle in either of polygonal shapes in only *One step*.

4.2.6 Gripping the wire bundle

One of the key functions of a subsystem for planar forming of wire bundles is to grip the wire bundle. Main requirement is to grip all the single wires at once. However, holding the bundle firmly and allowing the motion of a bundle without dropping any of the single wires needs to be taken into account as well as gripping of different wire bundle sizes.

Gripping at the fixed point

In any of the forming procedures where gripping of a bundle is needed at the fixed point of a bundle in the winding head, in order to fulfil the operation, several steps need to be taken as illustrated in next figure.

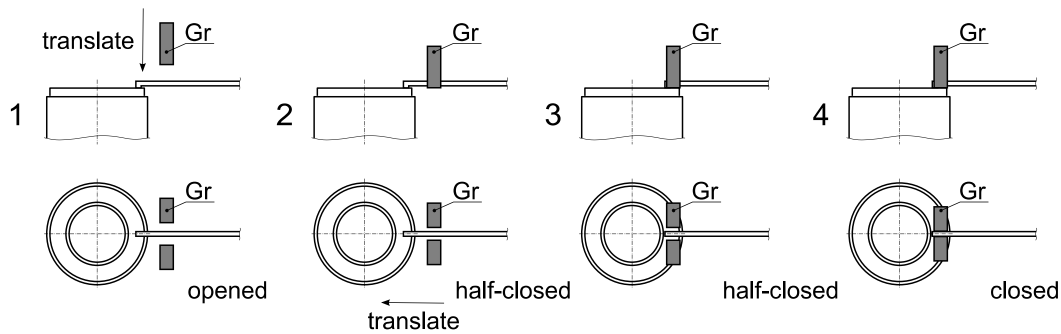


Figure 41 Gripping procedure at fixed point of a bundle

Regardless the type of a gripper (Gr), it needs to translate vertically until open fingers reach the plane of bundles (step 1). Next, gripper fingers need to close partially in a way that the collect all the single wires of a bundle, but not yet hold the bundle firmly (step 2). In a following step, half-closed gripper fingers translate in radial direction along the gripped bundle towards the winding head until they reach the fixed point of the bundle and/or middle of a winding head (step 3). In the last stage, the gripper with a gripped bundle is positioned closely over winding head. There, the gripper fully fixes the wire bundle position by closing gripper fingers completely (step 4). (Figure 41)

Gripping profile

In Figure 42 the possibility to deal with different wire bundle sizes is illustrated by the same type of gripper fingers with a gripping profile which, when dimensionally scaled, can be used for both maximum and minimum wire bundle size. Moreover, the overlap shown in the view from the bottom is one of the possibilities on how to loosen the grip in order to allow the bundle to translate but without dropping any of the single wires. Additional advantage of this kind of a gripper finger design is relatively easy manufacturability regardless the size of the bundle. However, please note that the sketched dimensions need to be adjusted to fit the requirements of the used material and manufacturing process.

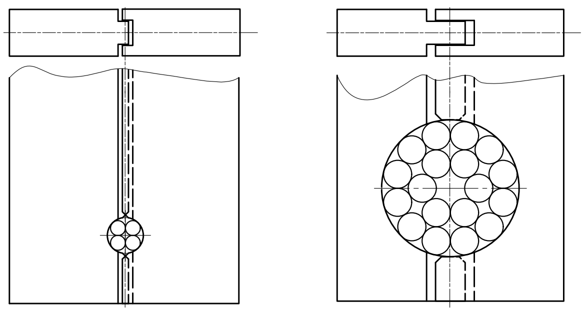


Figure 42 Scalable gripping profile

Some other possible shapes of gripping profiles are shown in the next figure taking possible arrangements of the wires in a bundle into account. For the illustration, gripping profile is shown to be in one gripper finger of gripper finger pair (Figure 43). However, the same gripping profile can be manufactured as well in, for example, a pair of rollers which than serve as gripping fingers.

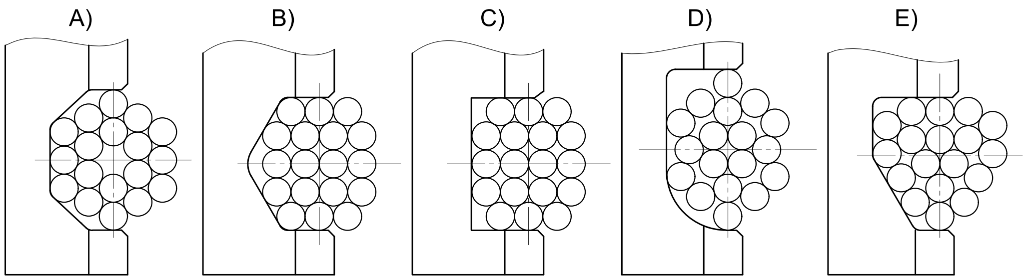


Figure 43 Alternative shapes of gripping profile

What can be seen is that most of the gripping profiles provide better gripping possibilities as they leave less space for wires to redistribute. The exception is profile D) with which not big enough force can be produced in order to hold all the wires firmly in a position. However, only for purposes of guiding a wire bundle that is desirable feature. Additionally, when no movement of any of the wires in a bundle is allowed, other profiles are a better choice. When choosing the most appropriate gripping profile, manufacturing possibilities need to be taken into account as well. From a point of view of manufacturing small parts, profile C) is relatively easy to manufacture with a milling machine in almost any size, whereas the manufacturability of the rest of the profiles might be limited.

4.2.7 Forming concepts

Forming concepts are developed on basis of *Forming procedures*. Es explained in Figure 24, *Forming procedures* are a result of combining all of so far analyzed elements: (a) *Forming method* (consisting of *Forming principle* and appropriate *Realisation*), (b) *Forming tool* and (c) *Handling principle*. Since the desired end result is a formed *Shape* of a bundle, in the following table, alternatives for the elements are provided with respect to which shape they can form. Possible combinations of *Forming principles* and *Realisations* are sorted with respect to which *Tool radius* and which *Handling principle* needs to be used to enable forming of a desired shape. The aim of including combinability analysis of elements, already at this stage of concept generation, is to reduce the number of combinations, thus to ease the process of generating forming procedure concepts.

In Table 5, *Forming principles* are marked with circles and letters from *e* to *n*, while corresponding *Realisations* are marked with triangles and numbers from 3 to 7 including additional :

- label *mod* implies that the appropriate modification described in *Possible adaptations* for that experiment should be included in forming procedure concept
- label *(mod)* implies that the appropriate modification described in *Possible adaptations* for that experiment can but does not have to be included in forming procedure concept
- label + implies that a forming tool similar to the one illustrated in Figure 31 should be used in forming procedure concept

Since in a procedure for forming a polygonal shape, the only difference lays in the bending angle and side length, all suggested alternative forming methods are the same for both polygon types. The difference occurs in controlling the operation of forming and has virtually no influence on a design of a planar wire bundle forming system.

Apart from choosing among the alternatives given in Table 5, there is still a need to choose two more elements in order to generate a full planar forming concept. Those elements

Table 5 Table of alternatives for elements of *Forming procedure*

Shape	Arc		Polygon n_{min}		Polygon a_{const}	
Tool radius R_t	$\approx R_h$	$<< R_h$	$<< R_h$		$<< R_h$	
Handling principle	One step		One step	Multiple steps	One step	Repetitive steps
Forming method	(e) △3	(m) △7	(e) △3+ mod	(h) △4 (mod)	(e) △3+ mod	(h) △4 (mod)
	(f) △3	(n) △7	(f) △3+ mod	(i) △4 (mod)	(f) △3+ mod	(i) △4 (mod)
	(g) △3		(g) △3+ mod	(j) △4 (mod)	(g) △3+ mod	(j) △4 (mod)
	(k) △5 (mod)		(l) △6+ A)1 mod	(k) △5 (mod)	(l) △6+ A)1 mod	(k) △5 (mod)
	(l) △6 A)1 mod			(l) △6 A)1		(l) △6 A)1

consider where to start the forming of a bundle as well as which degrees of freedom should be associated with which elements of a system. Planar forming procedure ends in a collection point B, when a curved part of a bundle is formed.

Start point of forming

Two approaches to forming a wire bundle are possible from the point of the view of the first gripping position: (a) to grip the bundle at the free end and advance with forming towards the winding head or (b) to grip the wire bundle at the fixed end in the winding head and form it along the winding head.

In approach (a), the formed part of the bundle tends to stay freely in the air without a control over the formed shape. Moreover, after the forming is finished, the free end needs to be placed in the correct position. However, with an approach (b) there is a possibility of destroying a formed shape by adding force in it while forming the rest of the bundle. This suggests that, in both approaches, *Subsystem for assistance with wire bundle length* needs to assure that the formed part of a bundle, as well as the additional wire bundle length, stay in the plane of forming and do not collide with other parts of a system. At the same time, it has to be ensured that the shape of formed bundle, or its part, is not in any way changed.

Distribution of degrees of freedom

When relative motion between elements needs to be established it is possible to vary between which element keeps its position and which element moves. In general, there are three possibilities on how to distribute degrees of freedom between elements of a subsystem: (a) all degrees of freedom belong to a planar forming system, (b) degrees of freedom are distributed between planar forming system and the stator and (c) all degrees of freedom are on stator.

Due to bigger dimension and mass of stator than of wire bundles, it requires more energy to manipulate with a whole stator in order to form the bundles. For that reason, option (c) can be *rejected* as not economical one in comparison to other two options. For the same reason it could be concluded that option (a) is preferred to option (b). However, the more degrees of freedom the planar forming system has, the more complex the system is. Therefore, if shifting some of degrees of freedom to a stator simplifies the needed motion of elements of planar forming system, that is the preferred solution. Whenever possible, any motion should be kept as simple translation and rotation, especially if the whole stator is moved. Herby it is assumed that coordination of all the motions can be done electronically with acceptable precision and minimal time loses. In both cases (a) and (b), the relative motion of elements of planar forming system itself can be distributed in more than one way. This suggests that, in following concepts, it is possible to look for improvements as well by redistributing degrees of freedom from one element to another.

Forming concept A

This forming procedure conforms with the forming method according to forming principle *g*, realised in experiment 3. By using a tool of a radius approximately as big as the mean radius of a forming head, the aim is to produce arc like shape of a bundle in one handling step.

Description

Elements used for forming are a forming tool (FT) and two standard parallel two-finger pneumatic grippers, one of them (G1) being mounted on an axial system and the other (G2) on a 5-axis robotic arm. If wire bundles are pre-cut, there is no need for additional support system for handling extra wire bundle length. Moreover, forming in a collection point can be done by a rotation of a gripper (G2). Since the shape provided by this forming method is not self-reliant, it is necessary to fix the formed bundle in clamps mounted on a customized forming tool (FT). Unless gripper (G1) has more degrees of freedom than only for holding a bundle in a fix point, additional system is needed to place the wire bundle in a clamp after it is put in a vertical plane. (Figure 44)

Steps that need to be repeated for each of radially distributed wire bundles around one stator:

1. With a gripper (G1) grip the bundle at the fixed end and hold the wire bundle firmly over the winding head (Figure 44, I)
2. With gripper (G2) grip the bundle at a position where the distance between grippers (G1) and (G2) is equal to the length needed for forming a curved part of the bundle (Figure 44, I)

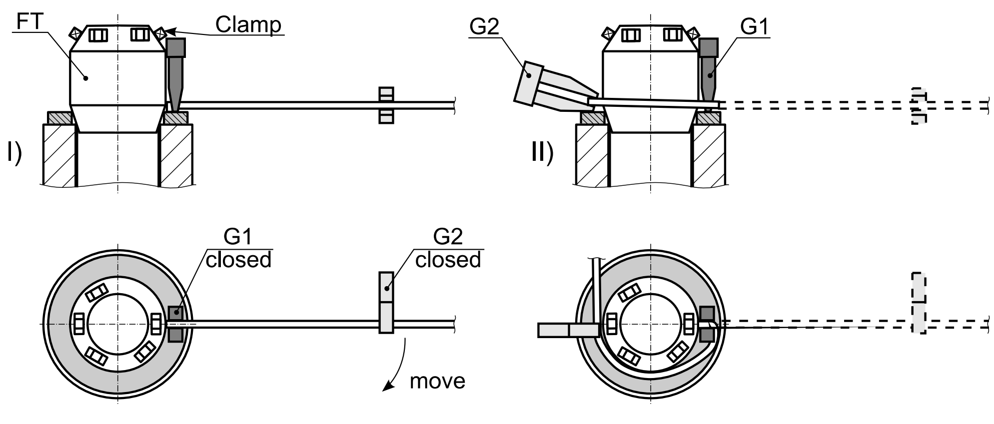


Figure 44 Forming concept *A*

3 Move the free end of the bundle in a way that the bundle takes shape of the forming tool (FT) placed in the middle of the stator (Figure 44, II)

For forming the next wire bundle, the whole stator should rotate until the gripper (G1), which has a fixed position in a working cell, is placed vertically above the desired bundle. For adjusting the forming length, coordinates of starting position of gripper (G2) have to be changed as well as the coordinates of collection point.

Adjustability

In case of changing only size of the wire bundle, it is enough to exchange gripper fingers of two parallel grippers with fingers that have an adjusted gripping profile. Due to the conical shape of the forming tool (FT) it is possible to use the same tool for smaller variations in stator sizes. However, if the diameter size exceeds the tolerance field of the forming tool (FT), the forming tool (FT) needs to be newly manufactured.

Forming concept B

This forming procedure uses the forming method according to forming principle *h* and modified realisation from experiment 4. In multiple steps, bundle is formed in a shape of a polygon with minimum number of sides. The diameter of the forming tool equals to the double diameter of a bundle of the maximum size.

Description

Forming is done by two standard parallel two-finger pneumatic grippers (G1) and (G2) and a forming tool (FT). While the forming tool (FT) is mounted on an axial system with range of motion concentrated in a centre of a stator, both grippers (G1) and (G2) are mounted on a 5-axis robotic arm operating around the stator. Since forming starts from a fixed bundle end, additional support system for handling extra wire bundle length is needed. However, forming in a collection point can be done by a rotation of those of the grippers (G1) or (G2) which is used for last step of forming.

