NAPREDNE METODE TEHNOLOGIJE PLASTIČNOG DEFORMISANJA

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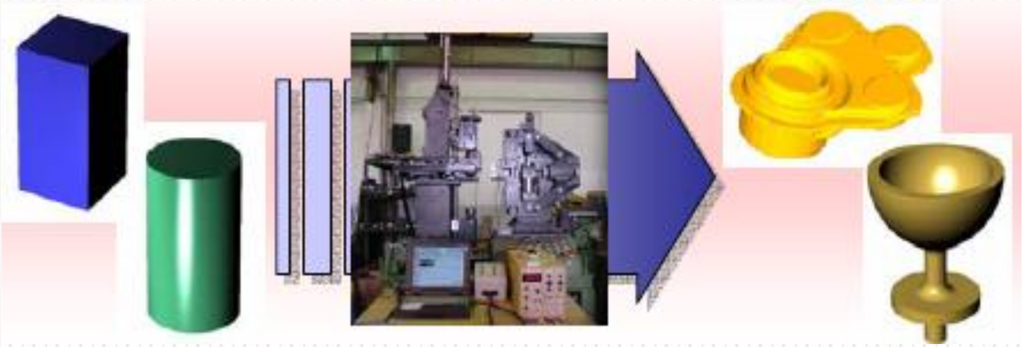
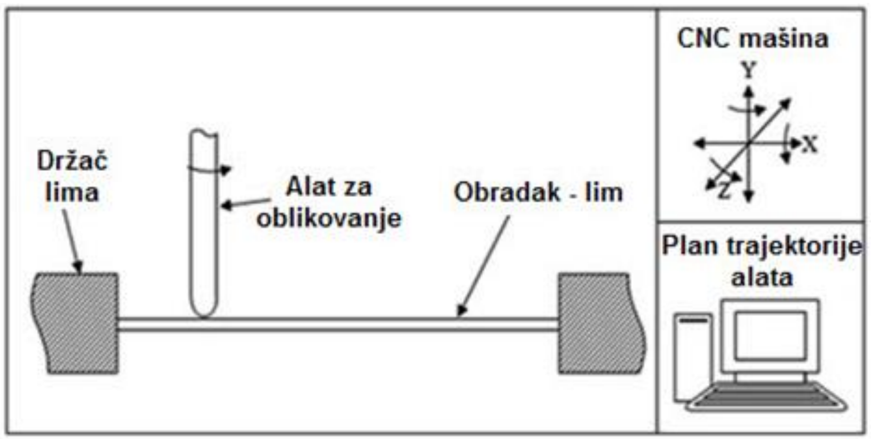
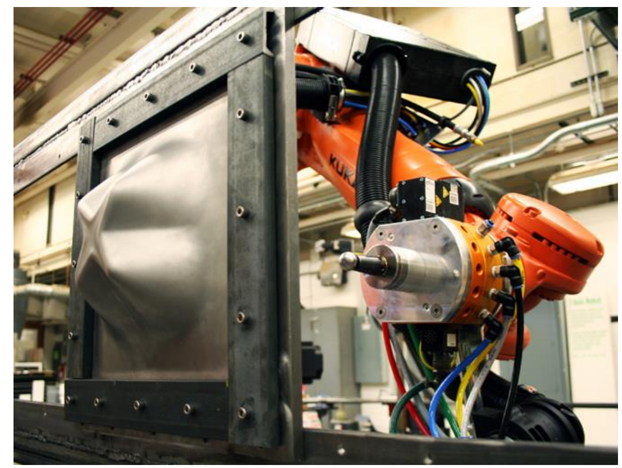


Inkrementalno deformisanje lima

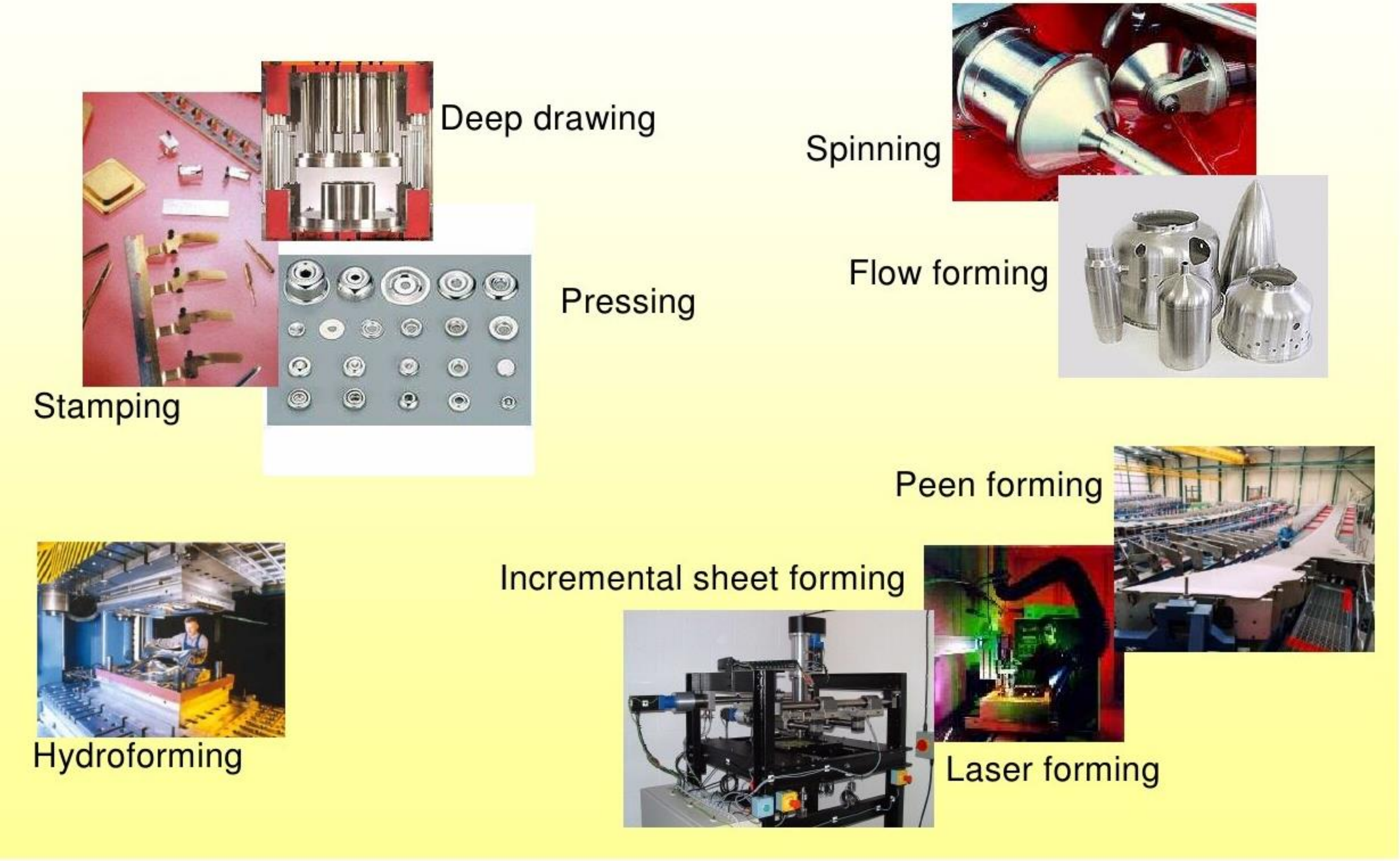
- Inovativna tehnologija obrade deformisanjem
- Visoka fleksibilnost
- “Dieless“ tehnologija - oblikovanje se vrši pomoću univerzalnog alata čiju putanju kontroliše računar (CNC mašina)





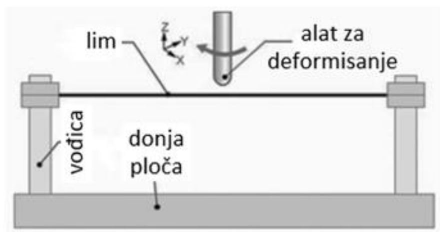
Inkrementalno deformisanje lima

Supstitucija klasičnih tehnologija

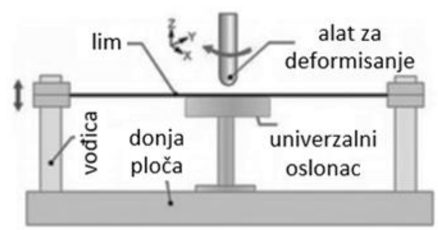


Podela procesa inkrementalnog deformisanja lima

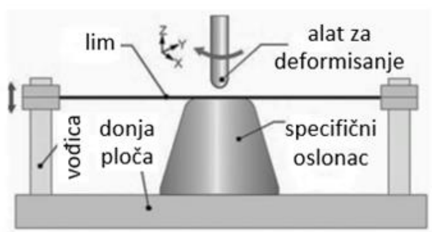
- procesi sa jednim alatom bez oslonca (engl. Single point incremental forming - SPIF);
- procesi sa dva alata (engl. Two-point incremental forming - TPIF);
- hibridni procesi.



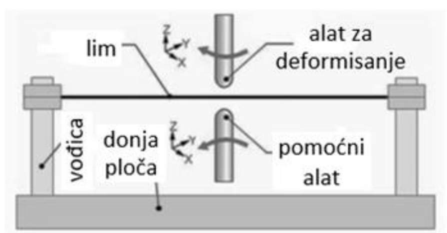
a) obrada sa jednim alatom



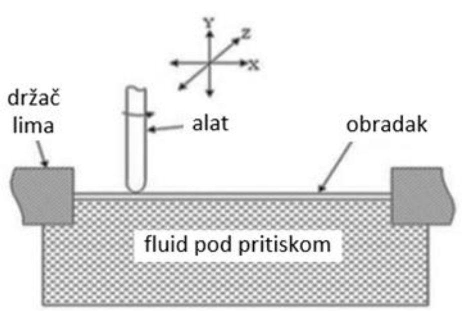
b) obrada sa alatom i univerzalnim osloncem



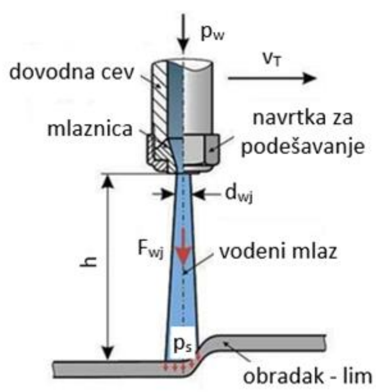
c) obrada sa alatom i specifičnim osloncem



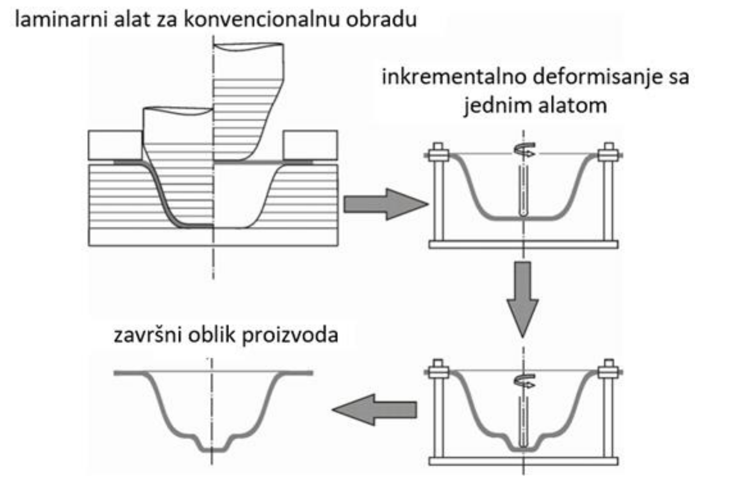
d) obrada sa dva identična alata



e) obrada hidrodeformisanjem



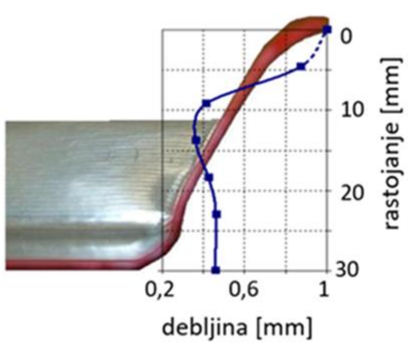
f) obrada vodenim mlazom

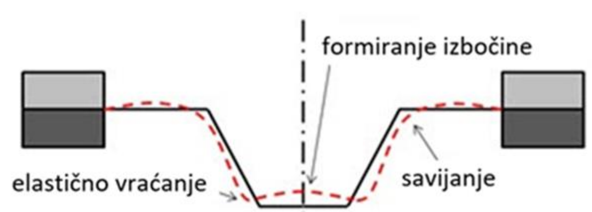


Integracija konvencionalnog i inkrementalnog deformisanja

Prednosti i nedostaci inkrementalnog deformisanja lima

	Ekonomske prednosti i nedostaci	Tehnološke prednosti i nedostaci
Prednosti (+)	• visoka fleksibilnost procesa (geometrija procesa se dobija direktno iz CAD modela, univerzalni alati, brza i jednostavna promena oblika i dimenzija dela) • modelovanje procesa pomoću CAD softvera • manja potrošnja sredstva za podmazivanje • mala investiciona ulaganja (univerzalni i jeftini alati, korišćenje postojeće opreme, npr. CNC glodalice) • smanjenje ukupnih troškova proizvodnje	• veličina obratka je ograničena samo radnim prostorom mašine na kojoj se realizuje proces obrade • veća deformabilnost materijala • mogućnost oblikovanja teško deformabilnih materijala • manja deformaciona sila • manje trenje, opterećenje i habanje alata • mogu se obrađivati (dorađivati) prethodno deformisani delovi • nivo buke je redukovan • veće deformaciono ojačavanje proizvedenih delova
Nedostaci (-)	• mala proizvodnost (posledica male lokalizovane zone deformisanja koja uslovljava duže kretanje alata, odnosno duže vreme obrade)	• relativno nizak kvalitet obrađenih površina i manja tačnost dimenzija • za oblikovanje delova sa pravim uglom (90°) mora se primeniti obrada sa više zahvata • smanjenje debljine lima





Prednosti i nedostaci inkrementalnog deformisanja lima

Advantages & disadvantages

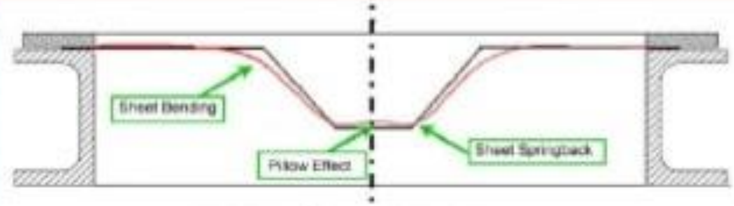


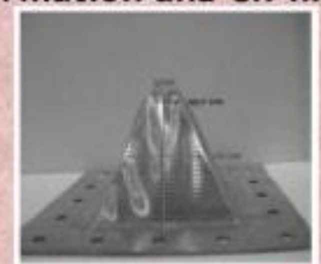
Fig. 2. Geometrical errors during the SPIF process.