Steps that need to be repeated for each of radially distributed wire bundles around one stator:

1. Move the forming tool (FT) in a position where first bend of the polygon is needed
2. With gripper (G1) grip the bundle at the fixed end and hold the wire bundle firmly over the winding head (Figure 45, I)
3. With gripper (G2) grip the bundle at a position where the distance between grippers (G1) and (G2) is equal to the length of two sides of the polygon (Figure 45, I)
4. Move the gripper (G2) in a way that the bundle takes a shape of the forming tool (FT) (Figure 45, II)
5. While holding the bundle with gripper (G2) in the same position from previous step, open the gripper (G1) and move it until it reaches a position over a wire bundle in a way that the distance between grippers (G2) and (G1) is equal to the length of two sides of the polygon (Figure 45, III)
6. Move the forming tool to a position of the third bend of a polygon (Figure 45, III)
7. After closing the gripper (G1), move the wire bundle around the forming tool by moving the gripper (G1) (Figure 45, IV)

8 If needed, to reach the collection point, repeat steps 5 to 7 with a changed function of grippers in a way that gripper (G1) fixes the bundle, and gripper (G2) provides forming operation; side length in a last forming operation may be longer or shorter in order to reach the collection point in an exact position

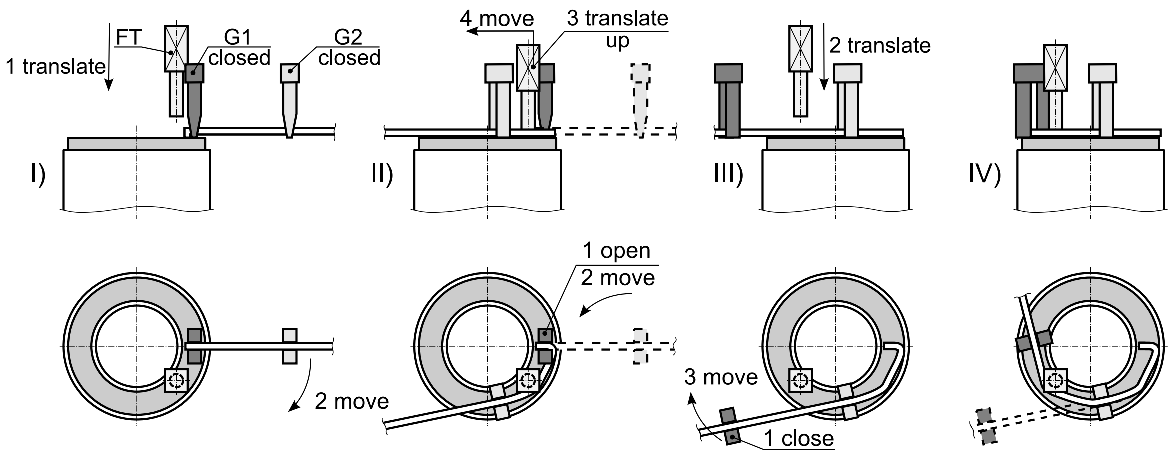


Figure 45 Forming concept *B*

If taken that initial position of gripper (G1) is fixed relative to the working station, for forming the next wire bundle, the whole stator should rotate until the gripper (G1), is placed vertically above the desired bundle. For adjusting the forming length, coordinates of starting position of gripper (G2) have to be changed as well as the coordinates of collection point and number of steps. Moreover, position of the forming tool (FT) needs to be adjusted for every bend of every bundle.

Adjustability

When only wire bundle size is changed, it is enough to adjust the gripping profile of grippers (G1) and (G2) by exchanging gripper fingers. Since the size of the forming tool (FT) satisfies the condition of minimum bending radius, all other modifications, which are required when the stator size is changed, need to be done by changing the coordinates of characteristic point in the control programme of the system.

Forming concept C

Forming method used in this forming procedure conforms to forming principle *h*, realised in experiment 4. Using a tool with a radius equal to a diameter of the biggest possible wire bundle, the aim is to produce polygonal shape of the bundle in a way that minimum number of sides is created in multiple steps.

Description

For forming, two standard parallel two-finger pneumatic grippers (G1) and (G2) are used. Since each of the grippers requires vertical translation, planar motion as well as rotation of a gripper, 4-axis system or a 5-axis robotic arm is needed for providing a motion of each of the grippers. In any case, axes are placed on opposite sides of the stator and care has to be taken to coordinate their movements to avoid collision. When mounted on a 5-axis robotic arm, grippers can as well be used for forming at a collection point and placing the wire bundle in a neutral zone. However, since forming starts from a fixed bundle end, additional support system for handling extra wire bundle length is needed.

Steps that need to be repeated for each of radially distributed wire bundles around one stator:

1 With gripper (G1) grip the bundle at the fixed end and hold the wire bundle firmly over the winding head (Figure 46, I)

2 With gripper (G2) grip the bundle at a position where the distance between grippers (G1) and (G2) is equal to the length of the side of the polygon (Figure 46, I)

3 Move the gripper (G2) to deform the bundle around gripper finger of gripper (G1) (Figure 46, II)

4 While holding the bundle with gripper (G2) in the same position from previous step, open the gripper (G1) and move it until it reaches a position over the wire bundle in a way that the distance between grippers (G2) and (G1) is equal to the length of the side of the polygon (Figure 46, III)

5 Close the gripper (G1) and deform the wire bundle by rotating the gripper (G1) (Figure 46, III)

6 If needed, to reach the collection point, repeat steps 4 and 5 with a changed function of grippers in a way that gripper (G1) fixes the bundle, and gripper (G2) provides forming

operation – in this way grippers (G1) and (G2) "walk" around each other. NOTE: side length in the last forming operation may be longer or shorter in order to reach the collection point in an exact position. (Figure 46, IV)

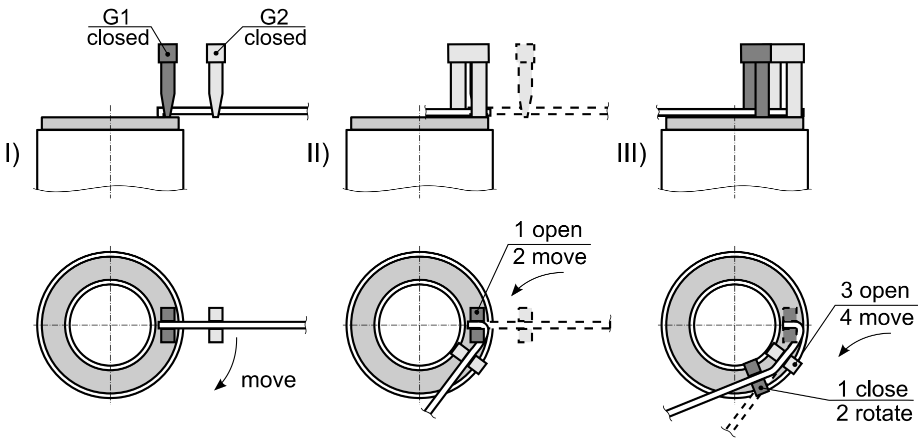


Figure 46 Forming concept *C*

Since degrees of freedom as well as operating area of axes cover the whole working station, for forming the next wire bundle, as well as for adjusting the forming length, coordinates of starting positions, collection point as well as of all other characteristic points of both grippers (G1) and (G2) have to be changed.

Adjustability

Only the change of wire bundle size results in a need for manufacturing new parts. Gripper fingers with adjusted gripping profile need to be newly manufactured for both of the grippers. All other modifications, which are required due to a change in a size of a stator, are done in the system control programme by changing the coordinates of specific points.

Forming concept D

Same as forming concept *C*, this forming procedure uses forming principle *h* realised through experiment 4. Target shape is a polygon with minimum number of sides, formed in multiple steps. Radius of the tool is equal to the diameter of the biggest possible wire bundle.

Description

Similar as in concept *C*, for forming two standard parallel two-finger pneumatic grippers (G1) and (G2) are used. However, in this concept gripper (G2) has an option to open in two steps, meaning that it can be either fully opened or only half-opened. Hereby, the possibility to regulate which of the opening positions is used needs to be automatic. Both grippers are mounted each on a 5-axis robotic arm or on a 4-axis system and they start forming from fixed bundle end. Thus, an additional system to support extra wire bundle length is needed. If grippers are mounted on the robotic arm, they can perform forming operation in a collection point as well as placing the bundle in a neutral zone without assistance of additional system.

The difference to concept *C* lays in the procedure of moving to the next bending operation as described in steps that need to be repeated for each of radially distributed wire bundles around one stator:

1. With gripper (G1) grip the bundle at the fixed end and hold the wire bundle firmly over the winding head (Figure 47, I)
2. With gripper (G2) grip the bundle at a position where the distance between grippers (G1) and (G2) is equal to the length of the side of the polygon (Figure 47, I)
3. Move the gripper (G2) to deform the bundle around gripper finger of gripper (G1) (Figure 47, II)
4. While holding the bundle with gripper (G1) in the same position from previous step, in order to preserve the plane of forming and keep all of the wires in a grip, half-open the gripper (G2) and translate it along the bundle for a distance equal to the length of a side of the polygon (Figure 47, III)
5. Close the gripper (G2) to secure the bundle shape and position while changing the gripping position of gripper (G1); gripper (G1) re-grips the bundle in a position where gripper (G2) was holding the bundle in a previous step (Figure 47, III)

6 Deform the wire bundle by rotating the gripper (G2) (Figure 47, III)

7 If needed, to reach the collection point, repeat steps 4 to 6; NOTE: side length in the last forming operation may be longer or shorter in order to reach the collection point in the exact position. (Figure 47, IV)

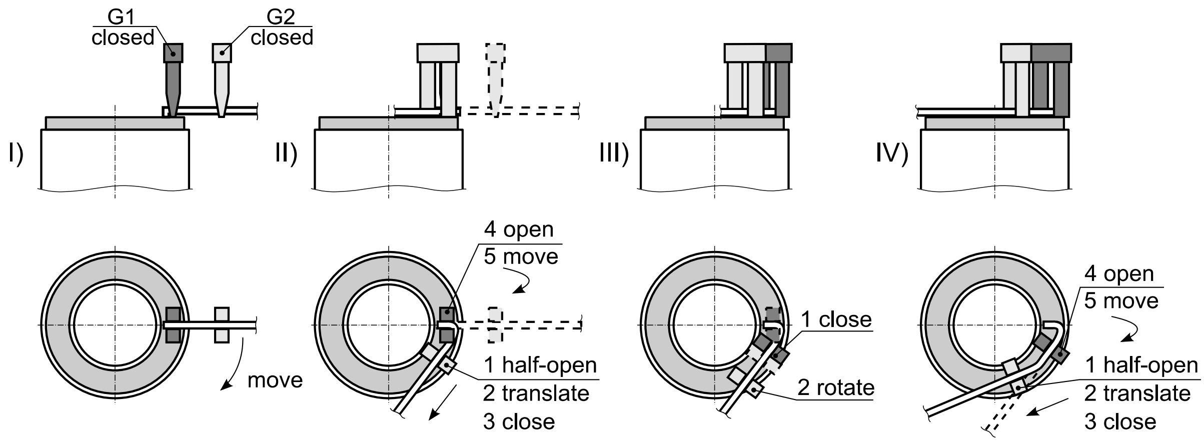


Figure 47 Forming concept *D*

This procedure requires less complicated motion of gripping elements in order to produce the same result as concept *C*. However, there is the possibility to disrupt the formed shape of the bundle while translating the gripper (G2) along the unformed part of the bundle. The mistake can occur if one of the single wires is not properly gripped or the cross section of a bundle varies outside of tolerable shape or size. In those cases, it can happen that translation is interrupted and formed bend is destroyed since gripper fingers are stumbled in the bundle.

Adjustability

Similar as in concept *C*, forming of the next bundle and adjustment of forming length as well as any other adjustments needed due to the change in stator size, are done by adjusting coordinates of characteristic point in the controlling programme of the system.

Forming concept E

Forming procedure for forming an arc like shape of a bundle in one step is generated on the basis of forming principle *n* realised similarly as in experiment 7. The forming tool with a radius bigger than the diameter of the wire bundle is used.

Description

To create a smooth shape, customized forming tool is used consisting of two pairs of rollers (R1) and (R2). Both roller pairs have at the same time a gripping function with the possibility to open and close. In addition, roller pair (R1) has a built-in drive for pushing the wire bundle through a second pair of rollers (R2). Due to a low friction coefficient of coated wires in a wire bundle, bigger gripping force needs to be established. Additionally, an appropriate gripping profile needs to be chosen in order to produce a push force great enough to resist bending forces that occur on a second pair of rollers (R2). Although rollers (R1) are pushing the bundle through the forming tool, they need to be mounted on a 2-axis system that enables translation of the tool along the wire bundle. For the correct operation of the system, pushing of the bundle and translation of the tool need to be synchronized. Forming starts at free end of the wire bundle, meaning that the additional system for supporting a formed shape is needed. Due to the design of the forming tool, the part of the bundle between the rollers always remains unformed. That means that the bundle can be formed neither at the fixed point nor at the collection point. Therefore, a support system is needed for placing the wire bundle in a neutral zone as well.