Disadvantages:

1- Spring Back.

2- Sheet fracture under Tool Pressure and friction.

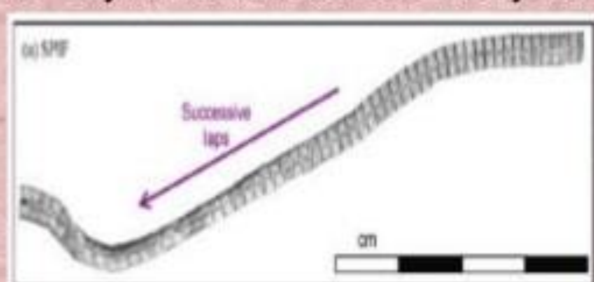
3- deformation and Un-like form

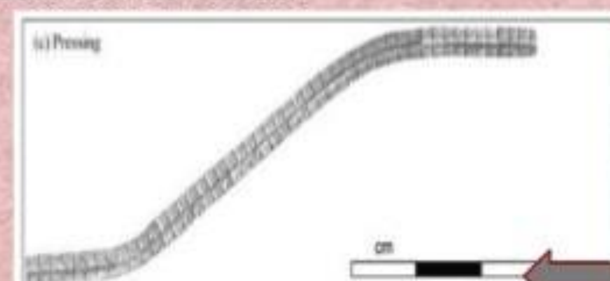


4- forming time is too large than deep drawing time.

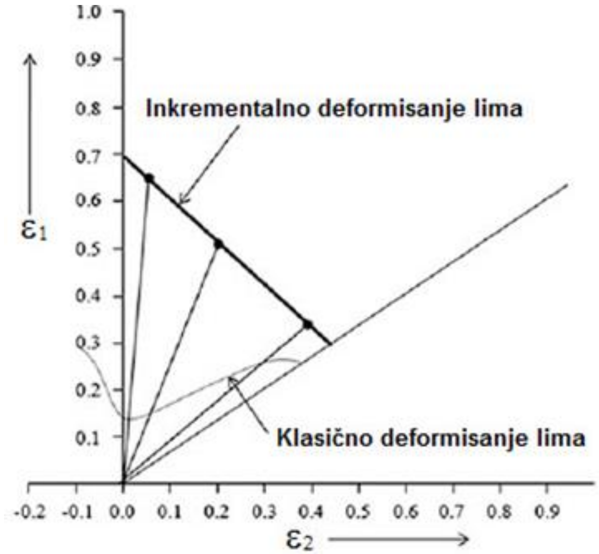
5- In negative forming ,it's difficult to form sharp corner & edge because crack easily occur.

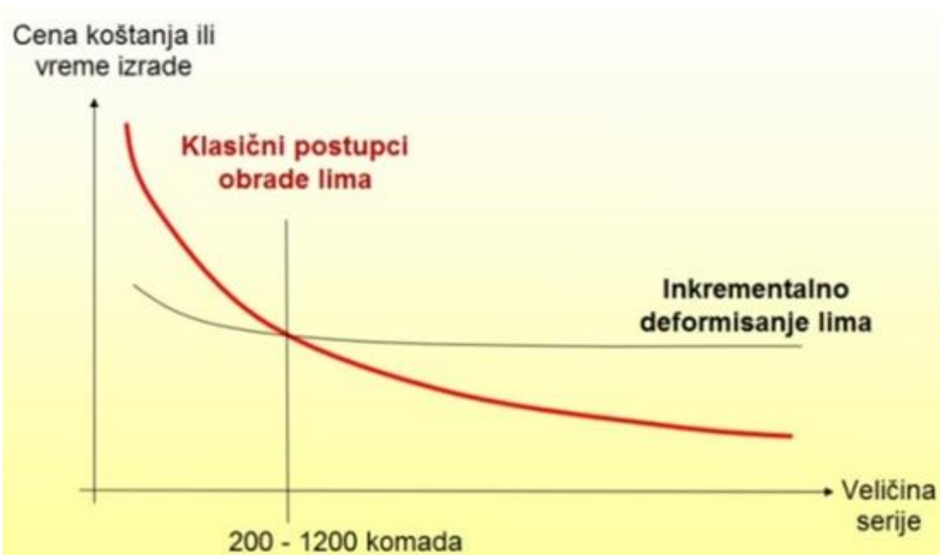
6- Deformation and Un-Like form sometimes occur.

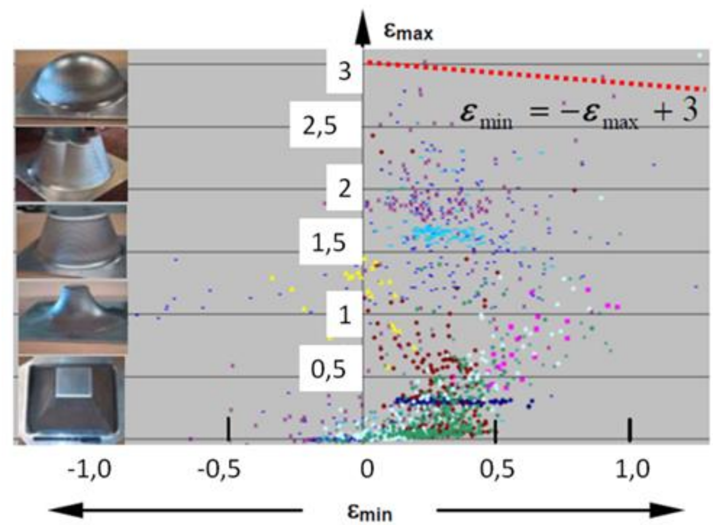




Osnovne tehnološke karakteristike inkrementalnog deformisanja lima

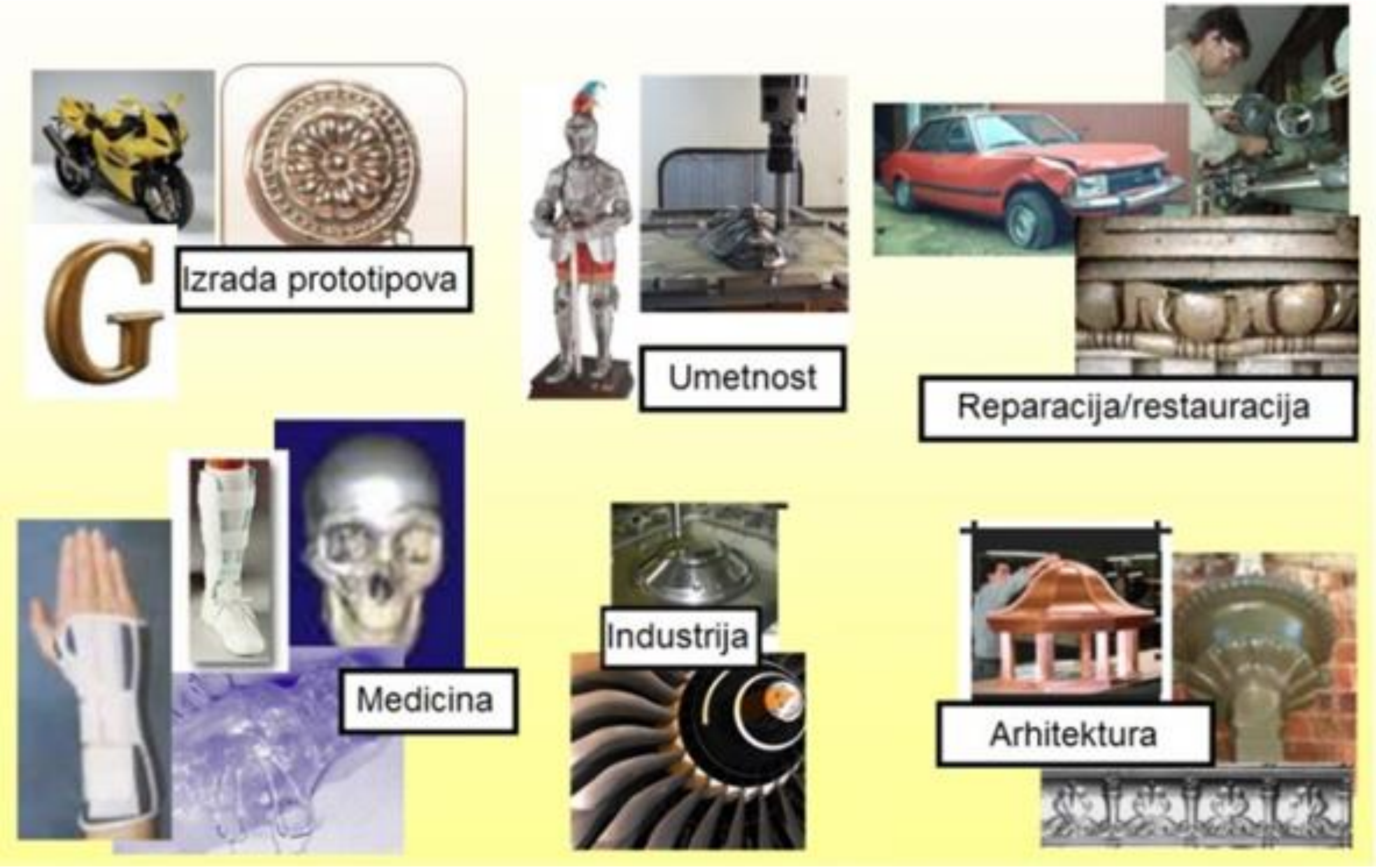




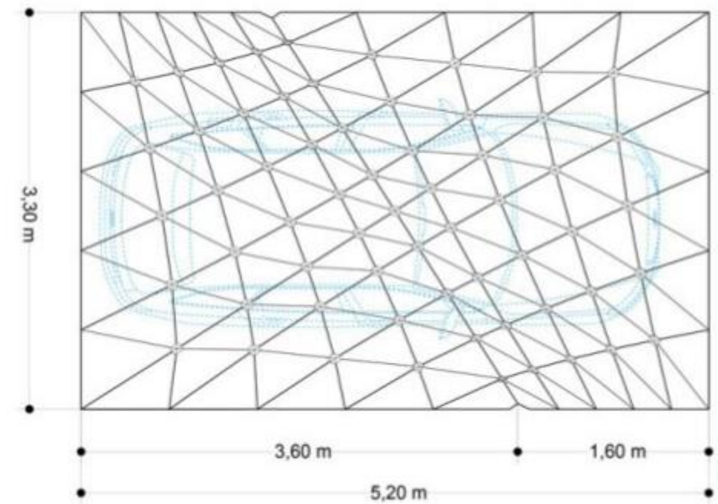


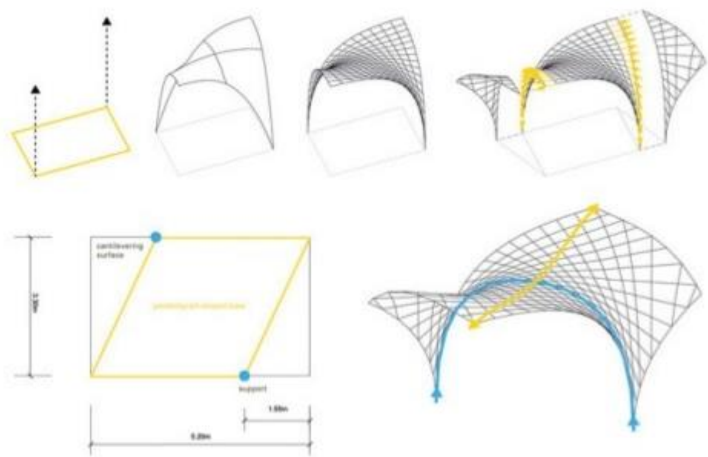
Inkrementalno deformisanje lima
- oblast primene -

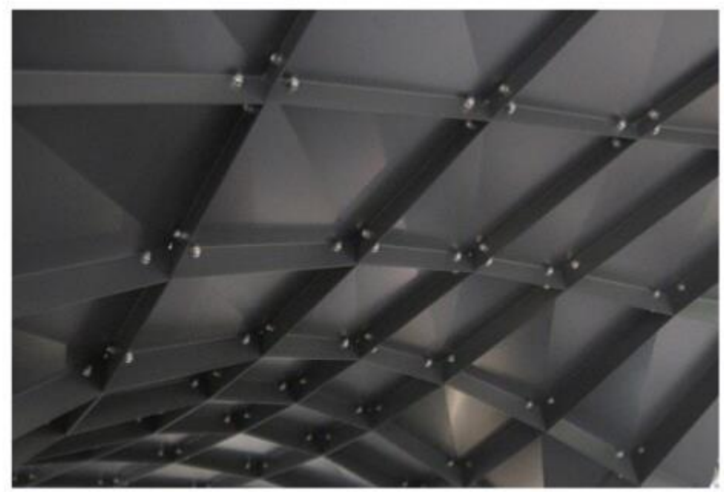
- Tehnologija inkrementalnog deformisanja lima primarno je razvijena za potrebe automobilske industrije.
- „Custom-made” proizvodi



Inkrementalno deformisanje lima
- oblast primene -







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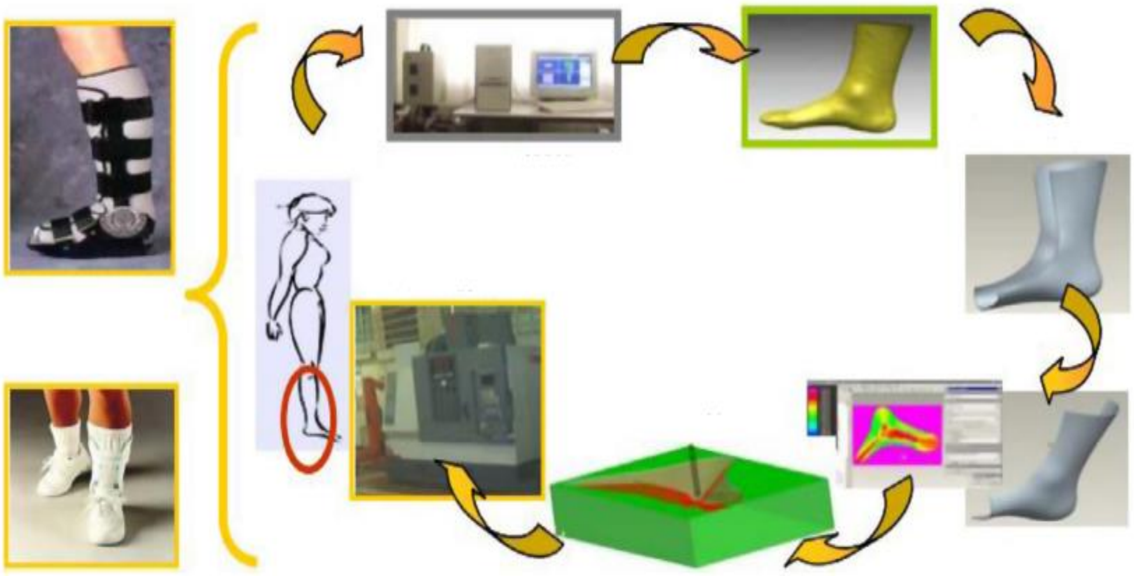
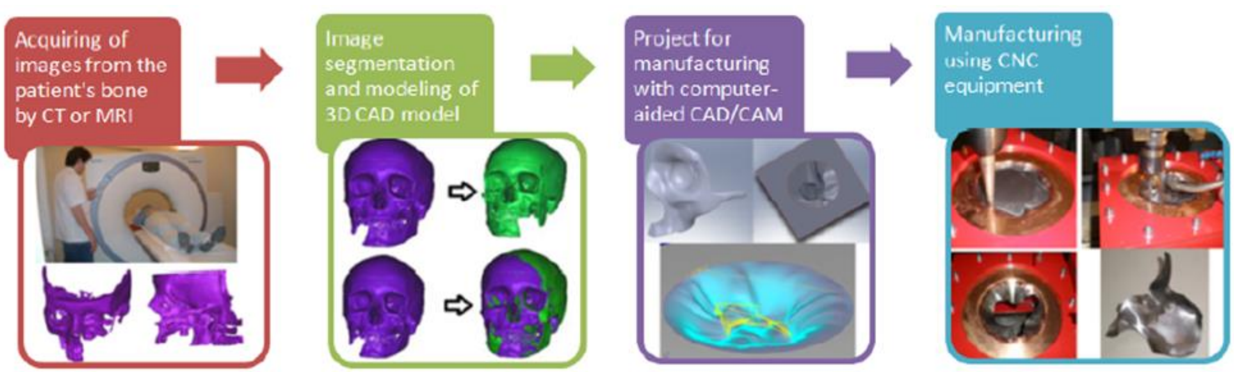
Inkrementalno deformisanje lima
- oblast primene -

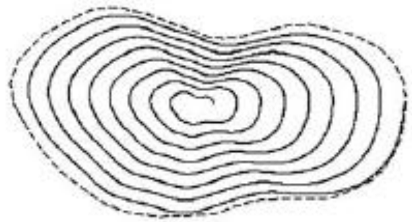


Izrada ortopedskog pomagala nožnog zgloba



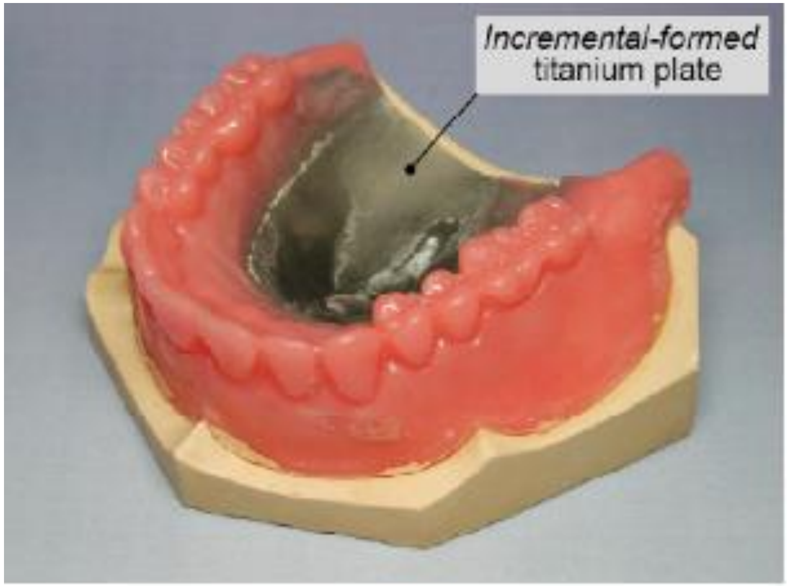
Izrada facijalnog implantanta

Inkrementalno deformisanje lima
- oblast primene -

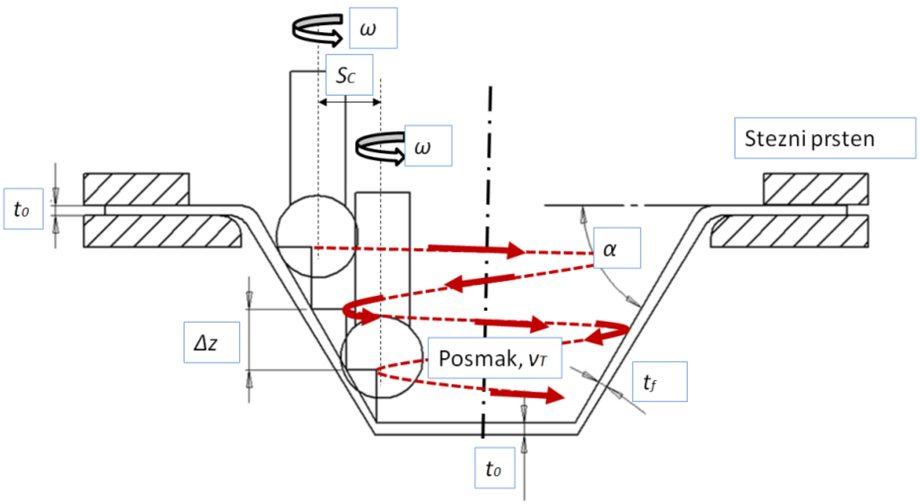


Implant lobanje i putanja alata u procesu inkrementalnog deformisanja

Implant kolena



Inkrementalno oblikovanje lima sa kontaktom u jednoj tački
Single point incremental forming - SPIF
- šema procesa-



Δz – vertikalni pomak alata -utiče na kvalitet obrađene površine i vreme izrade.

t_o - početna debljina lima

t_f - krajnja debljina lima

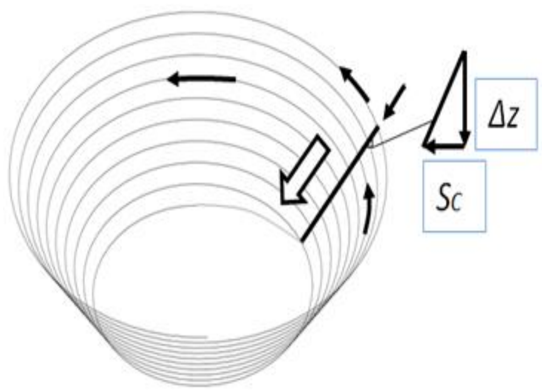
α - ugao nagiba alata

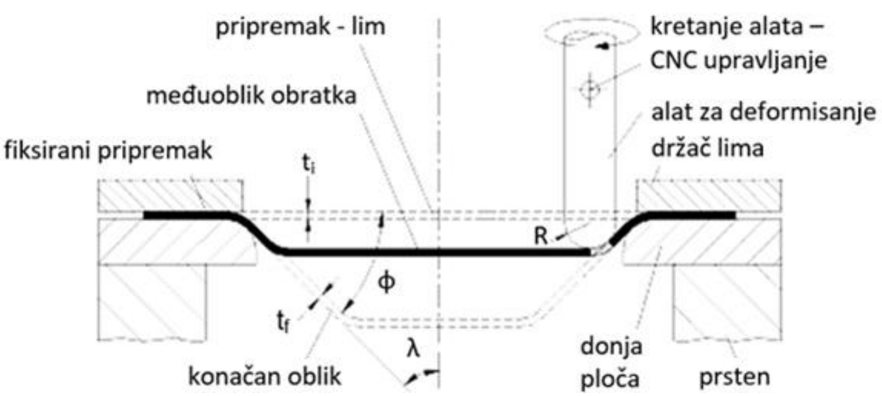
d - prečnik glave alata

S_c – razmak između horizontalnih prolaza alata

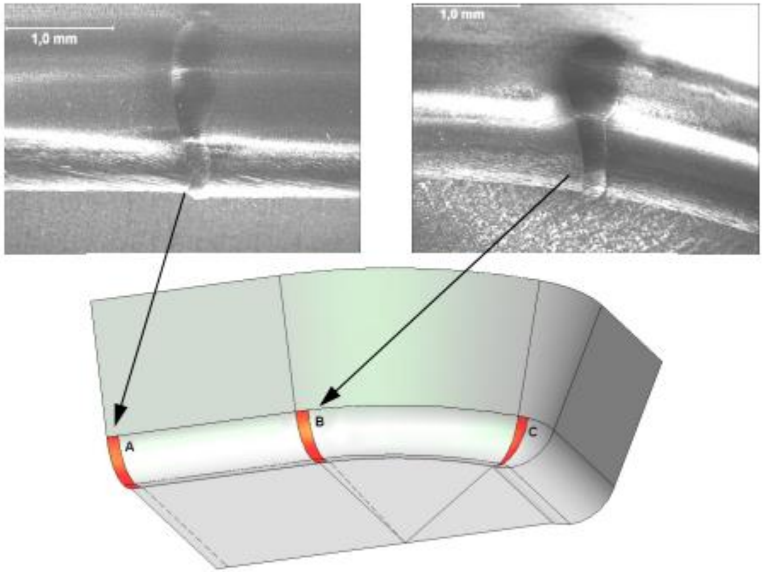
v_r – aksijalna brzina (posmak) alata

ω – ugaona brzina (broj obrtaja) alata



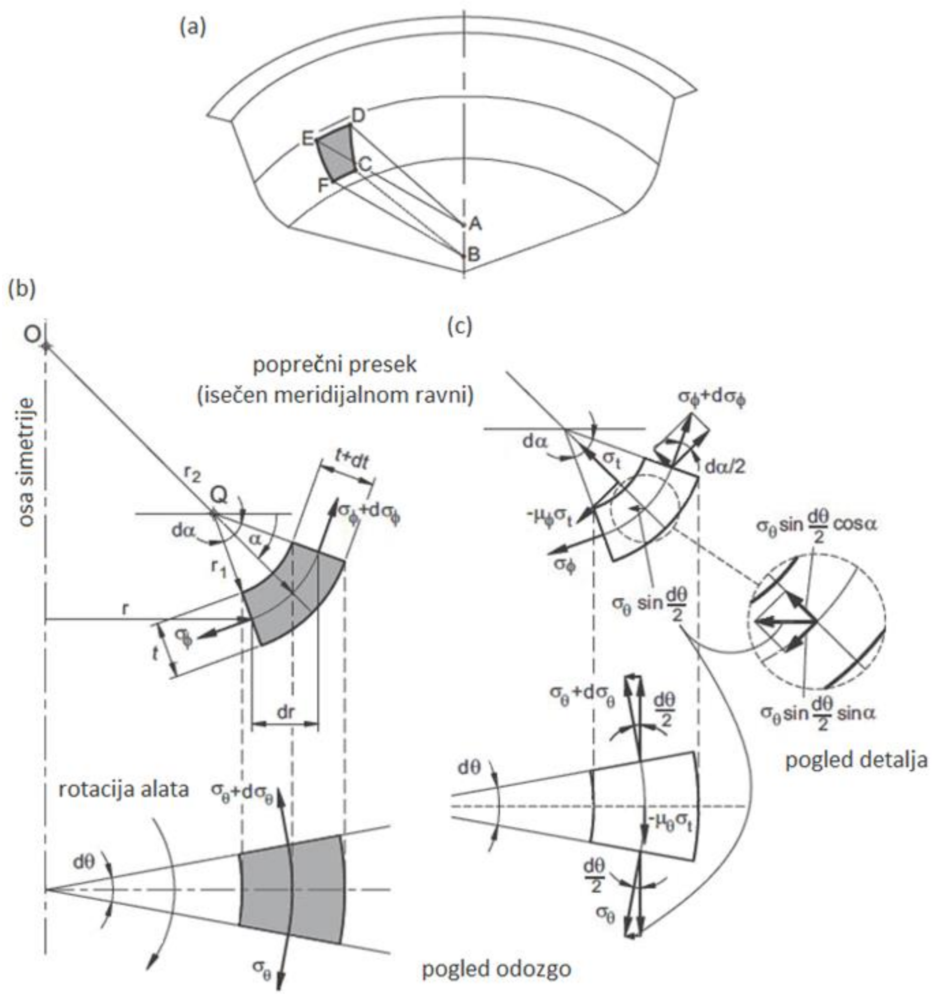


Inkrementalno oblikovanje lima sa kontaktom u jednoj tački
- naponsko-deformaciono stanje -



A. deformisanje ravnih površina u uslovima ravanskog deformacionog stanja pri dejstvu zateznog napona;
B. deformisanje rotaciono-simetričnih površina u uslovima ravanskog deformacionog stanja pri dejstvu zateznog napona;
C. deformisanje površina na uglovima obratka u uslovima jednakih dvoosnih zateznih napona.

Inkrementalno oblikovanje lima sa kontaktom u jednoj tački - naponsko-deformaciono stanje -



Jednačina ravnoteže sila u cirkularnom pravcu

$$\sigma_\theta r_1 d\alpha\left(t+\frac{dt}{2}\right)-\mu_\theta\sigma_t r_1 d\alpha\left(r+\frac{dr}{2}\right)d\theta-\left(\sigma_\theta+d\sigma_\theta\right)r_1 d\alpha\left(t+\frac{dt}{2}\right)=0$$

$$d\sigma_\theta=-\mu_\theta\sigma_t\frac{rd\theta}{t}\approx\mu_\theta\sigma_t$$

Jednačina ravnoteže sila u pravcu debljine lima

$$\sigma_t r d\theta r_1 d\alpha+\sigma_\Phi r d\theta t\sin\left(\frac{d\alpha}{2}\right)+\left(\sigma_\Phi+d\sigma_\Phi\right)\left(r+dr\right)d\theta\left(t+dt\right)\sin\left(\frac{d\alpha}{2}\right)+$$

$$+\sigma_\theta r_1 d\alpha t\sin\left(\frac{d\theta}{2}\right)\cos\alpha+\left(\sigma_\theta+d\sigma_\theta\right)r_1 d\alpha t\sin\left(\frac{d\theta}{2}\right)\cos\alpha=0$$

$$\frac{\sigma_t}{t}+\frac{\sigma_\Phi}{r_1}+\frac{\sigma_\theta}{r_2}=0$$

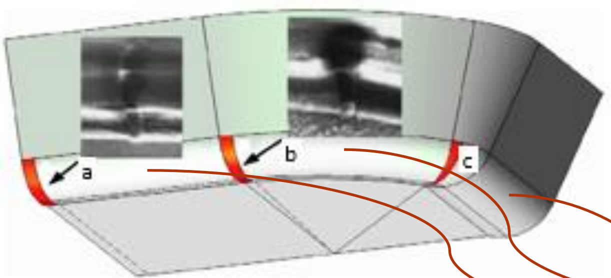
Jednačina ravnoteže sila u meridijalnom pravcu