Steps that need to be repeated for each of radially distributed wire bundles around one stator:

1. Position the forming tool vertically above the wire bundle in a way that the horizontal distance between point of positioning and fixed point of the bundle equals to the needed length of forming
2. Grip the bundle by bringing rollers of pair (R1) as well as rollers of pair (R2) together (Figure 48, I)
3. Automatically set the roller pair (R2) in a position for forming by rotating it around the centre of the pair and translating along the line closing 20° angle with a longitudinal axis of the roller pair (R1) (Figure 48, II)

4 Turn on the drive of roller pair (R1) in order to push the bundle through the roller pair (R2) (Figure 48, II)

5 Keep moving the tool along the wire bundle and at the same time form the bundle by using the drive of rollers (R1); operation stops when the tool approaches as close to fixed point as possible (Figure 48, III)

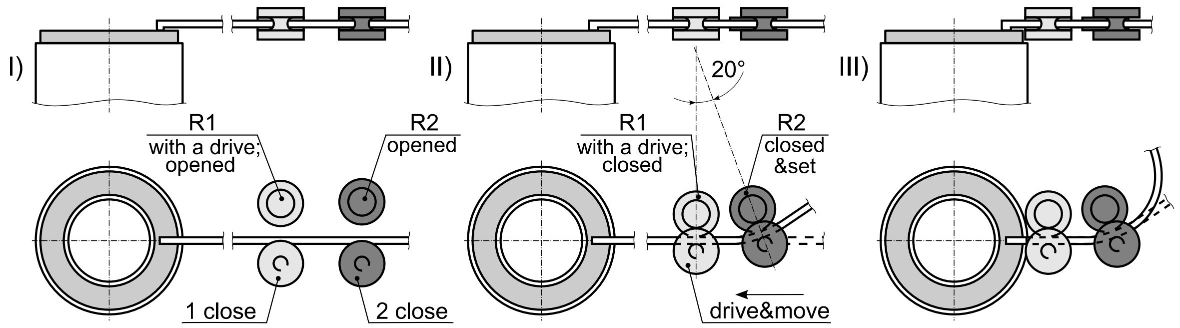


Figure 48 Forming concept *E*

Unless more degrees of freedom are enabled by the carrier of the forming tool, the whole stator should rotate until the tool is placed vertically above the desired bundle. For adjusting the forming length, the coordinates of starting position of rollers have to be changed together with travelling distance of rollers.

Adjustability

In the case of a change in the size of the stator, only the parameters related to setting the position of roller pair (R2) for forming. When wire bundle size is changed, it is necessary to adjust the gripping profile of both pairs of rollers (R1) and (R2).

Forming concept F

For forming a bundle in a shape of polygon with constant side length forming method according to forming principle *l* is used. The principle is realised with modifications of the setting given in first step of trial *A* of experiment 6. The forming tool with a radius equal to the diameter of the wire bundle is used in repetitive steps.

Description

One standard parallel two-finger pneumatic gripper is used with a bigger stroke and customized gripper fingers. The gripper is mounted on a 4-axis system providing (a) one vertical translation, (b) translation in a horizontal plane along the wire bundle length, (c) horizontal translation with a smaller range of motion in direction perpendicular to the bundle and (d) a rotation around the vertical axis. Forming starts at free end of the wire bundle, and, due to the gripper fingers design, it does not provide a possibility to form the bundle neither at the fixed point nor at the collection point. For that reason, two additional support systems are needed, one for placing the wire bundle in a neutral zone as well as the one for supporting the formed shape.

Steps that need to be repeated for each of radially distributed wire bundles around one stator:

1 Position the forming tool vertically above the wire bundle in a way that the horizontal distance between point of positioning and fixed point of the bundle equals to the needed length of forming

2 Translate the tool vertically down so that "hooks" of gripper finger (GF2) position bellow the bundle; translate the tool horizontally until the wire bundle is in the middle and then translate the tool vertically up to collect the wire bundle and hold it in a plane of forming (Figure 49, I)

3 Rotate the gripper around vertical axis so that the straight bundle leans diagonally on "hooks" of the gripper finger (GF2) (Figure 49, I)

4 In order to deform the bundle bring gripper fingers (GF1) and (GF2) closer by closing the gripper (Figure 49, II); NOTE: dimension of fingers need to be chosen in a way that the bending angle is achieved by full range of motion of fingers with no need for automatic adjustments during the process.

5 Open the gripper and translate it along the bundle for the length of a side of the polygon (Figure 49, II); NOTE: bending angle should be chosen in a way that the fingers, when opened can come around the bending point without disrupting it and without dropping any of the wires of a bundle.

6 Repeat steps 4 and 5 until the fixed point of the bundle is reached (Figure 49, III)

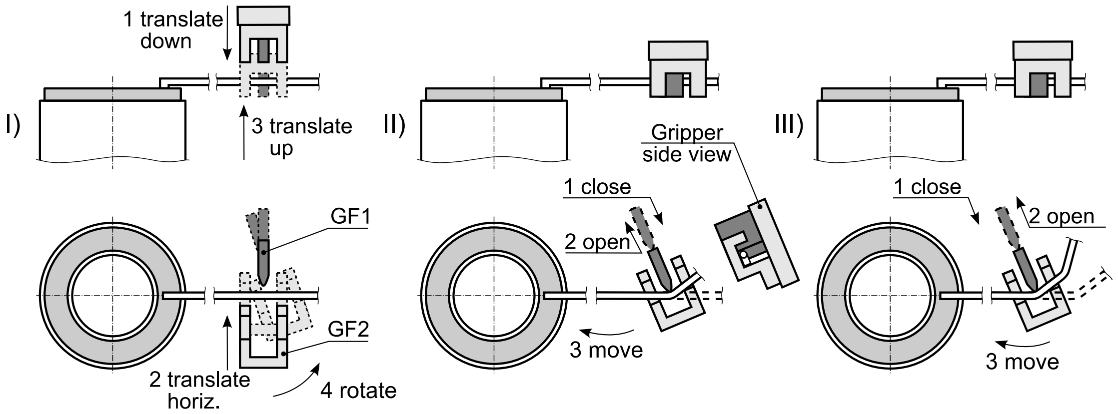


Figure 49 Forming concept *F*

For forming the next wire bundle, the whole stator should rotate until the forming tool is placed vertically above the desired bundle. Here, a modification of the concept is possible by shifting the rotation of the stator to the motion of the forming tool. In order to adjust the length of forming, beside the coordinates of start position for forming, number of repetitive steps needs to be changed in the control programme of the system.

Adjustability

The dimensions of gripper fingers are chosen in a way that any size of the wire bundle can be formed. If the size of the stator changes, modifications of starting positions for each of the bundles needs to be changed. However, it is assumed that the side length of the polygon is chosen in a way that it is suitable for wider range of different forming radii. That suggests that the same tool can be used for all stator types without changes of mechanical parts.

Forming concept G

The following forming procedure is generated according to forming principle *h* with modifications of realisation given in experiment 4. With a use of the forming tool that has a radius equal to the diameter of the biggest wire bundle, the resulting shape of the bundle is a polygon with constant side length.

Description

One standard parallel two-finger pneumatic gripper (G1) is used with an extension of customized rotating flange used for creating the form. Parallel gripper has an option of automatic regulation between two possible opening positions: open and half-open. The whole forming tool is mounted on a 4-axis system providing full horizontal motion consisting of two translations and one rotation, as well as a vertical translation. Forming starts at the free end of the bundle and finishes with forming the bundle at the fixed point. This suggests that additional system for supporting the formed shape is needed as long the forming takes place. After placing the formed bundle over the winding head, additional system finishes a forming at the collection point.

Steps that need to be repeated for each of radially distributed wire bundles around one stator:

1. Position the forming tool horizontally in the level of the wire bundle in a way that the distance between point of positioning and fixed point of the bundle equals to the needed length of forming
2. Translate the tool with open gripper (G1) in a plane of forming in a way that the bundle is collected from the side; after closing the gripper (G1) wire bundle is fixed (Figure 50, I)
3. Deform the bundle by the rotation of a flange for a certain bending angle necessary to achieve the desired polygonal shape (Figure 50, II)
4. Rotate the flange back to the initial position (Figure 50, II)
5. Half-open the gripper (G1) and translate it along the bundle for the distance equal to the side length of the polygon (Figure 50, II)
6. Close the gripper (G1) in the new gripping position and repeat steps 3 to 5 until the fixed end of the bundle is reached (Figure 50, III)

7 At the fixed point grip the bundle over the winding head and rotate the whole forming tool for an angle needed to make the 90° rotation of the flange sufficient for placing the formed bundle over the winding head (Figure 50, III)

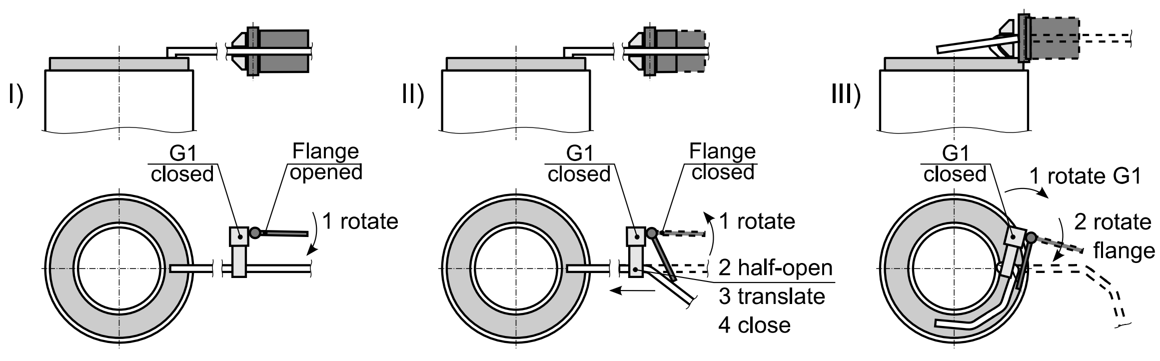


Figure 50 Forming concept *G*

If no additional degrees of freedom are available for moving the forming tool, for the forming of the next bundle, the whole stator rotates until the forming tool is vertically above the desired bundle. For the adjustment of the forming length, number of repetition of steps and coordinates of start position for forming are changed.

Adjustability

Nevertheless that the support for the wire bundle is provided by a gripper in a horizontal position, the function of the gripper is as well to hold the bundle firmly. For that reason, when the wire bundle size is changed, it is necessary to adjust the gripping profile of gripper (G1) by exchanging gripper fingers. Modifications required by a change of the stator size consist of changing the position of characteristic points and adjusting the side length of the polygon in a system control programme. Hereby, for the adjusted side length, bending angle needs to be adjusted by the angle of rotation of the flange.

Forming concept H

According to forming principle *j*, which is realised with modifications of the setting given in experiment 4, forming procedure is generated for forming a polygon with constant side length. In repetitive steps, a forming tool with a radius equal to the diameter of the biggest wire bundle is used.

Description

For forming, one standard parallel two-finger pneumatic gripper (G1) is used in combination with a forming tool (FT). The forming tool operates with a translatory motion perpendicular to the wire bundle and parallel to the gripper (G1). Both gripper (G1) and the forming tool (FT) are mounted on the same 3-axis system that provides the possibility of vertical translation as well as two translations in the horizontal plane. Similar as in a concept *G*, parallel gripper has two possible opening positions: open and half-open, where regulation between two position is done automatically. Forming starts at the free end of the bundle and finishes with forming the bundle at the fixed point. At the end of the forming in fixed point, the tool places the formed wire bundle over a winding head. During the forming, additional system for supporting the formed shape is needed. After forming in a fixed point, additional system for forming at a collection point is needed.

Steps that need to be repeated for each of radially distributed wire bundles around one stator:

1 Position the forming tool horizontally in the level of the wire bundle in a way that the distance between point of positioning and fixed point of the bundle equals to the needed length of forming

2 Translate the tool with opened gripper (G1) in a plane of forming in a way that the bundle is collected from the side; after closing the gripper (G1) the wire bundle is fixed (Figure 51, I)

3 Deform the bundle by the translation of the forming tool (FT) for a certain distance sufficient to perform bending angle necessary to achieve the desired polygonal shape (Figure 51, II)

4 Translate the forming tool (FT) back to the initial position (Figure 51, II)

5 Half-open the gripper (G1) and translate it along the bundle for the distance equal to the side length of the polygon (Figure 51, II)

6 Close the gripper (G1) in the new gripping position and repeat steps 3 to 5 until the fixed end of the bundle is reached (Figure 51, II)

7 At the fixed point grip the bundle over the winding head and increase the stroke of the forming tool (FT) in order to place the formed bundle over the winding head (Figure 51, III)

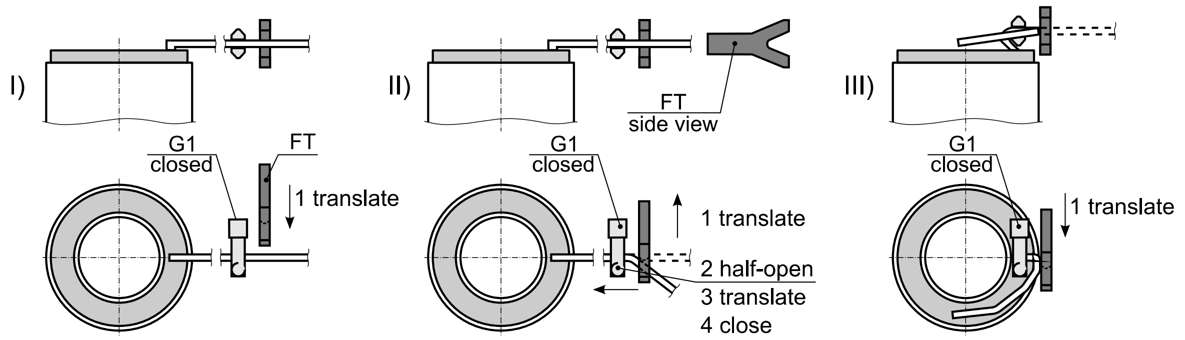


Figure 51 Forming concept *H*

For forming the next wire bundle, the whole stator should rotate until the gripper (G1), which has a position on a linear axis in a working cell, is placed vertically above the desired bundle. For adjusting the forming length, linear coordinate of a start point of forming for gripper (G1) on the axis is modified as well as the number of repetitive steps.

Adjustability

In case of changing only size of a wire bundle, gripper fingers of parallel gripper need to be exchanged by the ones with modified gripping profile. Other parameters, such as positions of characteristic points, which are influenced by a change in the size of the stator, need to be adjusted in the control programme of a system. Bending angle, which regulates the angle and the side length of the polygon, is adjusted by making a stroke of the forming tool longer or shorter.

Forming concept I

Setting from experiment 4 is modified to still represent forming principle *h*. The forming procedure aims to form a polygon with constant side length in repetitive steps. For that, forming tool of a radius equal to the diameter of the biggest wire bundle is used.

Description

Full repeatability of the bend can be described as forming with always exactly the same bending radius and exact bend position relative to the forming tool. Customized forming tool (FT), which can provide the full repeatability, consists of two pins (P1) and (P2) where pin (P1) rotates around the centre of pin (P2). The gripping function of the forming tool is accomplished by the possibility of relative translation of one pin to another. As in concepts *G* and *H*, forming starts at free end of a wire bundle, meaning that the additional system for supporting a formed shape is needed. Since the tool needs only to grip the bundle and move along the wire bundle length, it is sufficient to mount it on a 2-axis system providing vertical and horizontal translation. The last forming operation at the same time provides forming at the fixed point of the bundle and places the formed bundle over the winding head. Following, additional system for placing a bundle into neutral zone is needed as well for forming at the collection point.

Steps that need to be repeated for each of radially distributed wire bundles around one stator:

1 Position the forming tool vertically above the wire bundle in a way that the horizontal distance between point of positioning and fixed point of the bundle equals to the needed length of forming

2 Translate the tool vertically down so that all the wires of the bundle can be collected when the pin (P2) is translated towards the pin (P1); NOTE: in order to enable forming, the bundle should not be held firmly. (Figure 52, I)

3 Deform the bundle by rotating the roller (R1) around the centre of roller (P2) for the bending angle necessary to achieve the desired polygonal shape; static holder (H1) prevents the wire bundle from losing its straight form when deformation starts (Figure 52, II)

4 Rotate the roller (P1) back to the initial position (Figure 52, II)

5 Translate the whole forming tool along the bundle for the distance equal to the side length of a polygon (Figure 52, II)

6 Repeat steps 3 to 5 until the fixed end of the bundle is reached (Figure 52, II)

7 At the fixed point move the forming tool with a gripped bundle over the winding head; by bigger rotation angle of roller (P1) form the bundle in a fixed point; this operation at the same time places the formed bundle over the winding head (Figure 52, III)

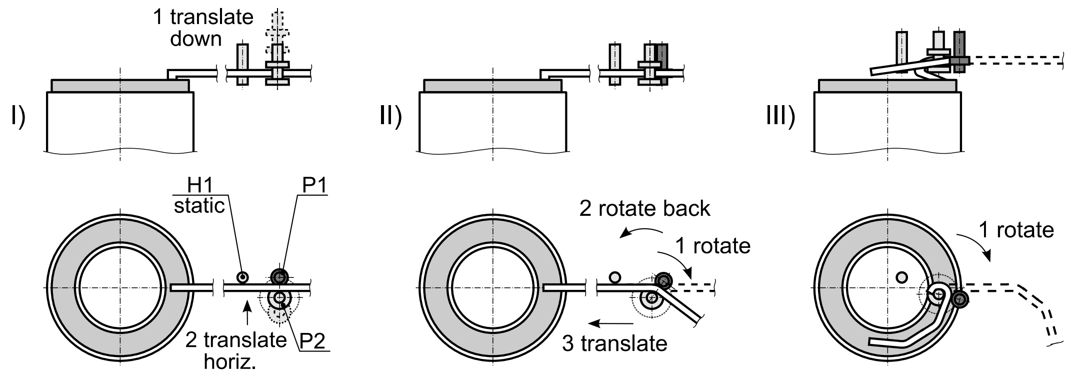


Figure 52 Forming concept *I*

Next wire bundle is formed in a way that the whole stator rotates until the forming tool is placed vertically above the desired bundle. Forming length is afterwards adjusted together with a change of the number of repetitive steps. For the forming tool which is mounted on a linear axis parallel to the wire bundle, linear coordinate of the start point for forming, needs to as well be changed in the system control programme.

Adjustability

In order to overcome the change in a size of a wire bundle, the position of one of the rollers is manually adjusted. Alternatively, instead of adjusting the position, it is possible to change the gripping profiles of pins. For changes in the size of the stator, coordinates of characteristic points are modified in the control programme of the system. In order to regulate the length of the side of the polygon, bending angle needs to be adjusted by increasing or decreasing the rotation angle of a rotating pin.

4.2.8 Evaluation of forming concepts

For *concept scoring* stage of overall concept selection process adapted from [2], evaluation of forming concepts is done by using Pugh's method of comparing all the variants to a chosen referent concept [41]. The used comparison scale consists of five grades where middle grade implies the same performance for a certain criteria and two more levels are provided to show if other concept conforms the criteria either better or less good. In specific, the following grades are used with corresponding meaning:

- 2 = conforms the criteria much better
- 1 = conforms the criteria (slightly) better
- 0 = conforms the criteria equally
- -1 = conforms the criteria (slightly) worse
- -2 = conforms the criteria much worse

Eight criteria are chosen to be appropriate to compare concepts on given level of detail. Due to elimination of unsuitable forming methods, all concepts fulfil the discriminating criteria of first level of adjustability, that is the adjustability of the forming length. However, now the concepts can be compared by the similar criterion *Ease of 1st level adjustment* considering the number of parameters that need to be changed for each system concept. Hereby considered changing parameters are (a) distance of start point of forming as well as (b) number of steps multiplied with number of elements for which the number of steps changes. It is considered to be better if less parameters for less elements need to be changed in order to adjust the forming length.

Next two criteria consider second level of adjustability, that is when a stator type is changed. In case of changing any of dimensional parameters provided in task description, adjustments need to be made on the system both considering the tool and system parameters. Hereby, as system parameters the forming radius and positions of fixed and collection points are taken. *Universality of a tool* criterion refers to if (a) new tool is needed, for example a die with a constant radius cannot be used if the forming radius is changed, (b) existing tool can be adjusted, for example gripper fingers with new size of a gripping profile need to be manufactured or (c) always the same tool can be used. Compared to case (b), case (a) is considered to be worse and case (c) is better. Considering the method used for adjusting the system, level of automation can be observed by the *Automatic adjustment* criterion. If all the needed adjustments of the tool and system parameters can be done automatically, that is considered to be the best. If only some of the parameters or a tool need to be adjusted manually, as when a new tool or a part of a tool needs to be manufactured, the adjustment is considered as semi-automatic and it is still rated as good. However, when all the adjustments need to be done manually, that is considered as less preferred option.

Fourth criterion addresses *Extended usability* of a system by inspecting an option to use the same system, or at least the same forming method, as well for an operation of forming in a collection point, that is placing a bundle in a neutral zone. When the concept itself provides extended usability, that is the best. Otherwise, it is still an advantage if the same forming method can be used. A concept for which completely new system needs to be designed for forming at the collection point is least preferable.

Repeatability criterion is the same as for elimination of forming methods, referring to the precision of a system in positioning and creating the same shape for all the bundles of a same stator type. A concept is considered to be better, the less possible variations in deforming of a bundle it provides.

Since the concept needs to be applied in a serial production, it is desired that, in a case of failure, elements can be replaced fast and easily. From that point of view, it is better when standard parts are used as elements of a system instead of elements customized especially for a purpose of a forming system. Accordingly, *Level of customization* criterion is used to compare the concepts by number of main elements that can be used as standard parts.

With each additional motion execution time for an operation increases as well as for maintenance. Moreover, control and synchronization of all of required motion becomes more complex. *Ease of handling* criterion is used to compare the concepts based on number and type of motion that need to be executed in order to move to the next step of forming. The more degrees of freedom single elements and a system in whole require, the less appropriate the concept is.

Last considered criterion refers to *Shape preservation* in terms of handling the formed part of a bundle during the forming procedure. When forming starts from the fixed point, additional system for assisting with wire bundle length is needed to support the straight wire bundle. However, when forming starts from a free end, the additional system has to support partially formed shape what is considered to be more complex task. Therefore, the concept that does not require the additional system is comparably better. Moreover, it is as well rated if the handling method of a concept, in terms of moving to a next forming step, ensures that the previously formed bundle shape stays in its form.

In order to differentiate between importance of listed criteria, adapted Likert scale for importance [40] is used to describe weight factors *WF*:

- 0 = not relevant
- 1 = relevant, but not important
- 2 = less important
- 3 = important
- 4 = very important
- 5 = key criteria

Although not used for given evaluation, extreme weight factors *0* and *5* are provided as options in order to make it easier to eliminate or increase the importance of given criteria. This is important for decision makers in charge for application of a solution in a production if requirements on a system change or new requirements appear. Moreover, the weighting of criteria is done according to the requirements and good practice of establishing solutions for serial production machines.

As a referent concept, concept *D* is chosen since it conforms to most of the criteria on a medium level. That makes it suitable to get a full range of grades when comparison is done with other concepts. The comparison is shown in Table 6. After assigning comparison grades, the grades are, for each concept separately, multiplied with the weight factor *WF* and summed up. According to an overall sum, ranking of concepts is done in a way that rank number one is given to a concept that was rated with a highest sum of comparison grades. The concept with a number one rank represents the most appropriate concept for further development.

From the evaluation table it can be observed that wining concept *I* differs from concepts *G* and *H* only by *Repeatability* criterion. The reason for that stands behind the fact that in concept *I* pin (R2) is used as a support for forming. Unlike in concepts *G* and *H*, where no direct support is provided, supporting pin in concept *I* ensures that the bend is always done at the same location. Although the concept *I*, unlike the referent concept *D*, requires in addition a system for preserving the formed shape of a bundle, it requires less and simpler motion of a tool to move to a next forming step. This results in lower grade for a *Shape preservation* criterion, but it keeps higher rating for *Ease of handling*. Similar comparison can as well be made between the criteria *Ease of adjustment* and *Level of customization*. Although the realisation of concept *I* is not merely a combination of standard parts available in offer of a certain supplier, the result of specifically designed solution is that less parameters need to be changed in order to adjust the forming length for every of the bundles. However, the advantage of a concept considering the *Universality of a tool* when stator type is changed stays the same as for the referent concept *D* since minor manual changes need to be done in order to adjust the tool for different dimensions.

Table 6 Evaluation of forming concepts

Criteria	***WF***	**Concepts**								
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Ease of 1st level adjustment	*4*	1	-1	0	0	2	1	1	1	1
Universality of a tool	*2*	-1	0	0	0	1	2	0	0	0
Automatic adjustment	*3*	-1	0	0	0	0	2	0	0	0
Extended usability	*2*	2	-2	0	0	-2	-2	-1	-1	-1
Repeatability	*4*	-1	1	0	0	1	-1	0	0	1
Level of customization	*4*	-1	0	0	0	-2	0	-1	-1	-1
Ease of handling	*4*	1	-2	-2	0	-2	-1	2	2	2
Shape preservation	*3*	0	2	2	0	-2	-2	-2	-2	-2
	Σ SUM	-1	-6	-2	0	-12	-4	0	0	4
	RANK	**3**	**6**	**4**	**2**	**7**	**5**	**2**	**2**	**1**

4.3 Detailed concept

According to the evaluation of forming concepts, concept *I* is rated as the most appropriate concept for forming a wire bundle. For that reason, a more detailed technical realisation is provided for the conceptual forming tool. Concept *I* relies on a forming tool that uses two pins in order to locally deform a bundle, thus to produce polygonal resulting bundle shape. The principle of bending is shown one more time in the next figure.

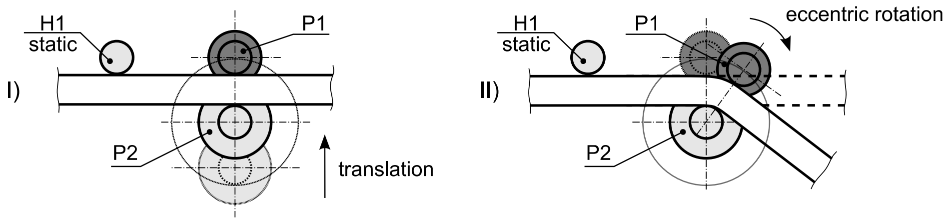


Figure 53 Pin forming method of chosen concept *I*

Motion that needs to be integrated in a tool is one translation and one rotation (Figure 53). Since, for the purpose of serial production, pneumatic solutions are preferred to electrical ones, pneumatic cylinder is chosen to provide a translatory motion. Unlike for the translation that has always the same stroke, the angle of rotation of pin (P1) defines the bending angle. For that reason, the rotary motion needs to be automatically controllable what makes electrical drive more appropriate.

Description

In Figure 54, a cross section of a forming tool is shown. To enable more clear view, part of the housing, which enables mounting of the tool on an axis system, is not shown in the image.

The tool is used to first grip the bundle by translating the pin (P2) towards the rotary pin (P1). Hereby, the gripping profile of the translatory pin (P2) is designed to collect all the wires of a bundle and to hold them in a forming plane. Gripping profile of rotary pin (P1) is designed in a way to provide a support for the bundle of a certain size. As two pins come into the contact, sliding of a rotary pin (P1) in the gripping profile of translatory pin (P2) ensures that none of the wires are left out during the gripping process. When the translation is finished, the bundle is held between two rollers with a clearance that enables bundle still to translate. That enables movement of a tool to a position for a next bending and reduces the friction while rotating the pin (P1).

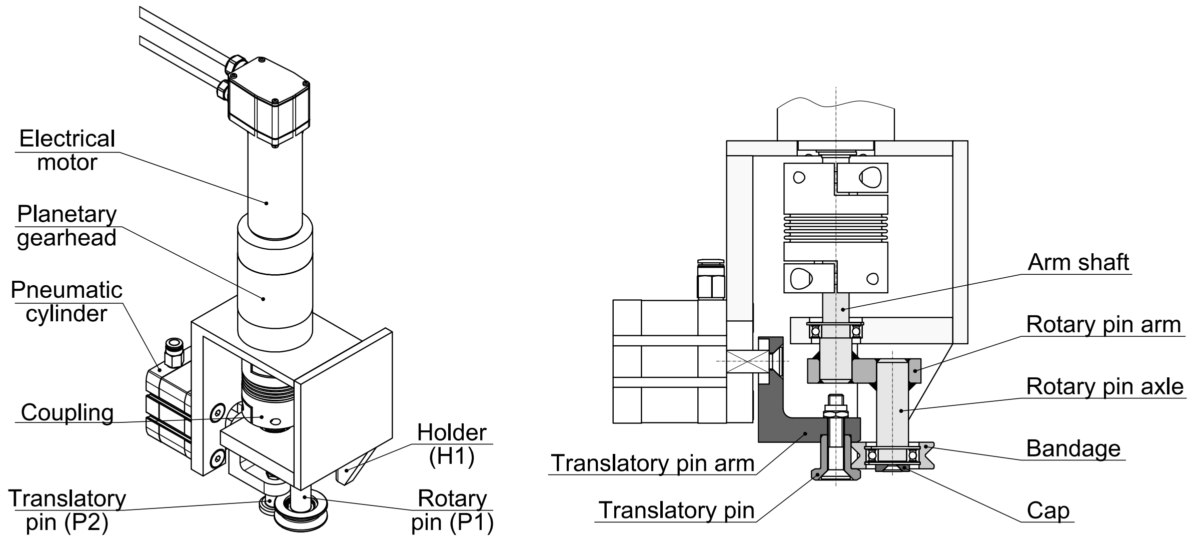


Figure 54 Forming tool for bending with pins

To enable the rotation of a pin (P1) around the centre of a translatory pin (P2), rotary pin (P1) is mounted eccentrically to the shaft of electrical drive. On the contrary, pneumatic cylinder, which carries the translatory pin (P2), is mounted in a way that the centre of translatory pin aligns with the centre of rotation of electrical drive when bundle is gripped.