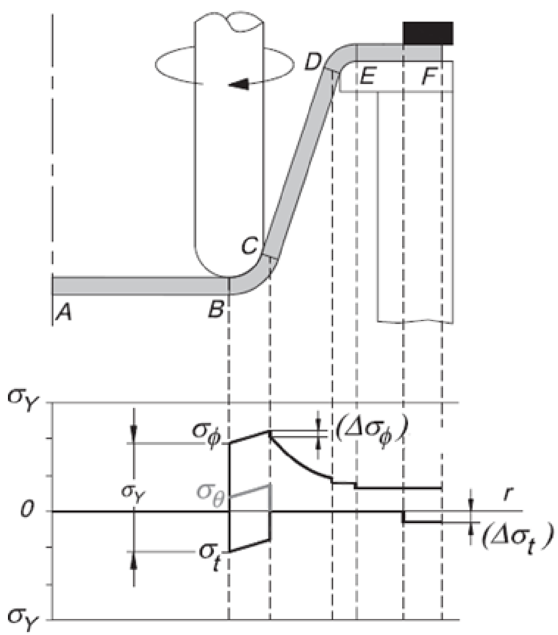
$$(\sigma_\Phi+d\sigma_\Phi)(r+dr)d\theta(t+dt)-\sigma_\Phi r t d\theta+\mu_\Phi\sigma_t r d\theta r_1 d\alpha-$$

$$-\sigma_\theta\frac{d\theta}{2}r_1 d\alpha t\sin\alpha-(\sigma_\theta+d\sigma_\theta)\frac{d\theta}{2}r_1 d\alpha t\sin\alpha=0$$

$$\frac{d\sigma_\Phi}{dr}+\frac{\sigma_\Phi-\sigma_\theta}{r}+\frac{\mu_\Phi\sigma_t}{t\sin\alpha}+\frac{\sigma_\Phi}{t}\frac{dt}{dr}=0$$

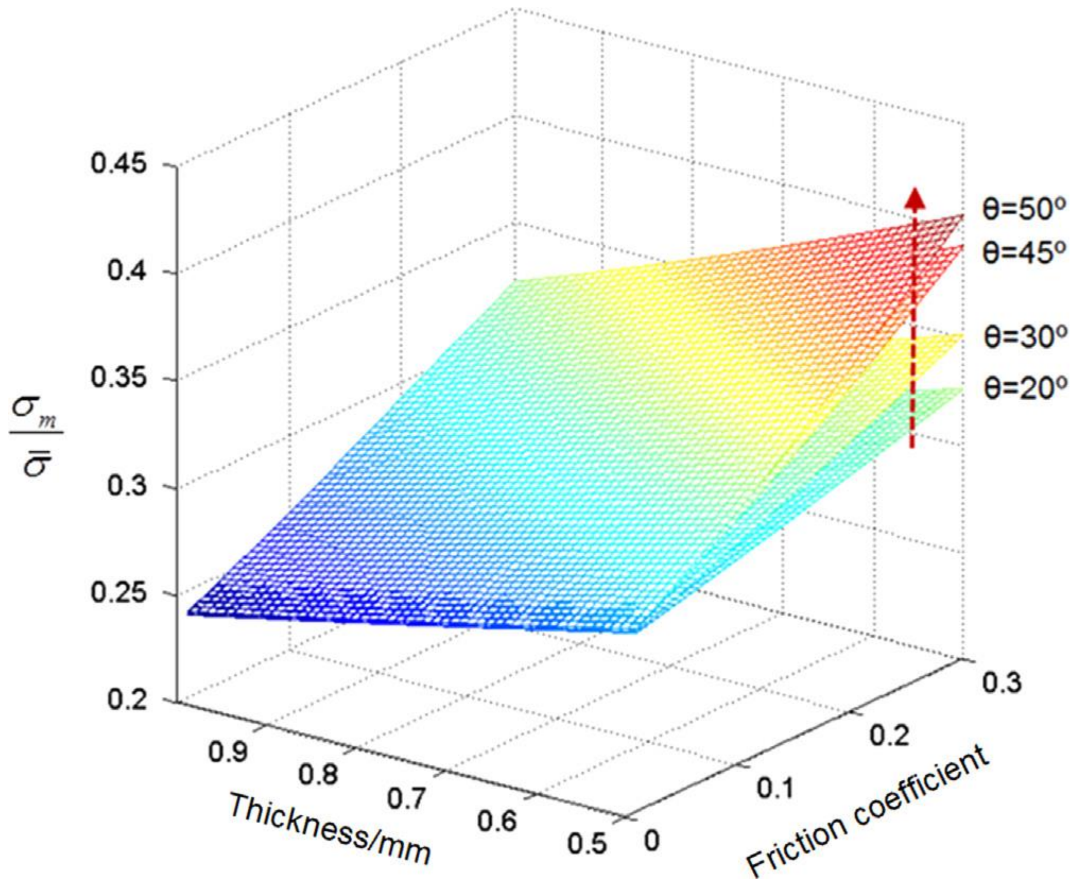
Inkrementalno oblikovanje lima sa kontaktom u jednoj tački - naponsko-deformaciono stanje -





Proces	Pretpostavka	Naponsko stanje	Deformaciono stanje
SPIF – ravne i rotaciono-simetrične površine (modeli a i b)	Ravansko deformaciono stanje	$\sigma_{\Phi}=\sigma_1=\dfrac{\sigma_Y}{1+t/r_a}>0$ $\sigma_{\theta}=\sigma_2=0,5(\sigma_1+\sigma_3)$ $\sigma_t=\sigma_3=\dfrac{-\sigma_Y t}{r_a+t}<0$	$d\varepsilon_{\Phi}=-d\varepsilon_t>0$ $d\varepsilon_{\theta}=0$ $d\varepsilon_t<0$
SPIF- deformisanje površina na uglovima (model c)	Dvoosno zatezanje u uslovima jednakih napona	$\sigma_{\Phi}=\sigma_{\theta}=\sigma_1=$ $=\dfrac{\sigma_Y}{1+2t/r_a}>0$ $\sigma_t=\sigma_3=\dfrac{-2\sigma_Y t}{r_a+2t}<0$	$d\varepsilon_{\Phi}=d\varepsilon_{\theta}>0$ $d\varepsilon_t<0$
Konvencionalna obrada lima (rotaciono-simetrične površine obratka)	Dvoosno zatezanje u uslovima jednakih napona	$\sigma_{\Phi}=\sigma_{\theta}=\sigma_1=$ $=\dfrac{\sigma_Y}{1+t/r_a}>0$ $\sigma_t=\sigma_3=\dfrac{-\sigma_Y t}{r_a+t}<0$	$d\varepsilon_{\Phi}=d\varepsilon_{\theta}>0$ $d\varepsilon_t<0$

Inkrementalno oblikovanje lima sa kontaktom u jednoj tački - naponsko-deformaciono stanje -



σ_m – srednji normalni napon

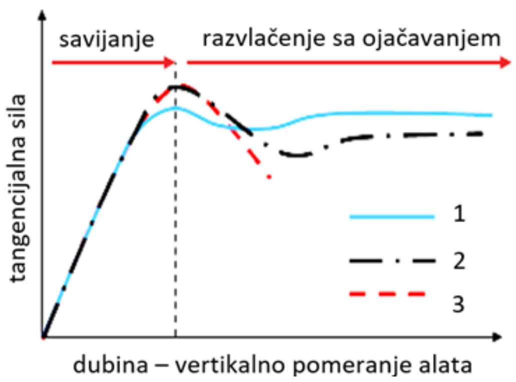
$\bar{\sigma}$ - napon tečenja

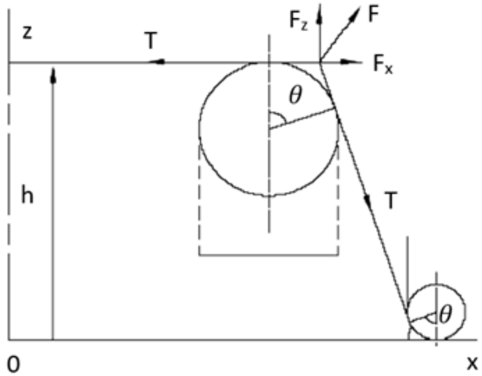
Inkrementalno oblikovanje lima sa kontaktom u jednoj tački - deformaciona sila -

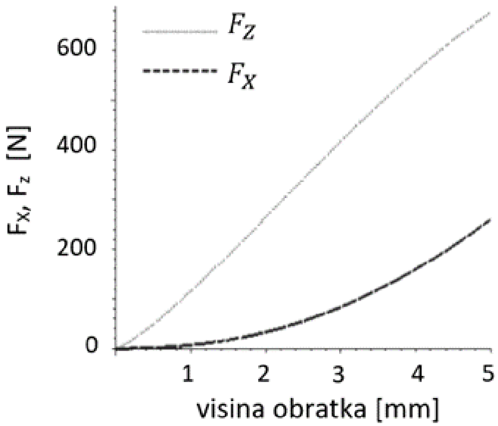
Na vrednost deformacione sile u SPIF procesu utiču:

- vrste materijala,
- početna debljina lima,
- ugao kontakta alata sa obratkom,
- veličina vertikalnog koraka,
- prečnik alata.

$$F_z = 0.0716\, R_m\, t^{1.57} d_t^{0.41} \Delta h^{0.09} \alpha \cos\alpha$$







Sila zatezanja lima *(T)*

$$T = 2r_a \cdot t \cdot K \cdot \varepsilon^n$$

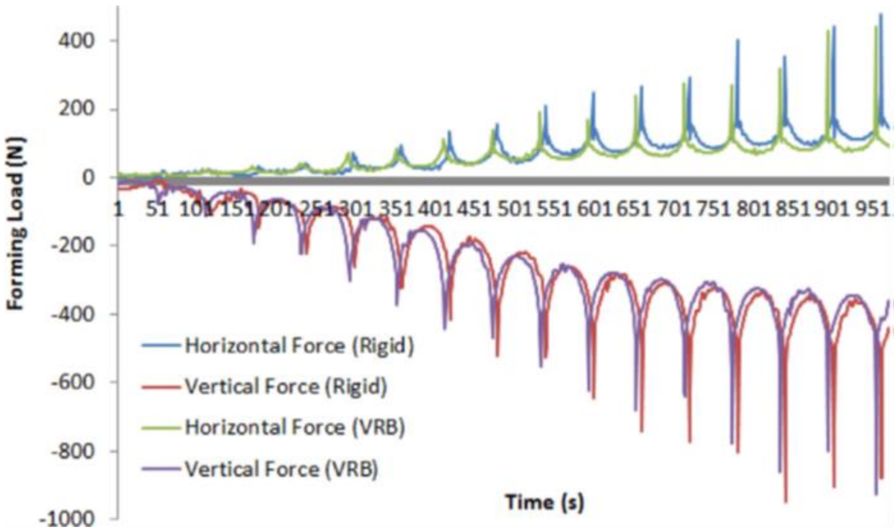
r_a – poluprečnik alata za deformisanje;
t – trenutna debljina lima;
K – koeficijent koji zavisi od vrste materijala;
n – koeficijent deformacionog ojačavanja.

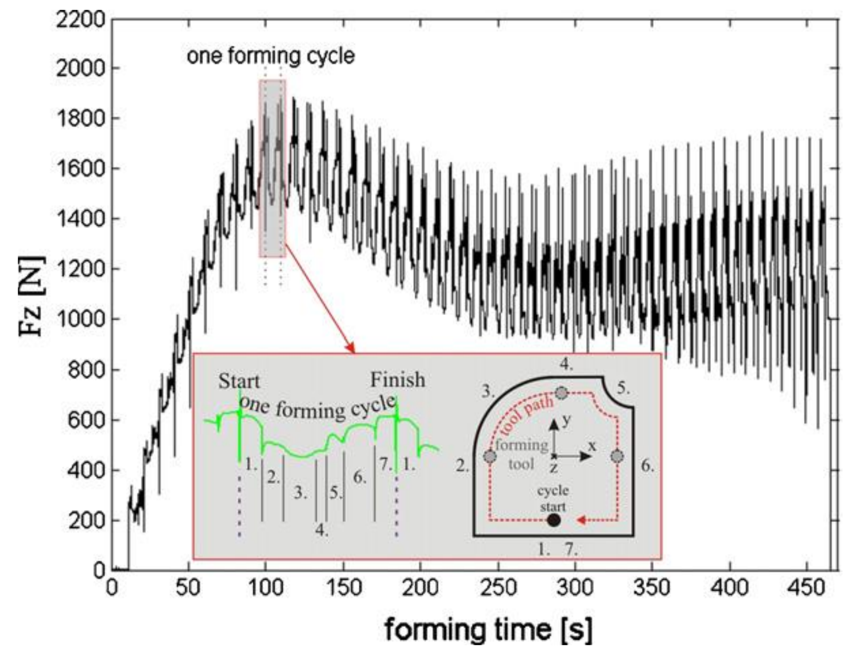
$$F_X = T(1-\cos\theta)$$

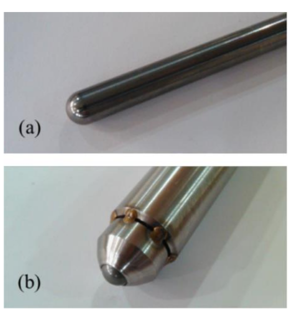
$$F_Z = T\sin\theta$$

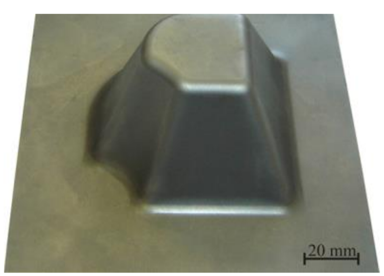
Inkrementalno oblikovanje lima sa kontaktom u jednoj tački - deformaciona sila -

Sila u toku inkrementalnog deformisanja lima ima složen trend promene, što je posledica promene početne debljine materijala (tendencija smanjenja sile) i efekta deformacionog ojačavanja materijala obratka (tendencija povećanja sile).