Since the shaft of the chosen planetary gearhead does not withstand radial force as big as the bending force, additional bearing is needed to release the load from the shaft. For that reason, the rotating arm that carries the rotary pin (P1) needs to be connected with a shaft by a coupling. In order to perform fast rotation rigid coupling is desired, however, the coupling should still be able to overcome reduced manufacturing precision.

In order to avoid mutual loosing of parts during the operation, for joining of rotary elements, weld joints are used rather than bolts. Where bolts are used, they need to be able to prevail the torque.

Adjustability

The translatory pin (P2) is designed with a flat gripping surface, making it suitable for any wire bundle size. On contrary, the gripping profile of rotary pin (P1) is dependent on the bundle size. For that reason, when size of a wire bundle changes either by changing the number of wires or by changing the wire diameter, a bandage of a rotary pin (P1) is the only mechanical component that needs to be replaced. For any other changes in size of the stator, automatic adjustments are possible through the controlling programme of a planar forming system.

One of the requirements for the system is to enable forming of wire bundles in both clockwise and counter-clockwise direction. To achieve that feature, for a planar forming system that uses a tool designed according to the forming method and forming procedure given in concept *I*, the whole forming tool needs to be able to rotate for 180° around its vertical axis. Since the rotation is always 180°, pneumatic drive can be used. The rotating unit is installed then between the forming tool and the linear 2-axis system.

Dimensioning

For purposes of a conceptual design, choice of key components, which provide a dimension frame of a concept, is described in next paragraphs. Such components are pneumatic and electrical drive, both dimensioned according to the estimated bending force and bending moment.

Dimensions of other mechanical elements are chosen by approximate calculation of strength according to basic stress formulas. Due to taken simplifications, all the dimensions and chosen components need to be approved in detailed design by calculations. Additionally, customized mechanical parts need to be adapted according to requirements and possibilities of available manufacturing technologies.

In addition, if necessary, to prevent applying any load to a winding head, gripper for holding a wire bundle at the fixed point can be used as an assisting system to the planar forming tool.

Bending force

For a bending method with two rollers where one is rotating around the other, the bending force F on a wire bundle (WB) can be estimated as a shear force needed to cause plastic deformation. (Figure 55)

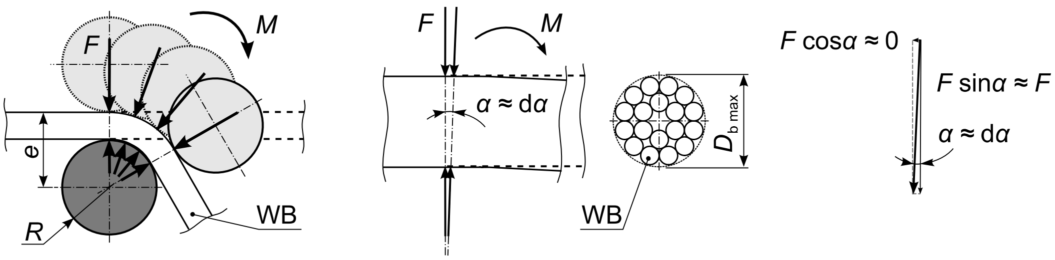


Figure 55 Bending force and bending moment

Due to the application of a force F to a wire bundle with an area of cross section A, shear stress τ has to become greater than the Yield strength σ_{Y} of a copper wire:

$$\tau = \frac{F}{A} > \sigma_{\mathrm{Y}} \tag{18}$$

If we take, according to [28] and [23], that the Yield strength of an annealed copper wire is $\sigma_{\mathrm{Y}} = 80\ \mathrm{N/mm^2}$ and calculate with the biggest area of a wire bundle, the bending force equals:

$$F > \sigma_{\mathrm{Y}}\ A = 80 \times 12{,}8 = 1\ 024\ \mathrm{N} \ \Rightarrow\ F \approx 1{,}1\ \mathrm{kN} \tag{19}$$

where

$$A = n_{\mathrm{b\,max}} \frac{\pi\ d_{\mathrm{w\,max}}^2}{4} = 18 \times \frac{\pi \times 0{,}95^2}{4} = 12{,}8\ \mathrm{mm} \tag{20}$$

with $n_{\mathrm{b\,max}}$ referring to a maximum number of wires in a bundle and $d_{\mathrm{w\,max}}$ to a maximum wire diameter.

Bending moment

Bending moment M can approximately be calculated from the following formula, taking into account same principle of causing the stress σ_{f} greater than the Yield strength of material:

$$\sigma_{\mathrm{Y}} < \sigma_{\mathrm{f}} = \frac{M\ e}{I} \ \Rightarrow\ M > \sigma_{\mathrm{Y}}\ \frac{I}{e} \tag{21}$$

Here, cross sectional moment of inertia I is approximated for a full circular cross section with a maximum possible diameter of a wire bundle $D_{\mathrm{b\,max}}$. The size of the wire bundle is taken of an ideal arrangement of 18 single wires as shown in second sketch in Figure 9. The moment of inertia is calculated around the axis that passes through the centre of the roller with radius R as shown in Figure 55:

$$I = \frac{\pi\, D_{\mathrm{b\,max}}^4}{64} + \left(R + \frac{D_{\mathrm{b\,max}}}{2} \right)^2 \frac{\pi\, D_{\mathrm{b\,max}}^4}{64} =$$
$$= \frac{\pi \times 4,62^4}{64} + \left(8 + \frac{4,62}{2} \right)^2 \frac{\pi \times 4,62^2}{4} = 1\ 805\ \mathrm{mm}^4 \quad \textbf{(22)}$$

Value of radius R of a roller is chosen to be 8 mm by taking into account minimum bending radius of single wires.

The minimum value of moment for bending a wire bundle equals:

$$M > \sigma_{\mathrm{Y}} \frac{I}{R + D_{\mathrm{b\,max}}} = 80 \times \frac{1\ 805}{8 + 4,62} \approx 11\ 500\ \mathrm{Nmm} = 11,5\ \mathrm{Nm} \quad \textbf{(23)}$$

Here, distance e is calculated as shown in Figure 55.

Pneumatic drive

As a drive for translatory motion of one roller relatively to another, compact double-acting pneumatic cylinder (designation: ADN-50-15-I-P-A-Q) is chosen from manufacturer *Festo*. The selection criteria is the axial force that the cylinder can withstand in an advance stroke. Since the theoretical force for chosen cylinder is greater than the bending force

$$F_c = 1\ 178\ \mathrm{N} > F = 1,1\ \mathrm{kN} \quad \textbf{(24)}$$

this cylinder satisfy the selection criteria.

Nominal diameter of a piston is 50 mm, and a chosen stroke is 15 mm. In addition, an option of preventing a rotation of a piston rod is chosen, meaning that the rod is of a squared cross section. Moreover, cylinder provides an option of position recognition.

Electrical drive

Electrical drive for a rotating roller is chosen according to the needed output moment. To ensure all the losses that occur in the system, such as losses due to friction in bearings or due to rolling of a roller along the pin, safety factor of 2 is applied to a calculated bending moment. This indicates that nominal torque of a gearhead needs to be minimally 23 Nm.

According to the requirement, 3-stage planetary gearhead (part No.: 110505) is chosen from the manufacturer *Maxon motor*. Nominal torque of the gearhead is 50 Nm, reduction ratio is 100:1 and maximum efficiency is 70%.

In order to reach an operating moment of 23 Nm, a motor is needed that has nominal moment of:

$$M_{\mathrm{mot}} > \frac{2\,M}{i\;\eta} = \frac{2\times 11{,}5}{100\times 0{,}7} \approx 329\ \mathrm{Nmm} \qquad \mathbf{(25)}$$

From the same manufacturer, brushless EC motor (part No.: 136209) is chosen with a power of 250 W and Hall sensors. Since the nominal torque of the chosen motor:

$$T = 347\ \mathrm{mNm} > M_{\mathrm{mot}} = 329\ \mathrm{mNm} \qquad \mathbf{(26)}$$

this motor satisfy the criteria on a needed torque.

Other standard components

For purpose of a concept design, metal bellows coupling with a clamping hub (designation: BK2) is chosen from manufacturer *R+W* that has a rated torque of 30 Nm what is compliant with a torque provided by planetary gearhead.

Bearings are chosen to be single row, deep groove ball bearings from manufacturer *SKF*. Chosen bearings (designation: 61902-2RS1) were checked by simple calculation provided by the manufacturer. Calculation showed that bearings are suitable to carry radial load equal to bending force, rotational speed of 30 rotations per minute and 40°C as a working temperature.

4.4 Next steps

In next steps, determined concept for forming the wire bundle with pins, needs to be further developed to a level of detailed design. Through calculations of strength, rigidity and durability of mechanical components, improvement and optimisation of initial dimensions should be provided. Additionally, the development of other two subsystems of the wire bundle forming system needs to be done to provide (A) assistance with extra wire bundle length and (B) free path for forming proceeding wire bundles by placing the formed bundle(s) in a neutral zone. Additional supporting subsystems (A) and (B) may be developed and used according to one of following strategies for overall forming of wire bundles:

Strategy 1 – Forming from free end:

1 Wire bundles are distributed radially around the stator and clamped in a way that all the clamps are on a distance bigger than the longest needed length of a wire bundle.
2 Grip free end of a bundle at the distance from the fixed point equal to the length needed for forming a full bundle shape of a bundle including the straight part.
3 Cut the bundle in order to unclamp it from initial position and simplify further handling.
4 Move along the bundle with half opened gripper in direction of winding head for a length of a needed straight part of a bundle.
5 Bend the straight part vertically up and keep the position of straight part while forming the rest of the bundle.
6 Form the bundle towards the winding head using one of forming procedures and take care of keeping a bundle in plane of forming and preserving the formed part.
7 Form the bundle at the point where it is fixed to the winding head.
8 If the curved part of a bundle was formed on a side of the stator and not over the winding head, place the formed bundle on the winding head.
9 Move back to the straight part.
10 Clamp the straight part of the bundle to a clamp in the middle of the stator.

Strategy 2 – Forming from fixed end:

1 Wire bundles are distributed radially around the stator and clamped.
2 With a subsystem for assisting with wire bundle length, grip free end of a bundle in order to unclamp it from initial position. At the same time, pre-cutting of a bundle can be done to simplify further handling. Keep a bundle in plane of forming and preserve the formed part by holding the bundle for full time of forming.
3 Form the bundle at the point where it is fixed to the winding head.
4 Form the bundle towards free end using one of forming procedures.
5 If the curved part of a bundle was formed on a side of the stator and not over the winding head, place the formed bundle on the winding head.
6 Bend the straight part vertically up and keep the position of straight part while forming the rest of the bundle. If possible, use the planar forming subsystem. Otherwise, use additional subsystem for placing the bundle in neutral zone.

7 Clamp the straight part of the bundle to a clamp in the middle of the stator.

In both of strategies, as a method for bending the straight part of a bundle in the collection point into the vertical plane, it is possible to apply the method provided by patent [13] and shown in Figure 60 in Appendix C.

5 CONCLUSION

In the frame of this thesis it is detected that the overall wire bundle forming system consists of three subsystem which might be developed separately: (a) planar forming of one bundle, (b) placing formed bundle to a neutral zone and (c) wire bundle length assistance. By using combined systems engineering [39] and engineering design approach [6] the wire bundle planar forming subsystem was developed for forming of curved parts of wire bundles in the plane on the top of the winding head. First search for the solution was through existing solutions to similar problems of wire, pipe and sheet metal bending. Those solutions were analysed which could have been found in normative documents for metal forming, in patents as well as in commercially available machines. Although none of the found solutions is directly applicable to the given problem, ideas gathered through the search can be used for parts of the wire bundle forming system.

The concept for planar forming of wire bundles is built in a bottom-up way. First, the investigation of solutions for a core function of *deforming the bundle* was done by means of systematic solution search as well as experimental testing. After the least appropriate forming methods were eliminated based on experimental results, basic core solution is extended by adding variants for dependent functions of *gripping the bundle* and *handling the bundle until the collection point is reached*. Nine concepts for forming procedure are then provided by combining offered alternative solutions for each of the required elements: (a) forming method, (b) forming tool, (c) handling principle, (d) start point of forming and (e) distribution of degrees of freedom between parts of a subsystem. Concept evaluation showed that the highest rated concept is the one that uses bending with a rotary pin as a forming method to achieve a polygonal shape of a curved part of a wire bundle. This concept is then developed further in the technical realisation.

Combined systems engineering [39] and engineering design approach [6] applied for the development of planar forming subsystem showed to be appropriate choice for a low number of restrictions given in the task description. In addition, concept selection method adapted from [2], although not used strictly by provided guidelines, offers a good support for high level of abstraction in first rough concepts.

The assumptions upon which the concept was built are: (a) initial position of wire bundles is in a horizontal plane of a winding head, radially distributed around the stator, (b) there is a unique laying order of bundles that enables forming of one bundle at a time without interruptions, (c) there is an additional subsystem for ensuring that the formed shape of a bundle is not damaged during the forming and (d) there is an additional subsystem for placing the straight part of a bundle in a vertical plane.