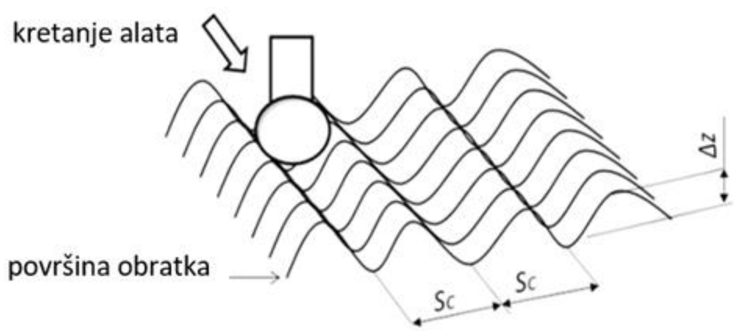


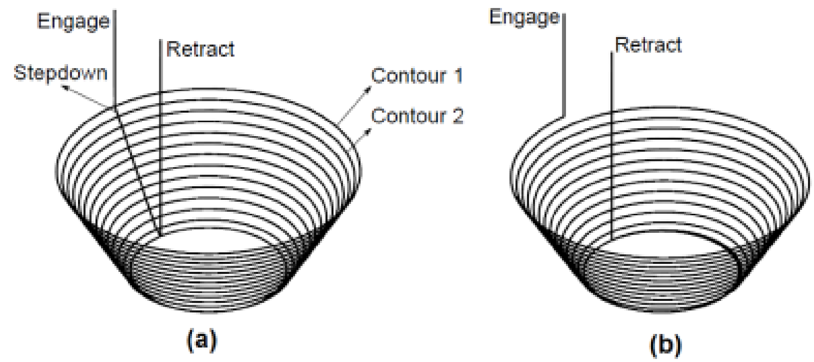






Inkrementalno oblikovanje lima sa kontaktom u jednoj tački - parametri -





(a) z-level contouring toolpath (b) helical toolpath

Parametar	*Oznaka*	*Interval vrednosti*
Materijal obratka		*čelik ili aluminijum*
Poluprečnik alata za deformisanje	r_a	*5 - 15 mm*
Početna debljina lima	t_0	*0,5 – 3 mm*
Vertikalno pomeranja alata	ΔZ	*0,02 – 2 mm*
Maksimalni ugao nagiba alata	$\Psi\ (\alpha)$	*60° - 80° (opt 30°- 60°)*
Tolerancije		*± 0,5 – 2 mm*
Efektivna deformacija	$\bar{\varepsilon}$	*max 2,5*
Vertikalna komponenta deformacione sile	F_Y	*300 – 1000 N*
Horizontalna komponenta deformacione sile	F_X	*100 – 500 N*
Relacije		r_a/t_0 *= 5 - 20*
		visina obratka » r_a
		radijus obratka » r_a

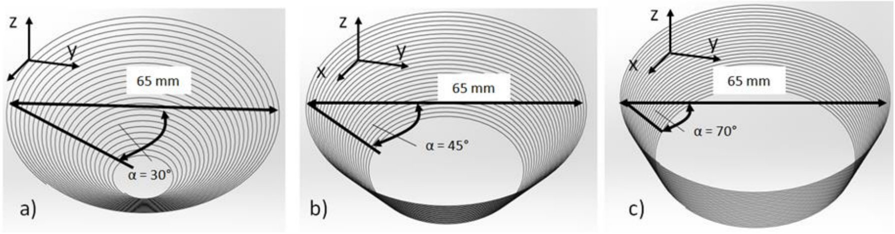
Deformabilnost pri inkrementalnom deformisanju lima

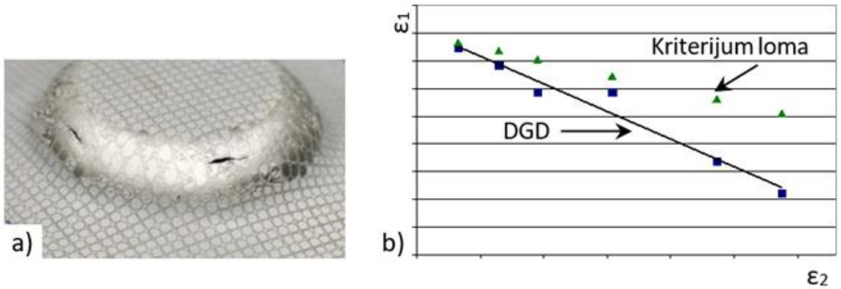
Deformabilnost lima pri inkrementalnom deformisanju je 2 do 3 puta veća u odnosu na klasične postupake (duboko izvlačenje, razvlačenje)

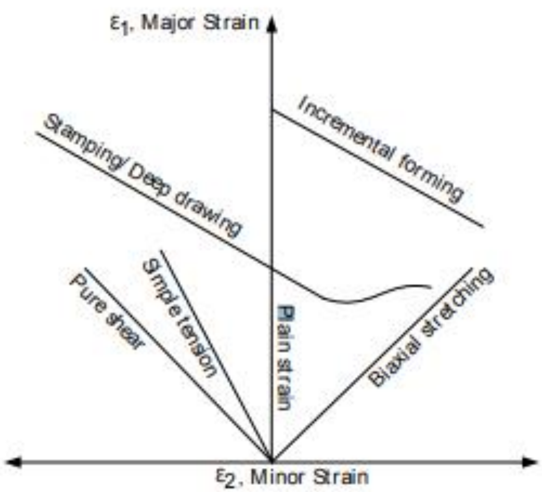
- ciklično defomisanje, lokalna deformacija, homogena deformacija

Metode ispitivanja:

1. Konvencionalna analiza
2. Specijalni postupci - jednostavni testovi, zasnovani na reprezentativnim oblicima obradaka sa različitim uglovima nagiba alata (npr. konusi, ili piramide) – povećava se ugao (polazni je obično 10°) dok se ne pojavi pukotina.





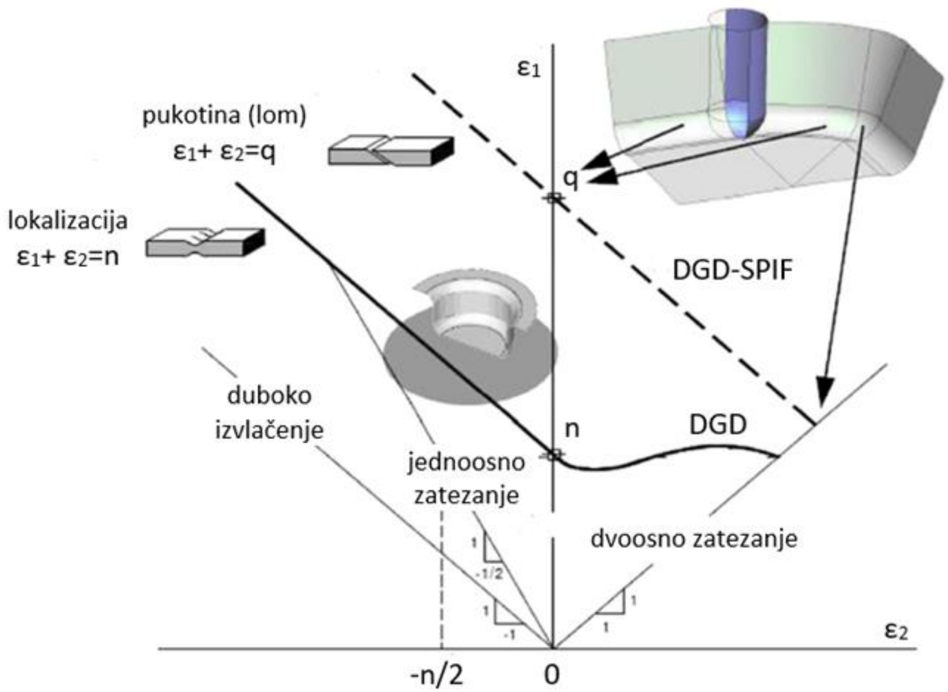


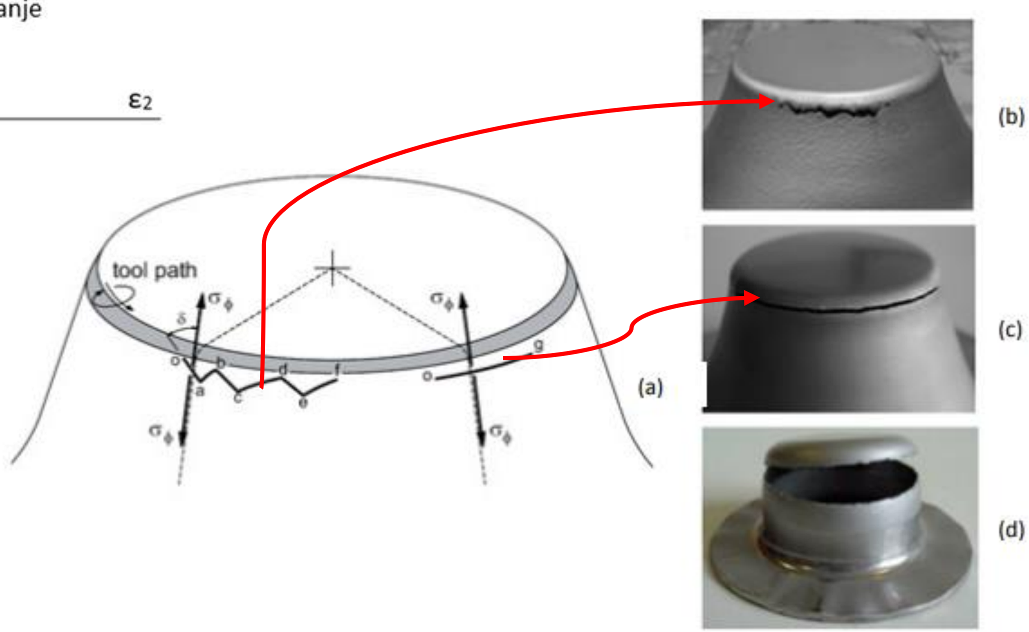
Maksimalni ugao nagiba alata predstavlja jednu od osnovnih pokazatelja sposobnosti oblikovanja (deformabiolnosti) lima inkrementalnim deformisanjem

Deformabilnost pri inkrementalnom deformisanju lima

Material	Formed specimen geometry	Tool diameter (mm)	Thickness (mm)	Max. achievable wall angle
65Cr2	Truncated cone	10	0.5	57°
AA 1050-O	Truncated cone	10	1.5	76°
AA 2024-T3	Truncated cone	10	1.0	42°
AA 3003-O	Truncated cone	10	0.85	70°
AA 3003-O	Truncated cone	10	1.2	71°
AA 3003-O	Truncated cone	10	2	76°
AA 3103	Truncated cone	10	1.5	75°
AA 5086-H111	Truncated cone	10	0.8	62°
AA 5182	Truncated cone	10	1.25	64°
AA 5182	Truncated cone	25.4	0.93	63°
AA 5754 (AlMg3)	Truncated cone	10	1	64°
AA 5754 (AlMg3)	Truncated cone	10	1.5	71°
AA 6111-T4P	Truncated cone	25.4	0.93	53°
AA 6114-T4	Truncated cone	12	1.0	60°
AISI 304	Truncated cone	10	0.4	63°
Brass	Truncated cone	12	1	40°
Copper	Truncated cone	12	1	65°
DC01	Truncated cone	10	1	67°
DC04	Truncated cone	10	1	64°
DDQ	Truncated cone	12	1	70°
DP600	Varying wall angle conical frustum	16	1	68°
DP780	Varying wall angle conical frustum	16	1	45°
DP1000	Varying wall angle conical frustum	16	1	39°
HSS	Truncated cone	12	1	65°
Ti grade 2	Truncated cone	10	0.5	47°
TiAl6V4	Truncated cone	10	0.6	32°
Polyamide	Varying wall angle conical frustum	10, 15	2, 3	75.4°*
Polyvinyl chloride	Varying wall angle conical frustum	10, 15	2, 3	75.4°*
Polyethylene	Varying wall angle conical frustum	10, 15	2, 3	81°**

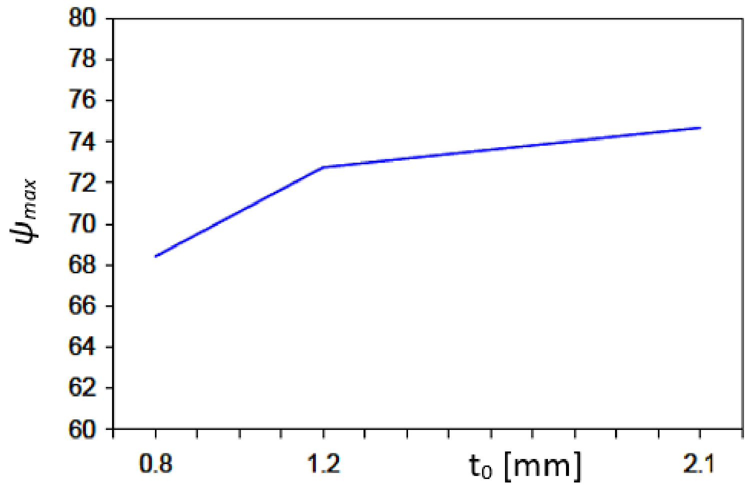
Deformabilnost pri inkrementalnom deformisanju lima



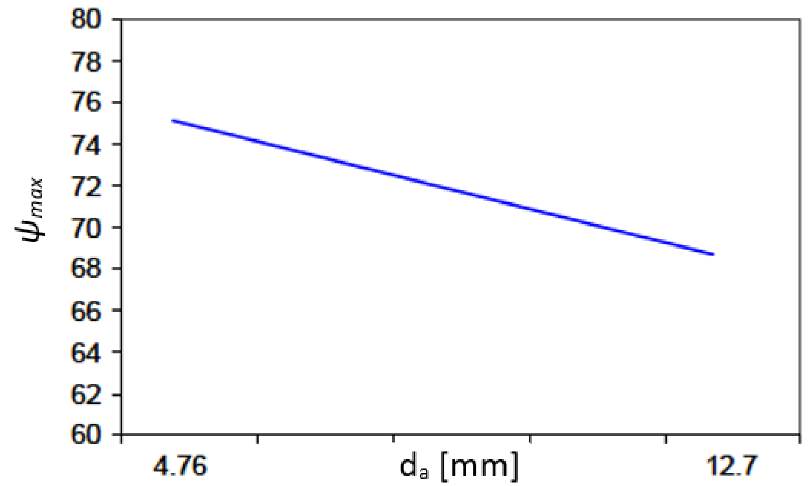


Deformabilnost pri inkrementalnom deformisanju lima

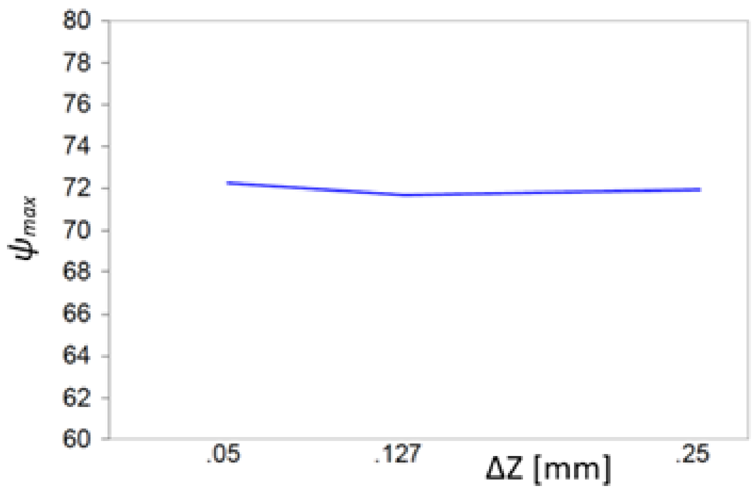
Uticaj debljine lima na max. ugao nagiba alata



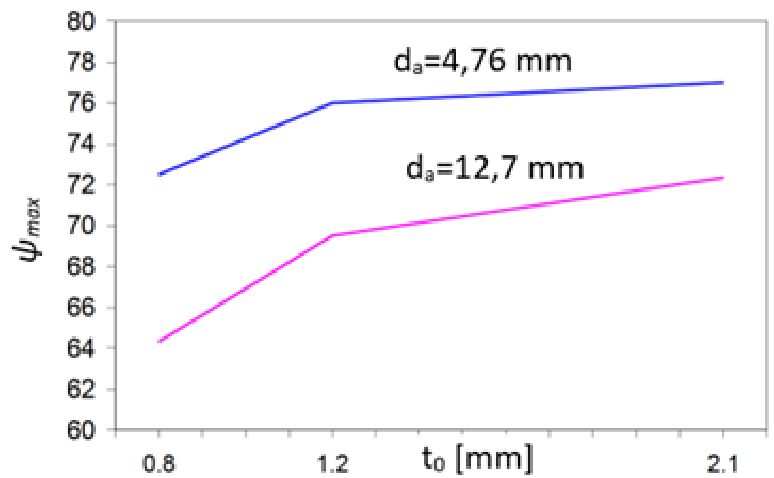
Uticaj prečnika alata na max. ugao nagiba alata



Uticaj vertikalnog pomaka na max. ugao nagiba alata

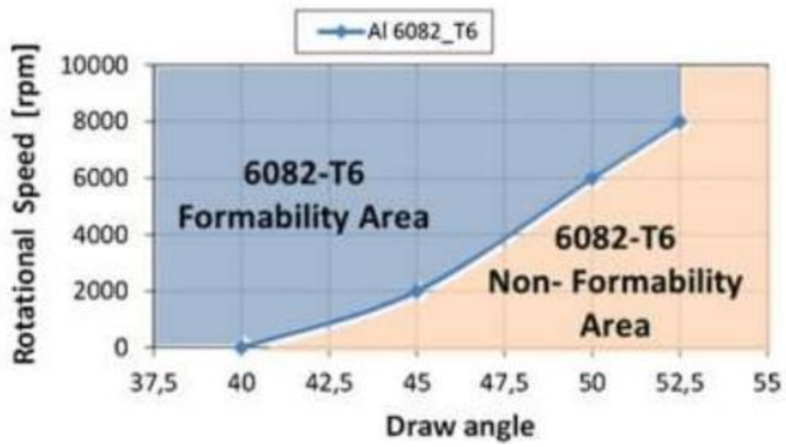


Uticaj debljine lima i prečnika alata na max. ugao nagiba alata

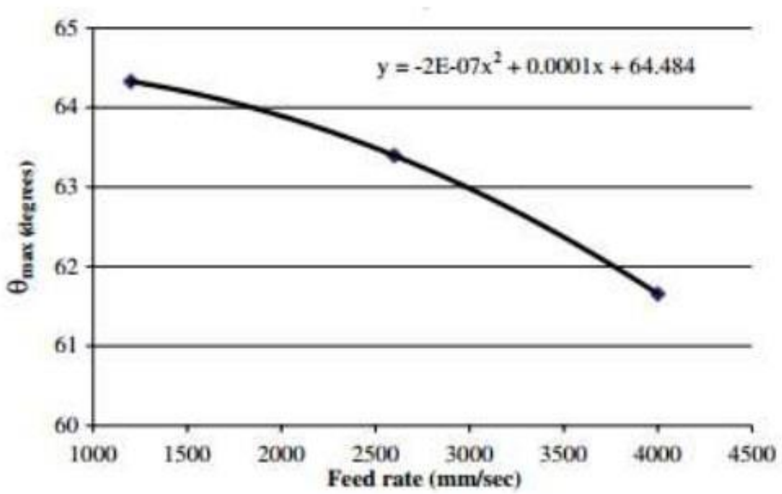


Deformabilnost pri inkrementalnom deformisanju lima

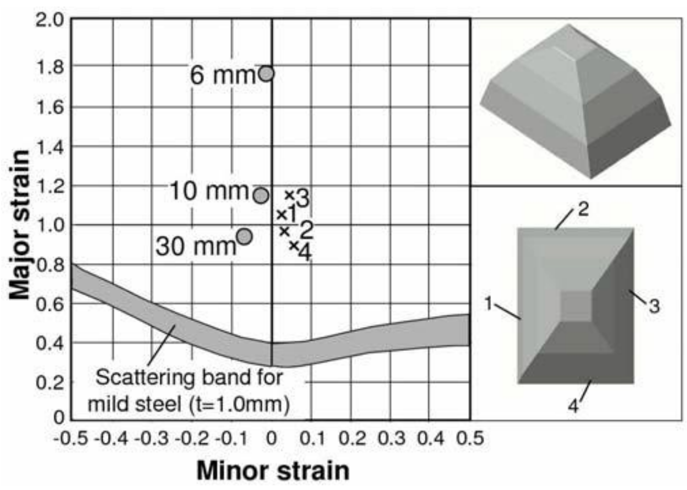
Uticaj ugaone brzine (broja obrtaja) alata



Uticaj aksijalne brzine (posmaka)



Uticaj prečnika alata

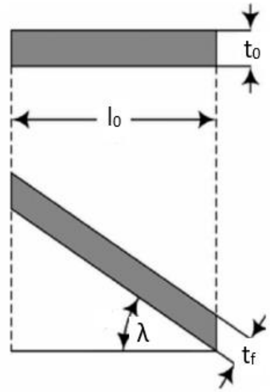


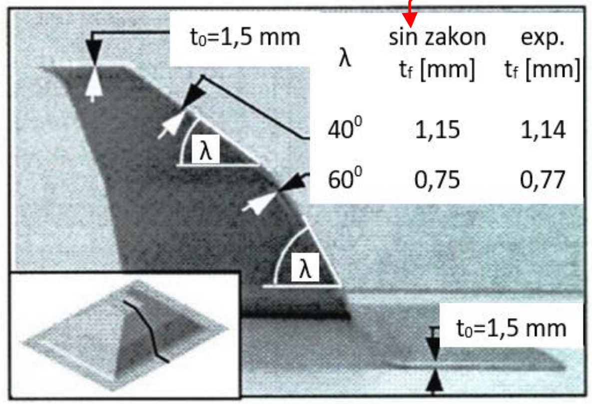
Maksimalni ugao nagiba alata

$$\Psi = \left| \frac{\pi}{2} - e^{\varepsilon_t} \right.$$

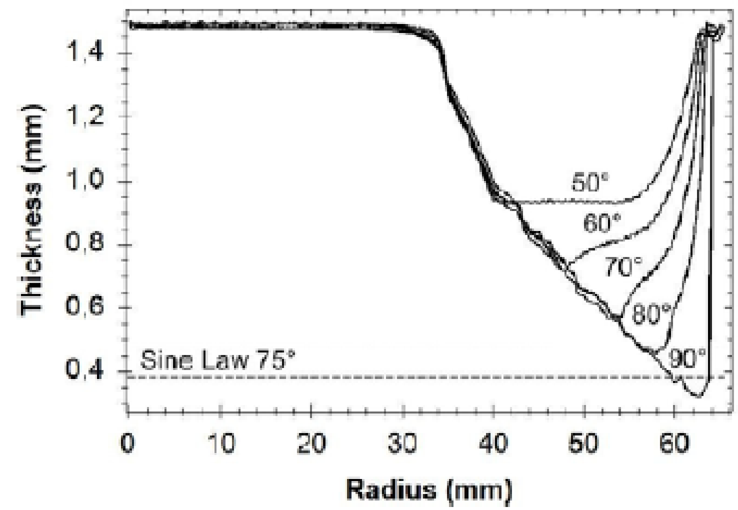
ε_t – *max. efektivna deformacija*

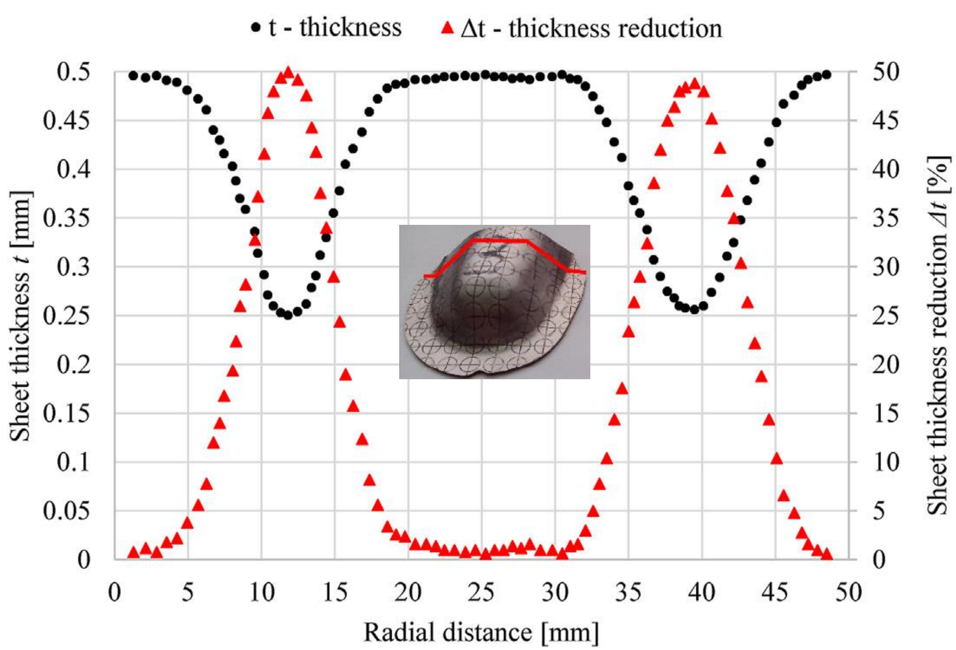
Redukcija debline lima

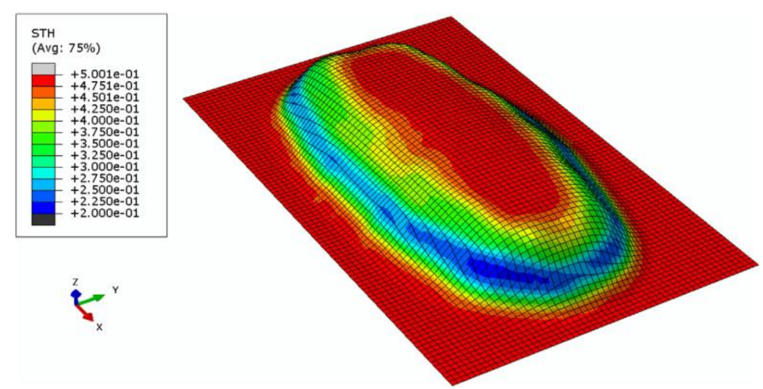




$$t_f = t_o \sin \lambda$$



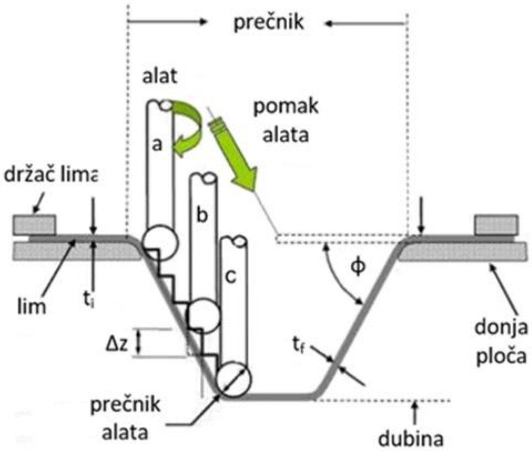




Kvalitet i tačnost delova dobijenih inkrementalnim deformisanjem

Uticajni faktori:

- mehaničke karakteristika materijala,
- debljina lima,
- dimenzije obratka,
- trajektorija alata,
- prečnik glave alata,
- brzina horizontalnog i vertikalnog pomaka alata,
- brzina rotacije alata,
- ugao obrade,
- trenje,
- tačnost pozicioniranja pripremka u stezni pribor i ravnomernost sile stezanja pripremka i otpuštanja obratka iz steznih čeljusti,
- veličina sile držača lima.



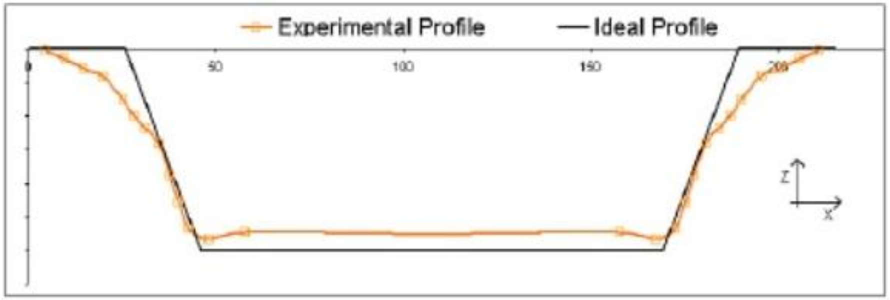
1- Increase in sheet thickness ⇒ Increase in strain ⇒ Increase in formability.

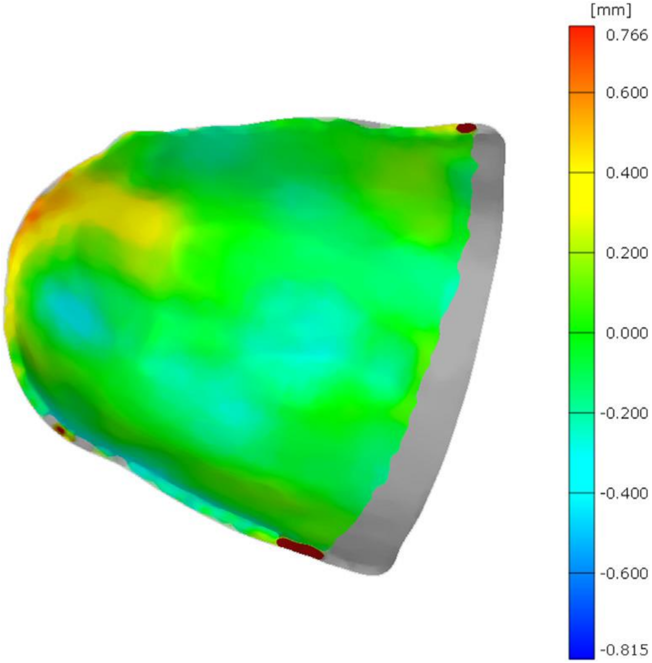
2- Increase in Tool diameter ⇒ decrease in stress ⇒ decrease in formability.

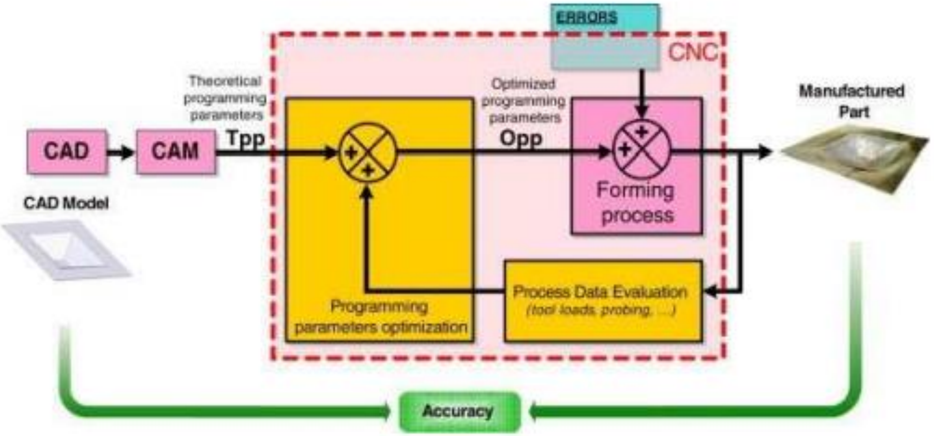
3- Increase in Tool Federate ⇒ Increase in stress ⇒ decrease in formability.