The advantage of the chosen concept is that it closely imitates one of the existing forming methods that is most often use for automatic bending of wires. The main problem in applying the existing solutions directly lays in the fact that wire bundle as a work piece has non-constant cross section with a possibility of single wires going apart from each other. In addition, mechanical properties of enamelled copper wire are sensitive to the operations through which the bundle passes in previous steps of production. For that reason, it is rather difficult to estimate the values of the properties correctly when the stator is delivered to the wire bundle forming station. Furthermore, it is difficult to assume how the properties of single wires, which have different mutual arrangement along the bundle length, are combined in the properties of the bundle. This especially refers to the prediction of springback, which is even more difficult when properties of several single wires are combined in properties of a wire bundle. According to [33], an increase in following parameters of free bending between two support points increases the springback: coating thickness, velocity of a punch, die opening, radius of a die and radius of a punch. Latter is confirmed as well by experiments conducted in the frame of this thesis. In the chosen concept, the intention is to reduce the springback by reducing the bending radius to a minimum. However, further conclusion from the experiments is that, due to insufficient exact information on mechanical properties, the predicted springback needs to be tested before the solution is implemented in the production. Suggested method for compensating the springback, that is as well applicable for the chosen concept, is *overbending* of the bundle for a certain angle [32].

For future work, the concept should be developed more in detail and adapted for application in a production line. All the dimensions and chosen components need to be approved by calculations and customized mechanical parts need to be adapted according to requirements and possibilities of available manufacturing technologies. Additionally, supporting subsystems for placing the formed bundle in neutral zone as well as subsystem for wire bundle length assistance need to be developed to fit the requirements of planar forming subsystem. Moreover, to fully clarify and define the task of a wire bundle forming system, the broader arrangement of a production line should be defined as well as specific design of a stator. When the design of a specific stator type is known, it is possible to define the need for production operations such as pre-forming of a winding head and pre-cutting of wire bundles. In that case, the requirements on a wire bundle forming system should be revised. For so far known requirements, a list of questions for approving the concept on both subsystem level of planar forming and system level of the whole wire bundle forming process are given in Appendix E. The list should ease the tracking of the system requirements in further steps of development and provide a basis for requirements revision. When all the requirements are known, system functions and according solutions need to be adapted in order to enable the implementation of the system in a production line.

REFERENCES

[1] Brettel, M., et al.: How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective, International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering, Vol.8, No.1, p.37-44, 2014

[2] Ulrich, K. T., Eppinger, S. D.: Product Design and Development, Third Edition, McGraw Hill, Boston, 2004

[3] VDI 2221: Methodik zum Entwickeln und Konstruiren technischer Systeme und Produkte, 1993

[4] Eversheim, W., Schuh, G.: Integrierte Produkt- und Prozessgestaltung, Springer, Berlin, 2005

[5] Zwillinger, D.: CRC Standard Mathematical Tables and Formulae, 32nd Edition, CRC Press, Boca Raton, 2012

[6] Pahl, G., Beitz, W., Feldhausen, J., Grote, K.-H.: Engineering Design – A Systematic Approach, Third Edition, Springer, Berlin, 2007

[7] DIN 8584-3:2003-09: Manufacturing processes forming under combination of tensile and compressive conditions

[8] DIN 8584-4:2003-09: Manufacturing processes forming under combination of tensile and compressive conditions

[9] DIN 8585-4:2003-09: Manufacturing processes forming under tensile conditions

[10] DIN 8586:2003-09: Manufacturing processes forming by bending

[11] VDI 3430: Rotary draw bending of profiles

[12] Shigematsu, H., Ide, T.: Conductive wire piece set forming method and conductive wire piece set forming device, US 20150059174 A1, 2015-03-05

[13] Tanaka, H., Onodera, K., Watanabe T., Fukaya Y.: Method and apparatus for treatment of stator coil lead wires for electric rotary machine, US 5613529 A, 1997-03-25

[14] Peterson, H. R.: Wire bending tool, US 2811064 A, 1957-10-29

[15] King, J. F., Horton, g. L.: Wire bending system, US 4280350 A, 1981-07-28

[16] Brewer, W. R.: Wire-bending tool, US 3187545 A, 1965-06-08

[17] Everett, F. K.: Wire bending apparatus, US 3407850 A, 1968-10-29

[18] Haltiner, K., Knoepfel, H.: Drahtbiegemaschine, DE 4110313 (C1), 1992-09-10

[19] Griswold, F. B.: Wire-bending machine, US 519812 A,1894-05-15
[20] Clouse, W. L.: Wire-bending machine, US 1639397 A, 1927-08-16
[21] Klemm, E. O.: Wire bending die unit, US 2659408 A, 1953-11-17
[22] Christofilis, T. J., Grapsas, C. S.: Devices, Systems and Methods for Automated Wire Bending, US 20140130567 A1, 2014-05-15
[23] Davis, J. R.: Copper and Copper Alloys, ASM International, Materials Park, 2001
[24] Bosch-Norm N28 CW0003 S001: Copper, oxygenic CW003A, 2011
[25] Bosch-Norm N34A WD200 S001: Enameled wire rods grade 1, class 200, 2014
[26] Bosch-Norm N34A WD200 S015: Enameled wire rods grade 2, class 200, moldable 2015
[27] Schwering & Hasse Elektrodraht GmbH: SH Therm 210, Data Sheet
[28] Kraut, B.: Strojarski priručnik, Tehnička knjiga Zagreb, 1976
[29] Filetin, T., Kovačiček, F., Indof, J.: Svojstva i primjena materijala, FSB, Zagreb, 2009
[30] Askeland, D. R., Wright, W. J.: Essentials of Materials Science and Engineering, Third Edition, Cengage Learning, Stamford, 2014
[31] Math, M.: Uvod u tehnologiju oblikovanja deformiranjem, FSB, Zagreb, 2007
[32] Groover, M. P.: Fundamentals of Modern Manufacturing: Materials, Processes, and Systems, 4 edition, John Wiley & Sons, Hoboken, 2010
[33] Vasudevan, D., Srinivasan, R., Padmanabhan, P.: Effect of process parameters on springback behaviour during air bending of electrogalvanised steel sheet, Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering), Vol.12, No.3, p. 183-189, 2011
[34] Sandler, B. Z.: Robotics - Designing the Mechanisms for Automated Machinery, Academic Press, San Diego, 1999
[35] Feng, J.: Drahtbündelbiegen – Handhabungsversuch 1, Robert Bosch GmbH, 2014
[36] Feng, J.: Drahtbündelbiegen – Handhabungsversuch 2, Robert Bosch GmbH, 2015
[37] Li, Y. , Yan, S. , Xu, L.: Roll position calculation for four-rolls plate bending process based on mathematical modelling, China Academic Journal, Forging & Stamping Technology, Vol.35, No.5, p. 80-83, 2010
[38] Feng, J.: Drahtbündelbiegen – Handhabungsversuch 3, Robert Bosch GmbH, 2015
[39] Haberfellner, R., et al.: Systems Engineering: Grundlagen und Anwendung, Orell Füssli, Zürich, 2012
[40] Gunkle, M.: Country-Compatible Incentive Design, DUV, Wiesbaden, 2006

[41] Kroll, E., Condoor, S. S., Jansson, D. G.: Innovative Conceptual Design, Cambridge University Press, Cambridge, 2001

[42] Herold, Z.: Računalna i inženjerska grafika, Zagreb, 2003

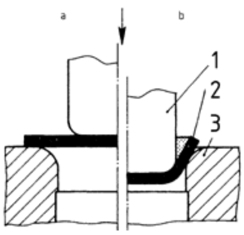
APPENDIX A – Metal forming according to DIN [7 to 10]

In the following table, those metal forming methods according to DIN standard are presented that can be adapted for forming of wire bundles.

Table 7 Forming methods according to DIN

DIN 8584-3:2003-09 - Manufacturing processes forming under combination of tensile and compressive conditions

Deep drawing without a holder

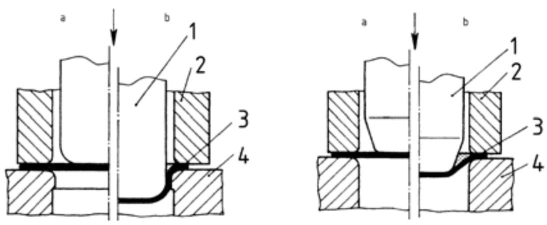


1 – Punch

2 – Work piece

3 – Die

Deep drawing with a holder



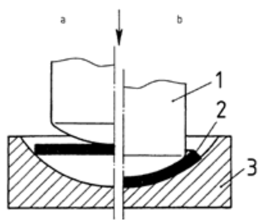
1 – Punch

2 – Holder

3 – Work piece

4 – Die

Pressing / Die forming[1]



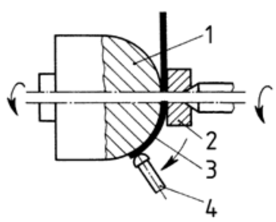
1 – Punch

2 – Work piece

3 – Die

DIN 8584-4:2003-09 - Manufacturing processes forming under combination of tensile and compressive conditions

Spinning*



1 – Die

2 – Holder

3 – Work piece

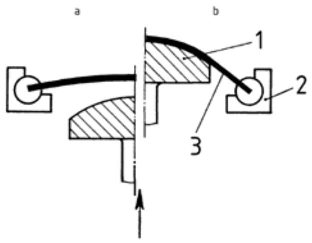
4 – Compression member

*By this method it is assumed that the die is rotating while the compression member forms the sheet metal. For use for wire bundle forming, this method can be adapted by removing the die rotation and keeping only the motion of a compression member.

Table 8 Forming methods according to DIN - continue

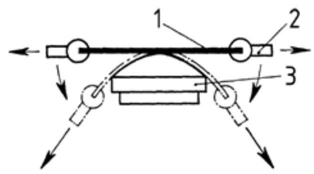
DIN 8585-4:2003-09 - Manufacturing processes forming under tensile conditions

Stretch forming



1 – Punch
2 – Clamp
3 – Work piece

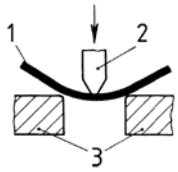
Stretch forming



1 – Work piece
2 – Clamp
3 – Form

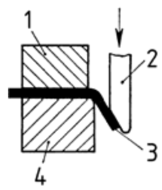
DIN 8586:2003-09 - Manufacturing processes forming by bending

Free bending



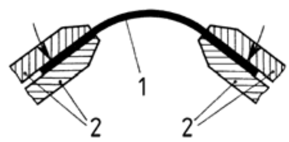
1 – Work piece
2 – Punch
3 – Work piece support

Free bending



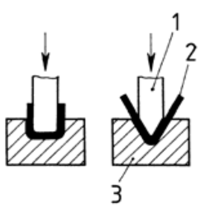
1 – Work piece holder
2 – Punch
3 – Work piece
4 – Work piece support

Lateral force (moment) free bending



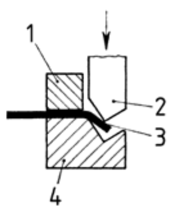
1 – Work piece
2 – Clamps

Bending in die – symmetrical



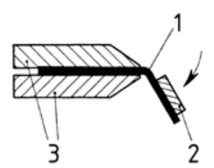
1 – Punch
2 – Work piece
3 – Bending die

Bending in die – not symmetrical



1 – Work piece holder
2 – Punch
3 – Work piece
4 – Bending die

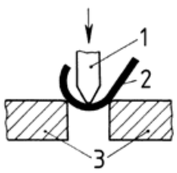
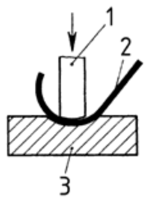
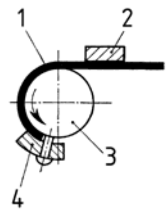
Folding

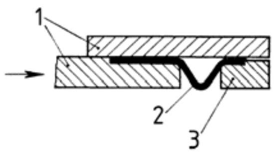
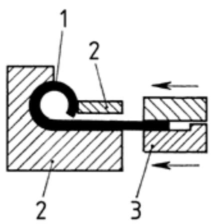


1 – Work piece
2 – Flange
3 – Clamping fingers

Table 9 Forming methods according to DIN - continue

DIN 8586:2003-09 - Manufacturing processes forming by bending

Free round bending	Round bending in die	Round bending[2]
		
1 – Punch 2 – Work piece 3 – Work piece support	1 – Punch 2 – Work piece 3 – Bending die	1 – Work piece 2 – Holder 3 – Bending mandrel 4 – Clamp

Bending by buckling	Curling
	
1 – Tool 2 – Work piece 3 – Clamp	1 – Work piece 2 – Tool 3 – Clamp

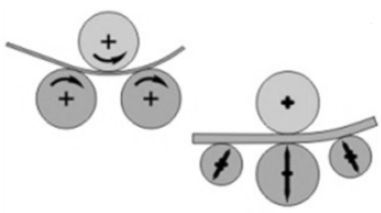
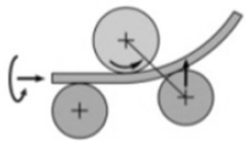
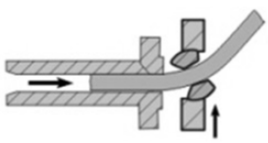
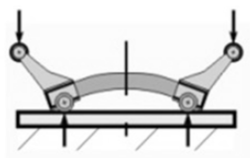
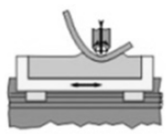
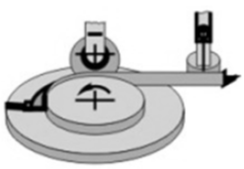
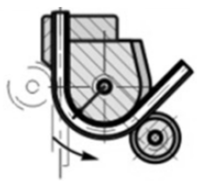
[1] Die forming belongs to norm DIN 8583-4:2003-09 Manufacturing processes forming under compressive conditions; however, the realisation of parts is similar to pressing method

[2] One of applications specifically for wires

APPENDIX B – Metal forming according to VDI [11]

In the following table, those metal forming methods according to VDI guidelines are presented that can be adapted for forming of wire bundles.

Table 10 Forming methods according to VDI

VDI 3430 – Rotary draw bending of profiles; Annex: Categorisation of bending processes		
(Three-)roll bending	**(Three-)roll push bending**	**Roll forming combined with bending**
		
Freeform bending with moveable die	**Bending without radial stress**	**Profile bending in an elastic die**
		
Rotary bending	**Classical pipe bending**	**End-controlled bending**
		

APPENDIX C – Patent US 5613529 A [13]

In following figures, methods for collecting and forming of wire bundles as well as corresponding mechanisms are described according to a patent US 5613529 A - *Method and apparatus for treatment of stator coil lead wires for electric rotary machine*.