4- Increase in Tool speed ⇒ Increase in heat ⇒ Increase in formability.

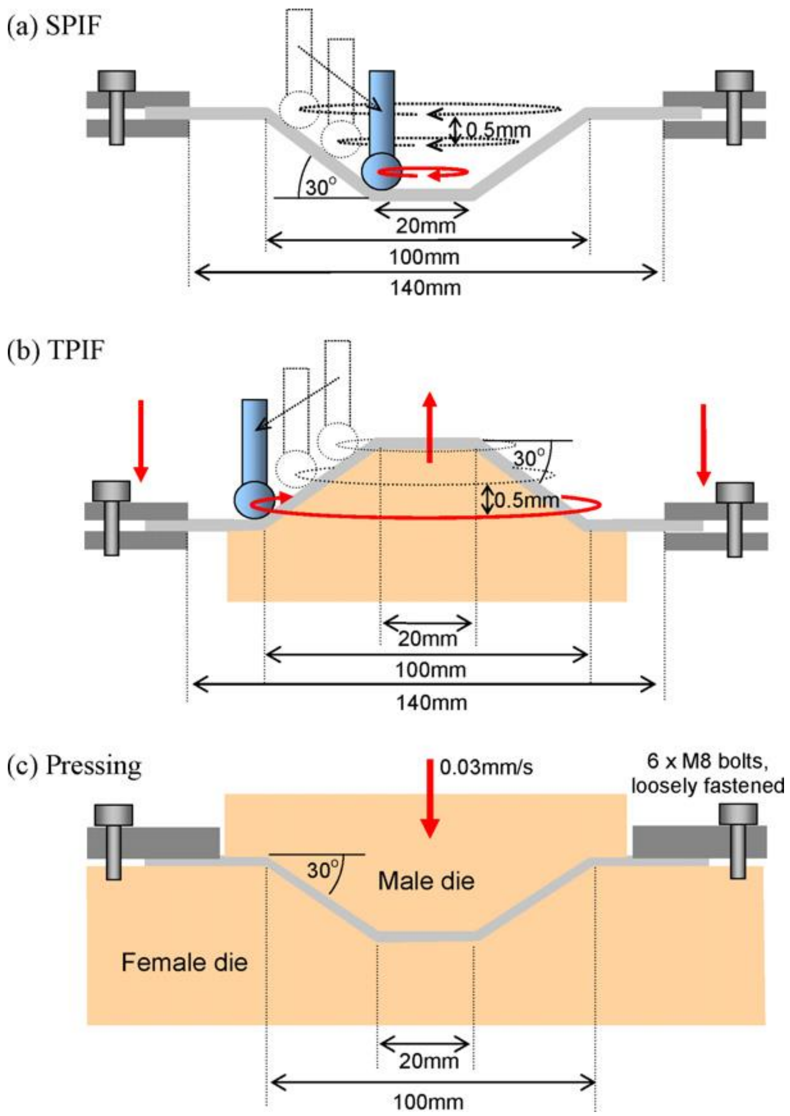
Kvalitet i tačnost delova dobijenih inkrementalnim deformisanjem

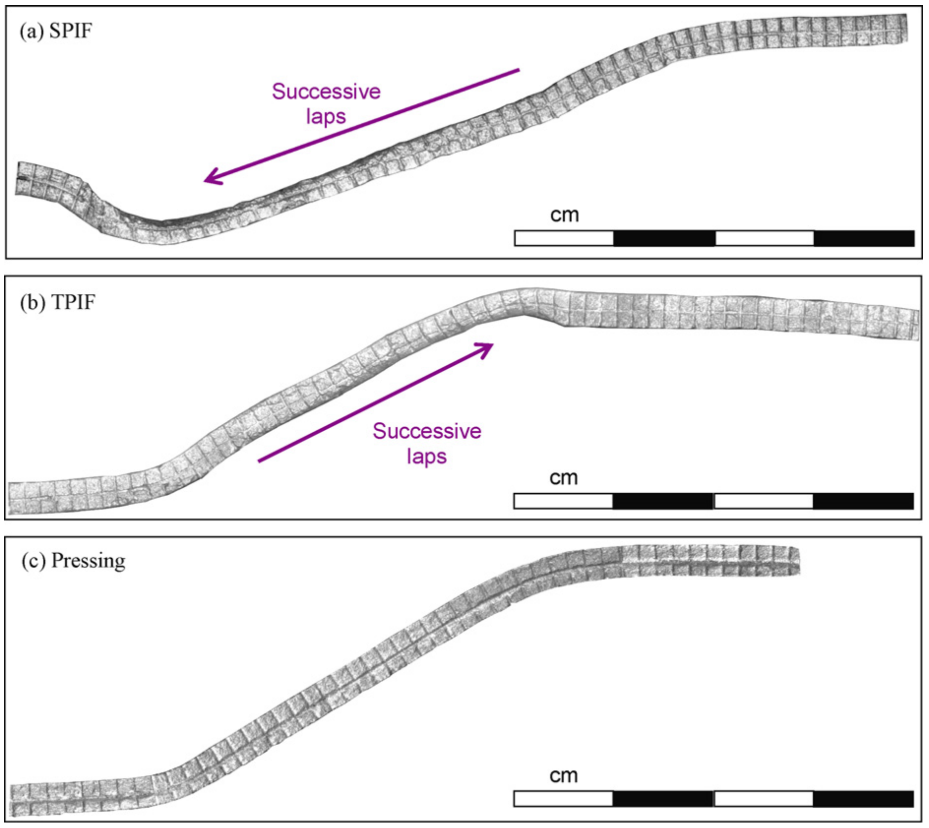




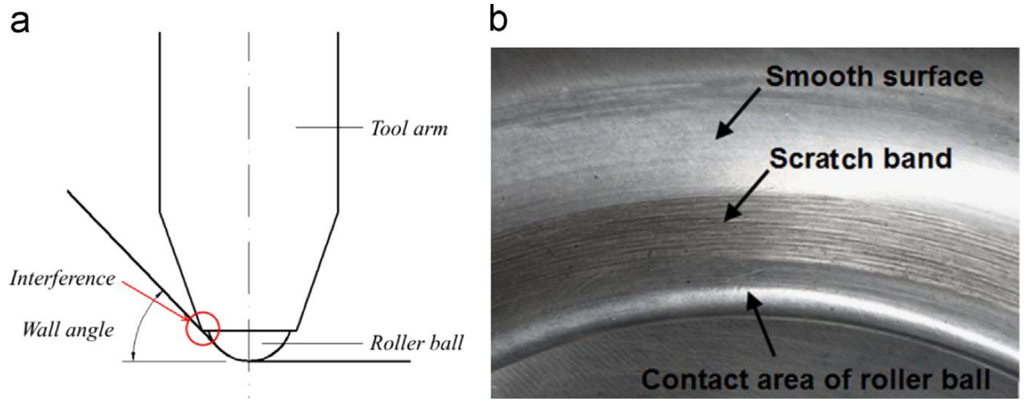


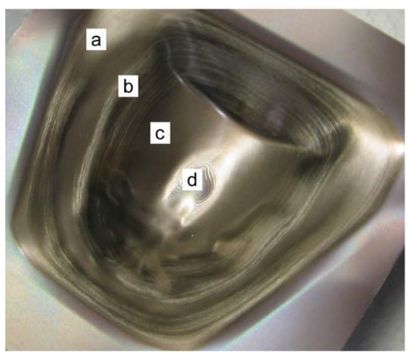
Kvalitet i tačnost delova dobijenih inkrementalnim deformisanjem



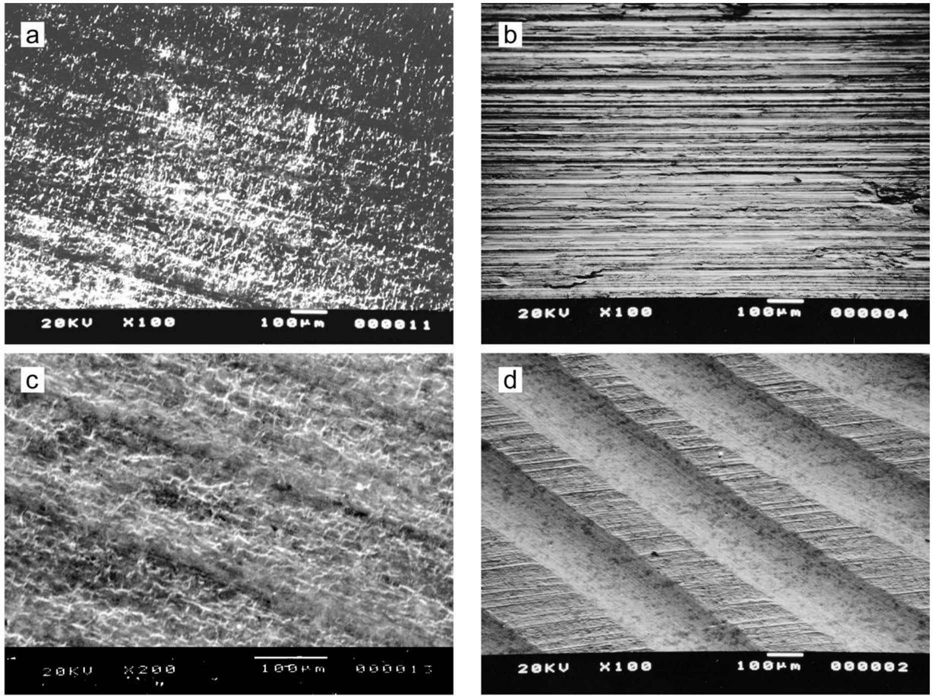


Kvalitet i tačnost delova dobijenih inkrementalnim deformisanjem





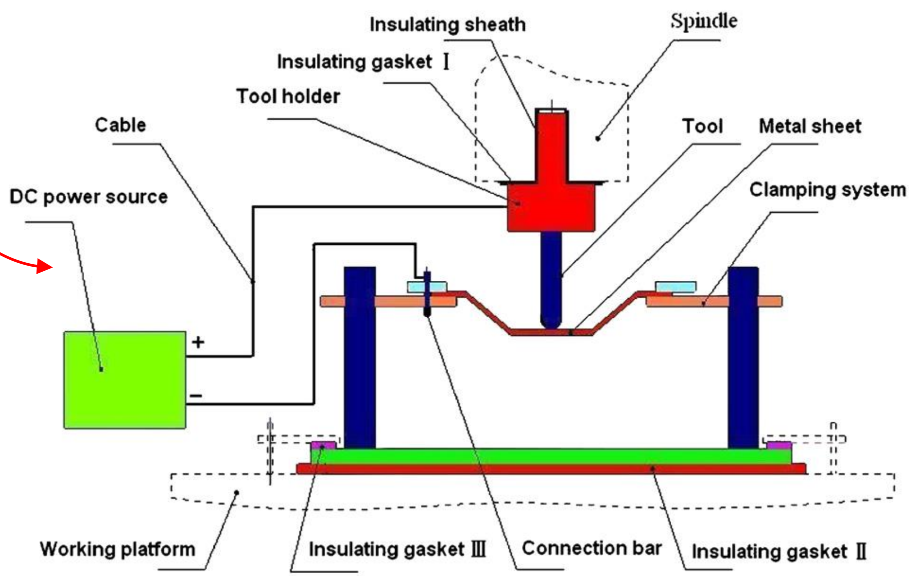
Anodic oxidation :	
solvent : phosphoric acid (1.0M)	
anodic forming voltage : 100V	
Lubricant :	vegitable oil
Tip radious :	r_p = 1.0 mm
Vertical feed :	p_z = 0.05 mm/rev.
Thickness :	t_0 = 0.2 mm

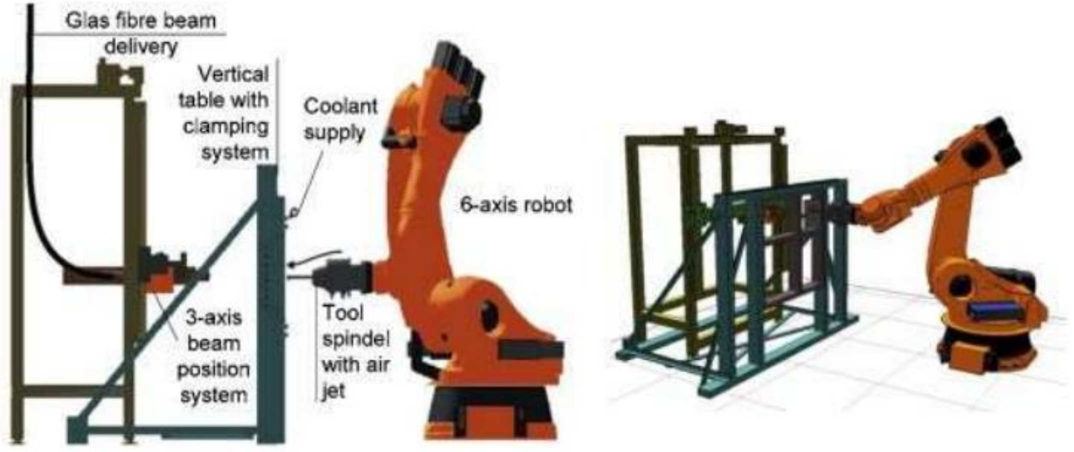


SPIF sa lokalnim zagrevanjem

Maksimalna temperatura 250C

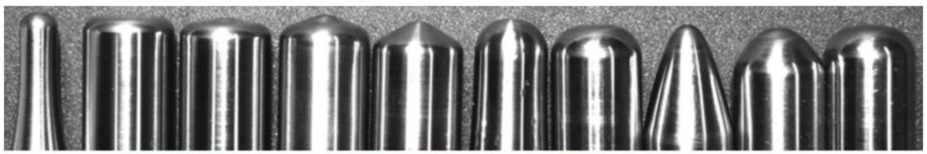
- Elektro-otporno zagrevanje
- Laser
- Trenje