Fig.1A Fig.1B Fig.1C

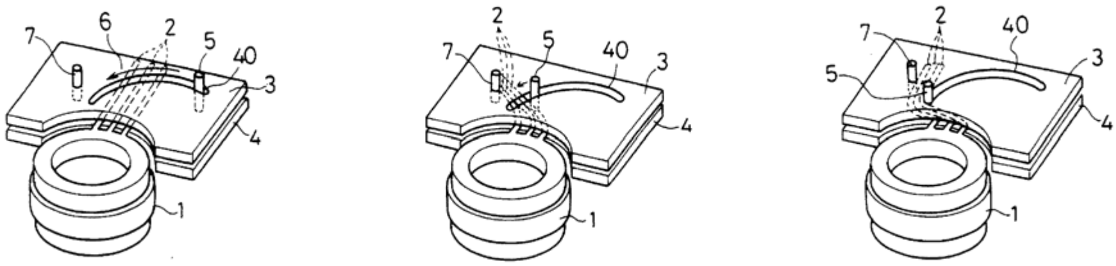


Figure 56 Collecting wire bundles – method 1, patent US 5613529 A

Fig.2A Fig.2B

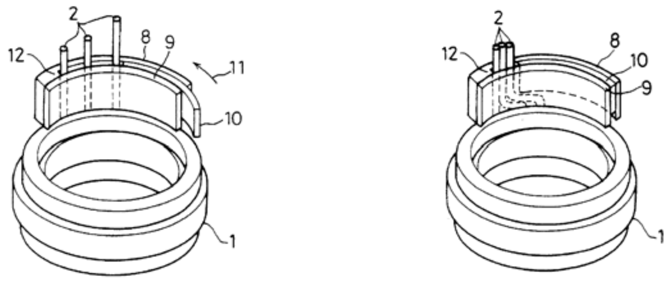


Figure 57 Collecting wire bundles – method 2, patent US 5613529 A

Fig.9A Fig.9B

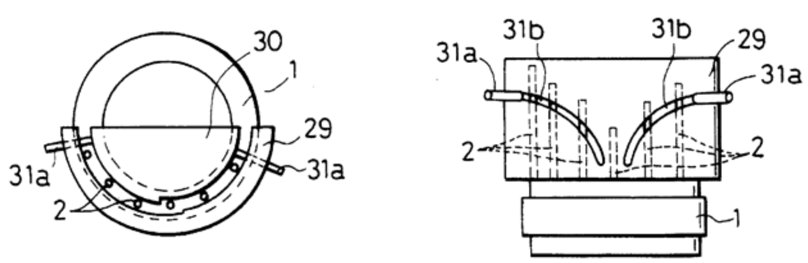


Figure 58 Collecting wire bundles – method 3, patent US 5613529 A

Fig.3A Fig.3B Fig.3C

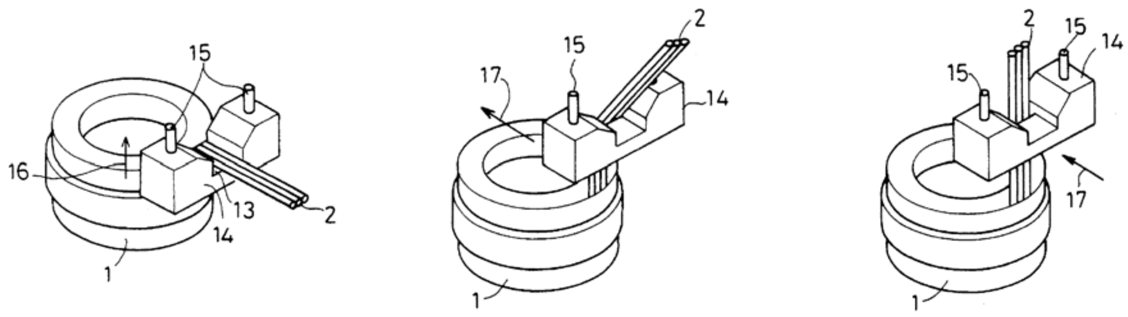


Figure 59 Forming wire bundles – method 1, patent US 5613529 A

Fig.4A Fig.4B

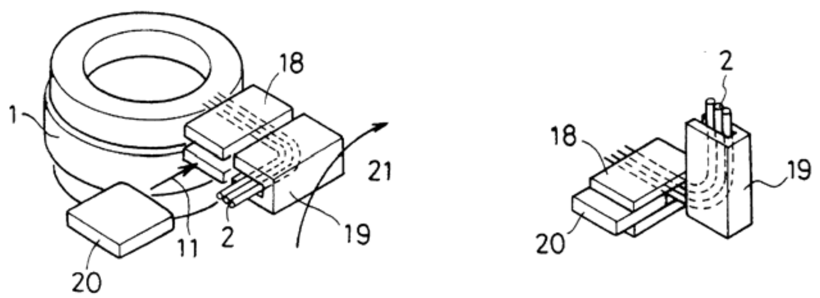


Figure 60 Forming wire bundles – method 2, patent US 5613529 A

Fig.6A Fig.6B Fig.7

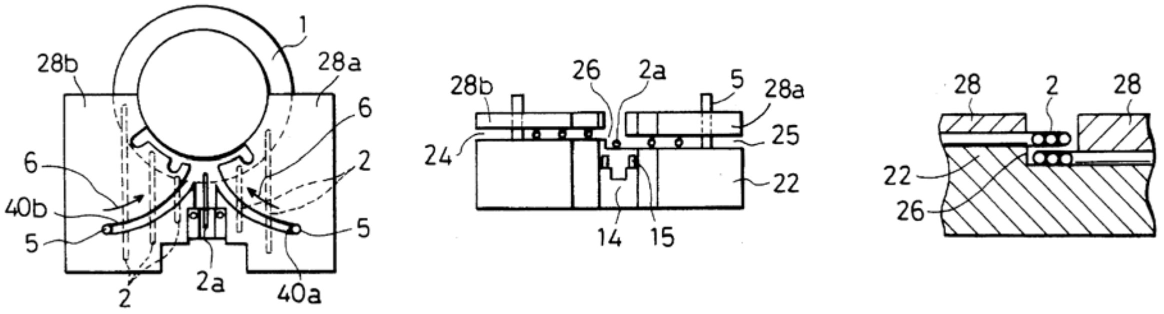


Figure 61 Collecting wire bundles – apparatus 1, patent US 5613529 A

Fig.11

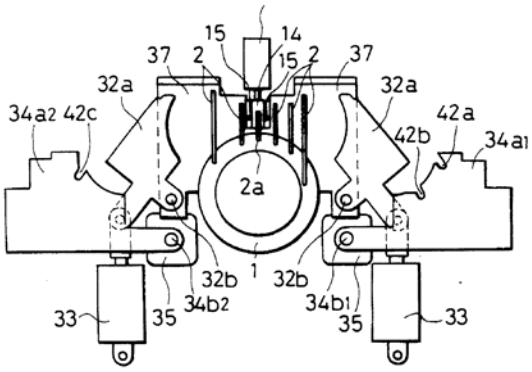


Fig.12A

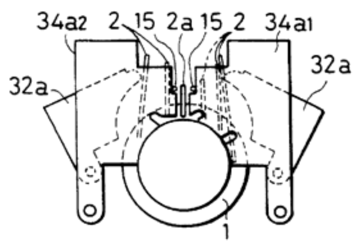


Fig.13B/E

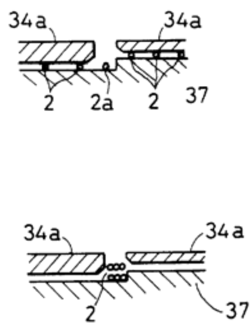


Figure 62 Collecting wire bundles – apparatus 2, patent US 5613529 A

APPENDIX D – Springback prediction

For a bending method with three rollers according to the experiment 7 following formulas are used to estimate the needed position of an adjustable roller in order to get the desired bending radius. Formulas related to steel plates are taken from [37]. The calculation was done with values of variables for copper wire bundle wherever that was possible, otherwise the original values from the literature were taken. [38]

The correction factor between desired bending radius R and the radius of curvature R':

$$k = \frac{R'}{R} \quad \textbf{(i)}$$

The radius of curvature

$$R' = \frac{R}{1 + 2\left(K_1 + \frac{TK_0}{2R}\right)\frac{\sigma_s R}{ET}} \quad \textbf{(ii)}$$

where:

R	radius of desired rolling (mm)
E	elastic modulus (MPa)
T	thicknes (mm)
K_1	shape factor (rectangular cross section is 1,5)
σ_s	yield limit of the processing material (MPa)
K_0	relative strengthening coefficient of material (1,1)

Geometrical variables are given in the next figure.

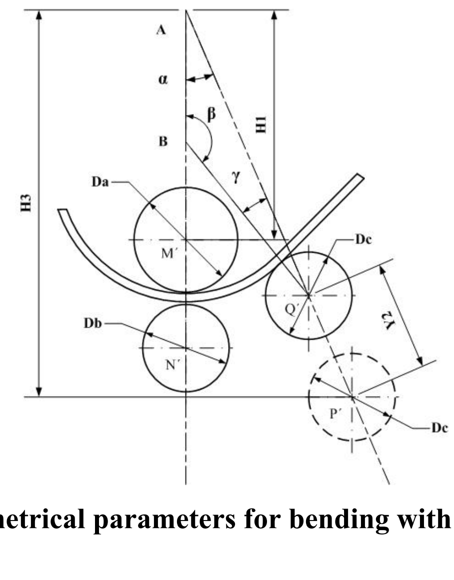


Figure I Geometrical parameters for bending with three rollers [37]

Since in the particular testing case it is

$$kR < H_1 + \frac{D_a}{2} \quad \textbf{(iii)}$$

the following formulas can be used to calculate the rest of needed parameters:

$$\frac{\mathrm{BQ'}}{\sin\alpha} = \frac{\mathrm{AQ'}}{\sin\beta} = \frac{\mathrm{AB}}{\sin\gamma} \quad \textbf{(iv)}$$

$$\sin\gamma = \frac{\mathrm{AB}\sin\alpha}{\mathrm{BQ'}} = \frac{(H_1 + D_a/2 - kR)\sin\alpha}{kR + T + D_c/2} \quad \textbf{(v)}$$

$$\mathrm{AQ'} = \frac{\mathrm{AB}\times\sin\beta}{\sin\gamma} = \frac{(H_1 + D_a/2 - kR)\sin\beta}{\sin\gamma} \quad \textbf{(vi)}$$

$$Y_2 = \mathrm{AP'} - \mathrm{AQ'} = H_3 - \frac{(H_1 + D_a/2 - kR)\sin\beta}{\sin\gamma} \quad \textbf{(vii)}$$

$$\beta = 180° - \alpha - \arcsin\frac{(H_1 + D_a - kR)\sin\alpha}{kR + T + D_c/2} \quad \textbf{(viii)}$$

APPENDIX E – Checklist of system requirements

In order to ensure that all the points are covered by the solution, all mentioned issues are collected together in a checklist for verification of concepts for both (a) planar forming subsystem level and (b) system level.

(a) Planar forming subsystem level:

1. Is it possible to adjust the subsystem to form a wire bundle on a bigger radius?
2. Is it possible to adjust the subsystem to manipulate a wire bundle of different size?
3. Is it possible to adjust the system to manipulate with more or less wire bundles?
4. Is it possible to achieve a different arc length for each of the bundles?
5. Is it possible to form a bundle in both clockwise and counter-clockwise direction?
6. Is it possible to grip all the single wires of a bundle?
7. Is it possible to hold all the single wires during the complete forming procedure?
8. Is it possible to remove any additional parts that support the forming process after the process is finished?
9. Can the solution overcome possible deviations such as differences in material properties or inconstant cross section of a bundle that may occur from forming of one bundle to another?

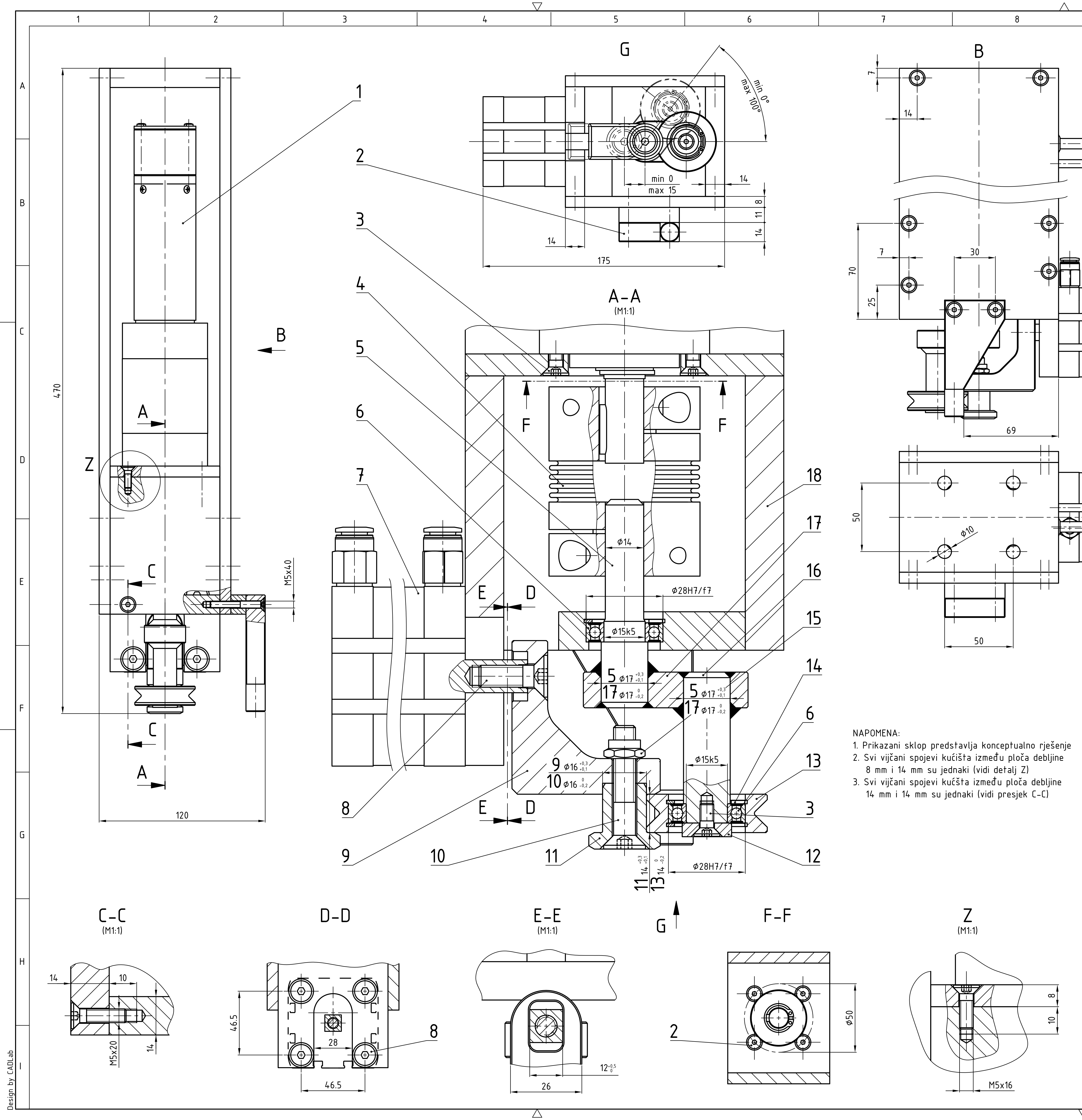
(b) System level:

1. Is the solution convenient for the application in serial production in terms of durability?
2. Is the system easy to maintain?
3. Is it possible to adapt the system (e.g. by adding a new functional module) to ensure the correct initial position of the wire bundle?
4. Is there enough space for the manipulation with the wire bundle considering any additional elements/devices that may be placed around the stator (e.g. holders for wire bundles in final position)?
5. Is there enough space for the manipulation with the wire bundle considering the position of the stator on the work piece carrier (e.g. is it possible to reach with the manipulator low enough)?
6. Is there a possibility of collision with any of the elements of the system?
7. Are all the necessary positions reachable?
8. Is it possible to fix the bundles in a vertical plane?

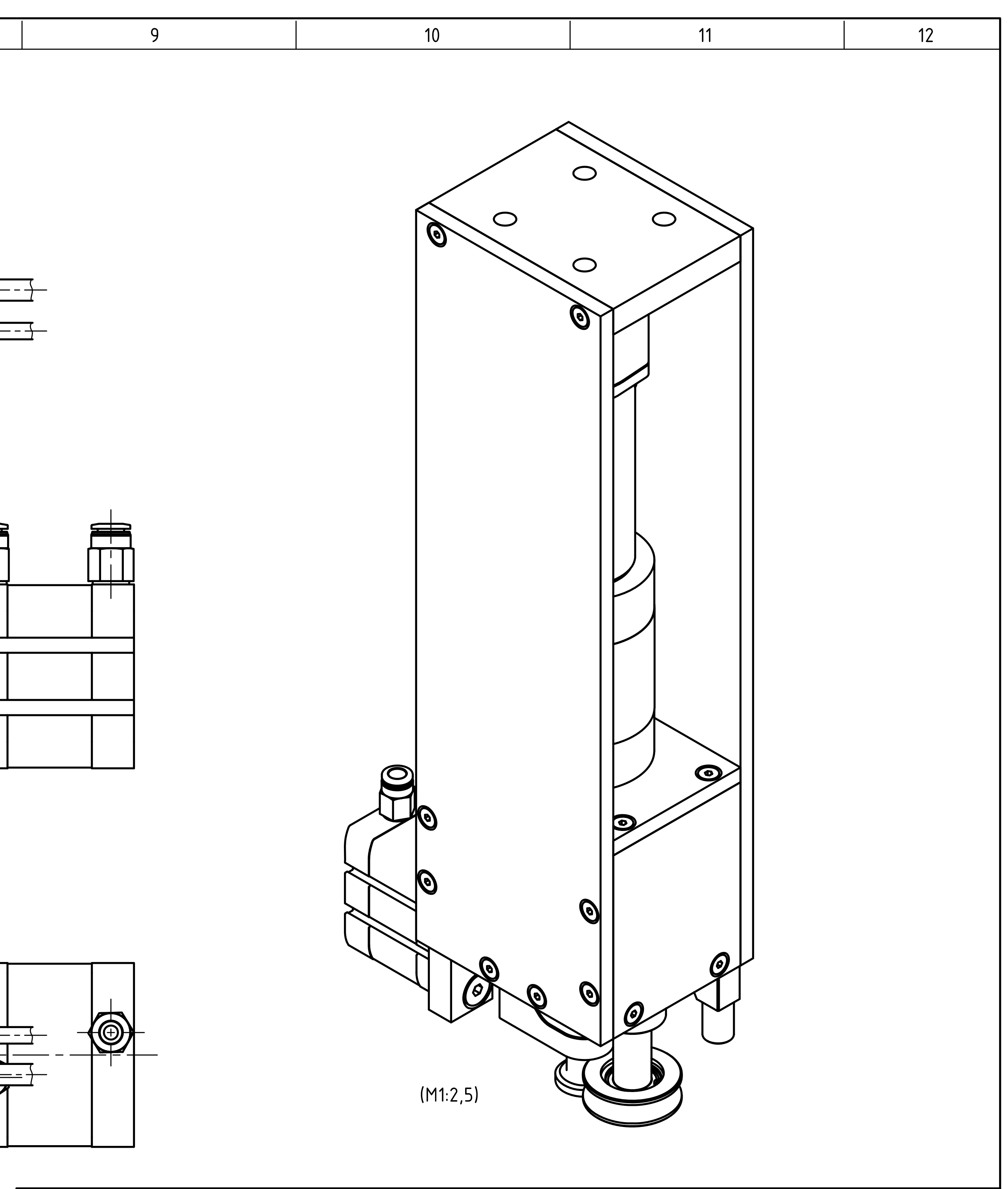
Requirements from the previous and following production steps are not known.

ATTACHMENTS

I CD-R disc
II Technical drawings



NAPOMENA:
1. Prikazani sklop predstavlja konceptualno rješenje
2. Svi vijčani spojevi kućišta između ploča debljine 8 mm i 14 mm su jednaki (vidi detalj Z)
3. Svi vijčani spojevi kućišta između ploča debljine 14 mm i 14 mm su jednaki (vidi presjek C-C)



Poz.	Naziv dijela	Kom.	Crtež broj	Materijal	Sirove dimenzije	Masa
18	Kućište	1	–	S235JR	440x135x96	10059 g
17	Ruka kotačića	1	–	S235JR	30x60x13	127 g
16	Osovina	1	–	S235JR	Ø17x55	94 g
15	Šesterokutna matica M8	1	DIN EN ISO 10511	X10CrMoV5	DIV	5 g
14	Uskočnik unutarnji 28	3	DIN 472	X10CrMoV5	DIV	2 g
13	Profilni prsten	1	pft_001_pm_15	S235JR	Ø44x14	73 g
12	Pločica	1	–	S235JR	Ø18x5	8 g
11	Valjčić	1	–	S235JR	Ø26x24	37 g
10	Vijak s upuštenom glavom M8 x 45	1	DIN EN ISO 10642	X10CrMoV5	DIV	20 g
9	Ruka valjčića	1	–	S235JR	54x56x26	238 g
8	Vijak s upuštenom glavom M8 x 25	5	DIN EN ISO 10642	X10CrMoV5	X10CrMoV5	12 g
7	Pneumatski cilindar	1	536309, 186098	–	Festo	645 g
6	Kuglični ležaj	2	61902-2RS1	–	SKF	19 g
5	Vratilo	1	–	S235JR	Ø17x75	105 g
4	Spojka	1	BK2-30-69	–	R+W	260 g
3	Vijak s upuštenom glavom M5 x 12	5	DIN EN ISO 10642	X10CrMoV5	X10CrMoV5	2 g
2	Držač	1	–	S235JR	85x44x14	233 g
1	Motoreduktor	1	110505, 136209	–	Maxon Motor	2600 g

Broj naziva - code

	Datum	Ime i prezime	Potpis
Projektirao	14.05.'15	Petra Močibov	
Razradio	14.05.'15	Petra Močibov	
Crtao	14.05.'15	Petra Močibov	
Pregledao	14.05.'15	N. Bojčetić, dr. sc.	
Mentor	14.05.'15	N. Bojčetić, dr. sc.	

FSB Zagreb

ISO - tolerancije	
Ø15 k5	+0,009 +0,001
Ø28 H7/f7	+0,062 +0,020

Objekt:

Objekt broj:

R. N. broj:

Napomena:

Materijal: S235JR, X12CrS13

Masa: 14,4 kg

Kopija

Mjerilo originala: M1:2

Naziv: Alat za oblikovanje žičanih snopova

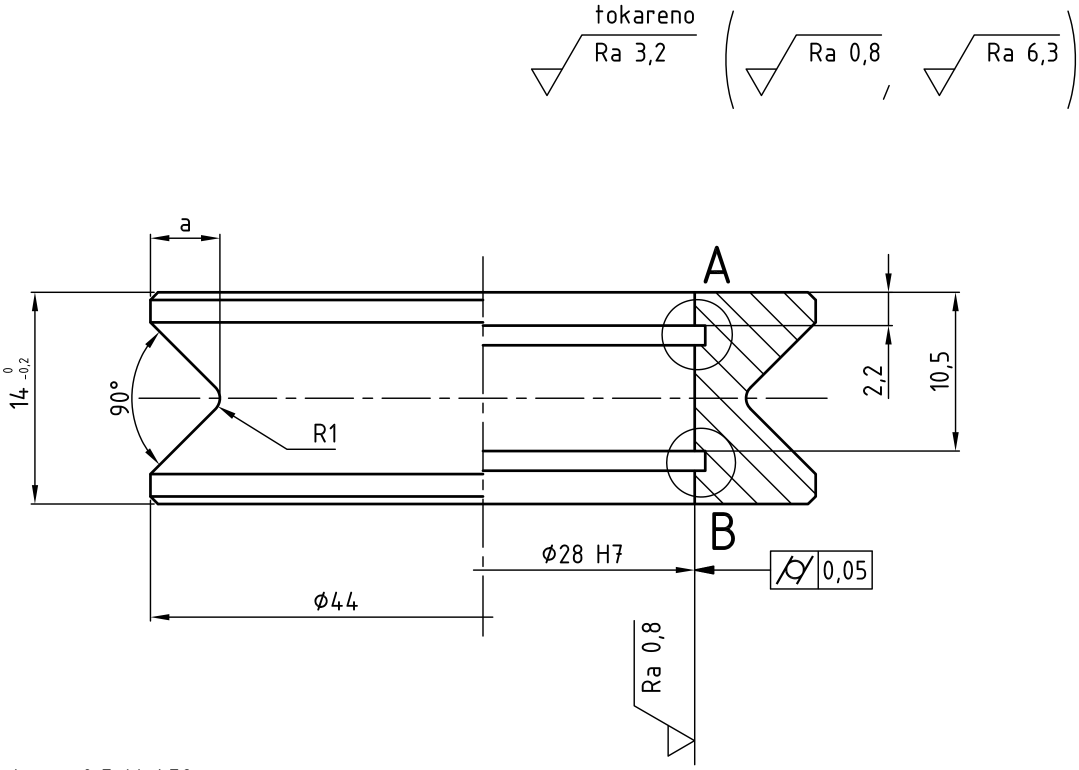
Pozicija:

Format: A2

Listova: 1

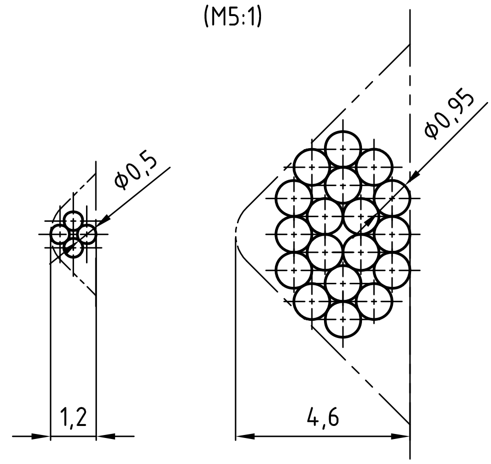
List: 1

Crtež broj: pft_100_pm_15

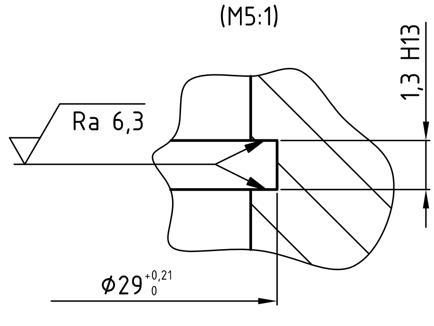


NAPOMENE:
1. Sva skošenja su 0,5 X 45°
2. Dimenziju a uzeti prema dimenziji žičanog snopa između 1,2 mm (snop 4 x Ø0,5 mm) i 4,6 mm (snop 18 x Ø0,95 mm)

Raspon dimenzija žičanog snopa
(M5:1)



A, B
(M5:1)



Broj naziva - code		Datum	Ime i prezime	Potpis	FSB Zagreb
	Projektirao	14.05.'15	Petra Močibov		
	Razradio	14.05.'15	Petra Močibov		
	Crtao	14.05.'15	Petra Močibov		
	Pregledao	14.05.'15	N. Bojčetić, dr. sc.		
	Mentor	14.05.'15	N. Bojčetić, dr. sc.		

ISO - tolerancije			
1,3 H13	+0,140 / 0	Objekt:	Objekt broj: / R. N. broj:
Ø28 H7	+0,021 / 0	Napomena:	Kopija
		Materijal: S235JR	Masa: 73 g

Mjerilo originala	Naziv:	Pozicija:	Format: A4
M2:1	Profilni prsten	13	Listova: 1
	Crtež broj: pft_001_pm_15		List: 1

Design by CADLab