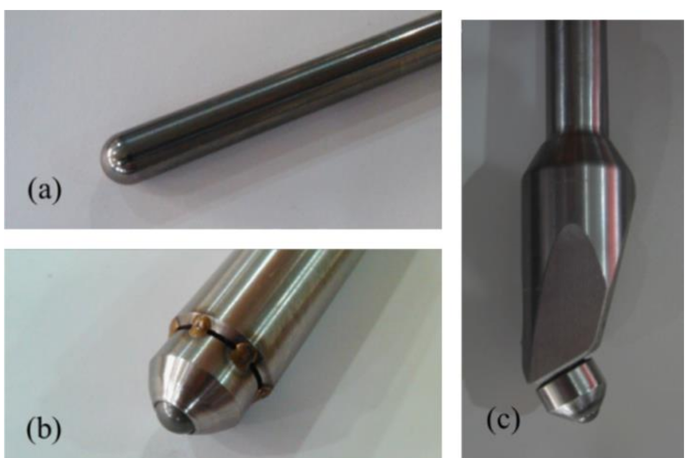




Alati i mašine za inkrementalno deformisanje lima

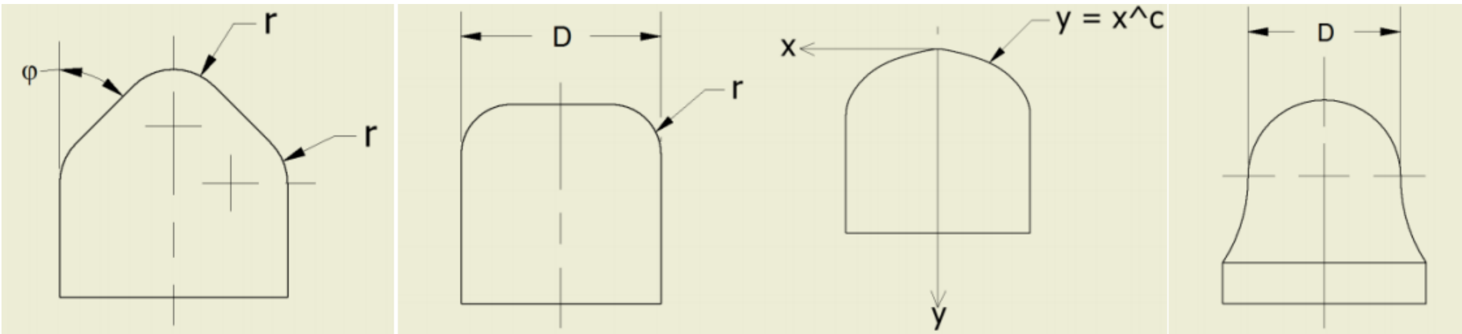
- Univerzalni alati
- Zahtev- dobar odnos između žilavosti i tvrdoće
- Alatni čelici
- Tvrdoća od 60-65 HRC
- Prevlake - cementit (Fe_3C), volfram-karbid, TiN
- Prečnik 6 ÷100 mm (10 ÷15 optimalmo)



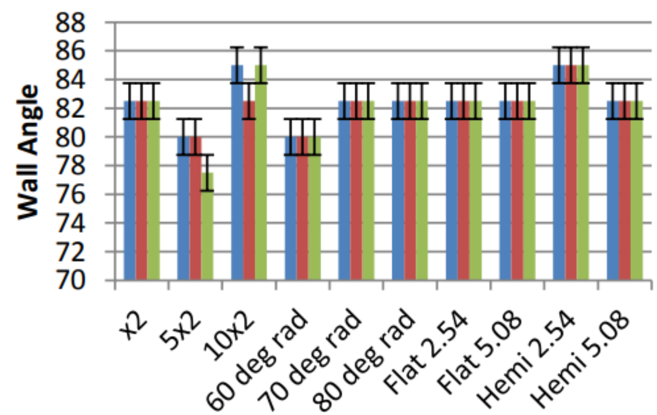


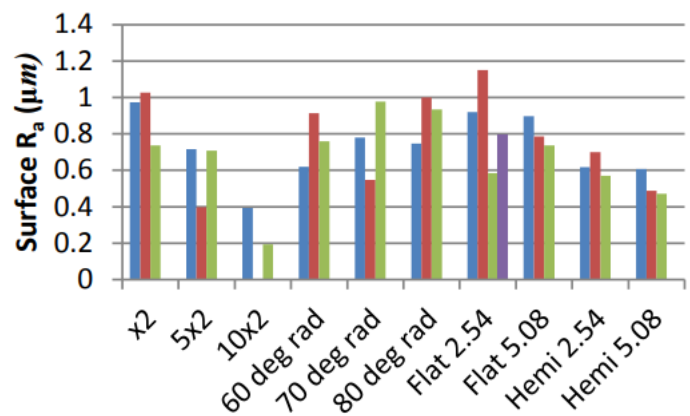
stezna glava

Alati i mašine za inkrementalno deformisanje lima

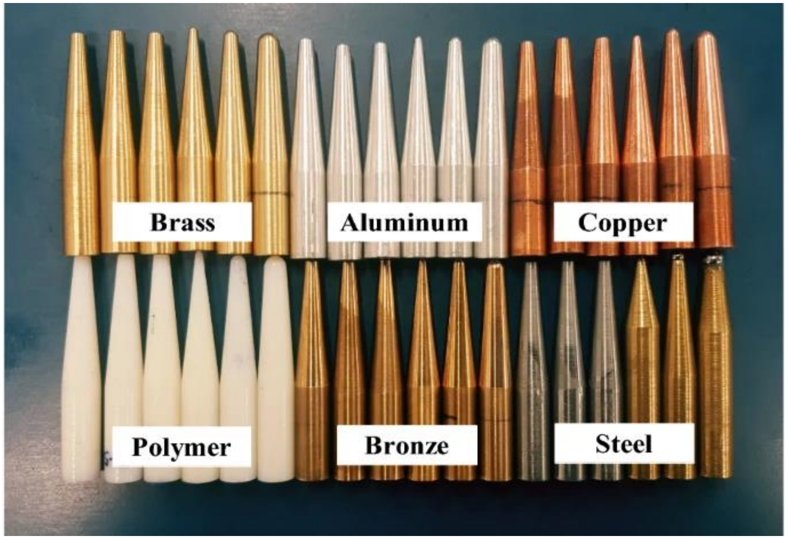


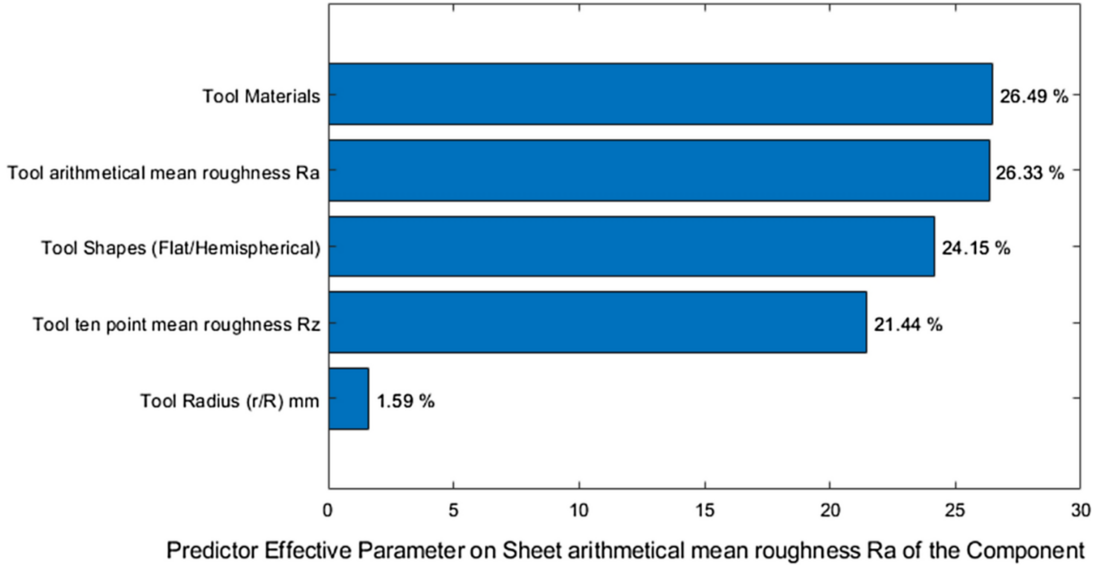
Tool Type	Parameter/Value
Angle r=2.54mm	Φ=60°
	Φ=70°
	Φ=80°
Flat D=12.7mm	r=5.08mm
	r=2.54mm
Hemispherical	D=5.08mm
	D=10.16mm
Parabolic D=12.7mm	$y=x^2$
	$y=5x^2$
	$y=10x^2$





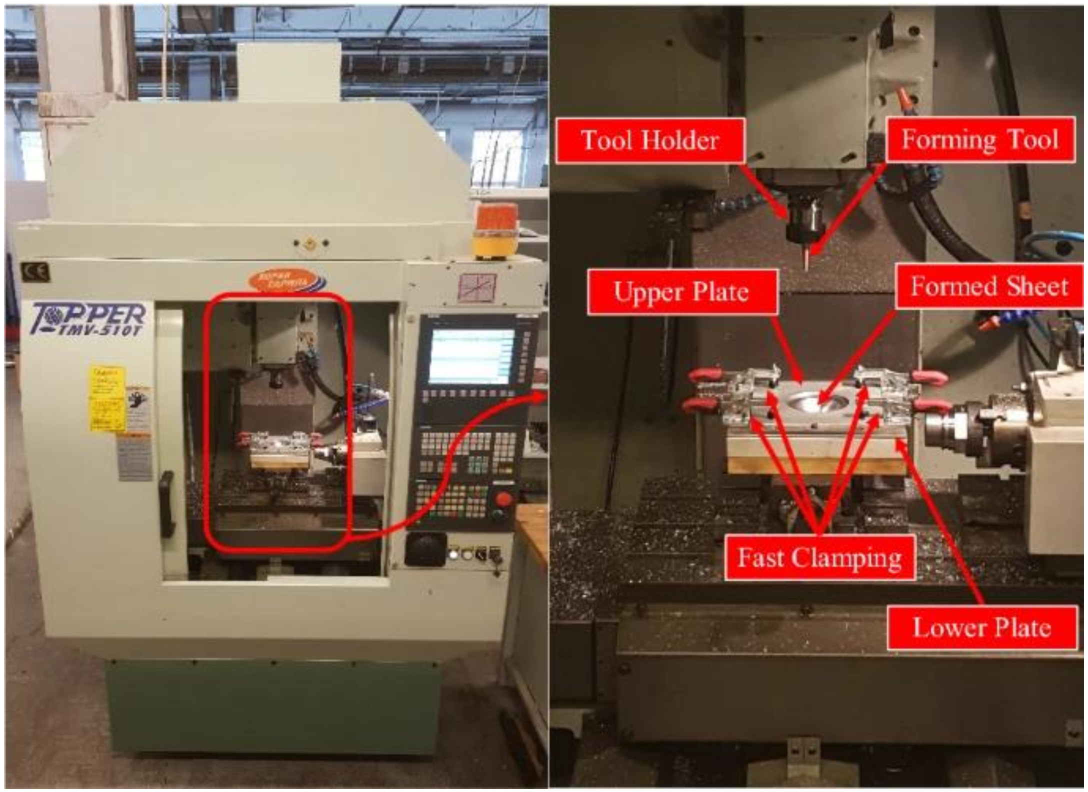
Alati i mašine za inkrementalno deformisanje lima

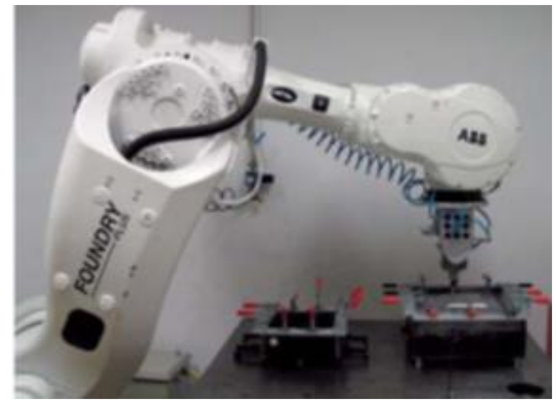




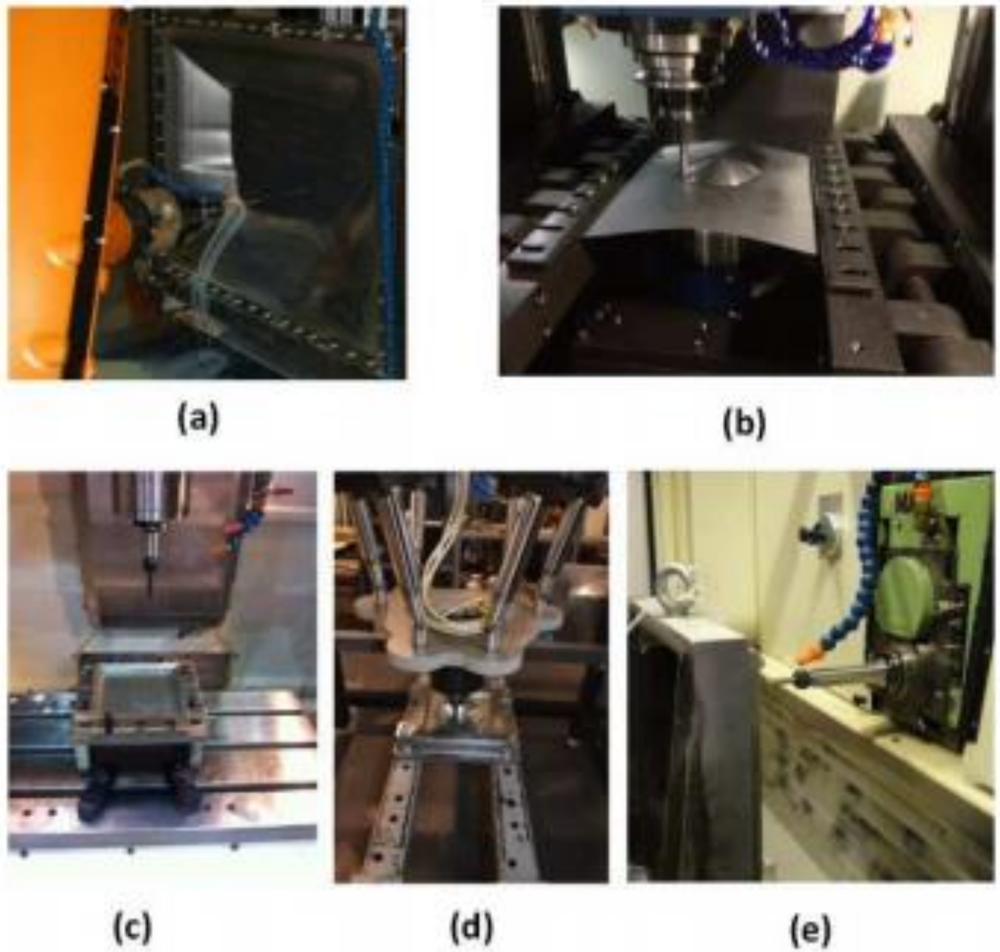
Alati i mašine za inkrementalno deformisanje lima

1. CNC mašine (glodalice)
2. Multi-osni roboti





Alati i mašine za inkrementalno deformisanje lima



(a) KUKA robot (b) forming on a die with sheet clamped on two sides and free on two(c) milling machine with a vertical spindle (d) Stewart platform (e) MAHO 600C milling machine with a horizontal spindle

Alati i mašine za inkrementalno deformisanje lima