

# ANALIZA PROMJENE TVRDOĆE PRI OBLIKOVANJU CJEVASTIH IZRADAKA IZ AL 99,5 % POSTUPKOM ISTOSMJERNOG HLADNOG ROTACIONOG ISTISKIVANJA

## ANALYSIS HARDNESS CHANGES OF TUBULAR WORKPIECES MADE OF AL 99.5% FORWARD COLD FLOW FORMING PROCESS

Plančić Ibrahim,  
Čabaravdić Malik,  
Begović Edin, \*Fakić  
Belma

University of Zenica,  
Bosnia & Herzegovina

**Ključne riječi:**  
tvrdoća, ojačavanje  
materijala, istosmjerno  
hladno rotaciono  
istiskivanje, Al 99,5

**Keywords:**  
hardness of material,  
material strengthening,  
forward cold flow forming,  
Al 99,5

**Paper received:**  
30.10.2015.

**Paper accepted:**  
15.12.2015.

*Originalni naučni rad*

### REZIME

*Pojava ojačavanja materijala tokom hladnog oblikovanja deformisanjem ključni je razlog koji ovu obradu čini superiornijom u odnosu na druge metode. Efekti ojačavanja se ogledaju u poboljšanju mehaničkih osobina izradaka. Upravo zbog efekata ojačavanja, a kao jedan od specifičnih postupaka oblikovanja rotaciono simetričnih dijelova u zahtjevnijim industrijskim granama sve više se primjenjuje istosmjerno hladno rotaciono istiskivanje (IHRI). U radu se na primjeru izrade cjevastih izradaka iz Al 99,5 % ovim postupkom analiziraju efekti ojačavanja materijala mjerenjem njegove tvrdoće poslije oblikovanja.*

*Original scientific paper*

### SUMMARY

*Final product of the cold forming process gain many advantages that are mostly produced by strengthening of the material in the process. Those advantages are primarily explained as improving mechanical characteristic of the work material. Because of the effects of strengthening and as one of the specific methods of forming rotationally symmetrical parts in demanding industries increasingly applied forward cold flow forming (FCFF). In this paper is shown an example of forward cold flow forming application process in production of 99,5% Al workpieces with focus on analysis of a strengthening effect of the processed material by the change in its hardness like HB.*

### 1. UVOD

Izrada dijelova zadovoljavajuće preciznosti u pogledu oblika i dimenzija, sa što manjom težinom i što boljim mehaničkim karakteristikama uz povoljne ekonomske efekte njihove izrade neprestano se postavlja kao zahtjev savremenih proizvodnih tehnologija. U širokoj lepezi tehnoloških postupaka izrade dijelova rotaciono simetričnog oblika kojima se ovo postiže značajno mjesto zauzimaju postupci obrade deformisanjem u hladnom stanju koji se nazivaju rotacionim oblikovanjem. Istosmjerno hladno rotaciono istiskivanje kao jedan specifičan postupak rotacionog oblikovanja omogućava pored dobijanja dijelova različitih dimenzija i redukciju debljine stijenke. Usljed redukcije debljine u hladnom stanju dolazi do efekta ojačavanja materijala koji je praćen poboljšanjem mehaničkih osobina i tačnosti finalnih izradaka.

### 1. INTRODUCTION

Production of parts with satisfactory accuracy in terms of shape and size, with the smallest weight and the best possible mechanical properties with favorable economic effects of their production is constantly a requirement of modern production technologies. In the wide range of technological processes for making parts with rotationally symmetric shape that achieves this, of significant importance are the processes of cold deformation, which are also known as rotational forming. Forward cold flow forming as a special method of rotational forming allows, in addition to the obtaining parts with different dimensions, also wall thickness reduction. The reduction of thickness in the cold state leads to the hardening effect of material which is accompanied by improving of the mechanical properties and the accuracy of the finished workpieces.

Stoga se njegovom primjenom stvaraju preduslovi za primjenu ekonomičnijih materijala i dijelova sa tanjim stijenkama. To je jako značajno za složene uslove eksploatacije dijelova gasnih turbina, artiljerijske municije, kućišta raketnih motora, hidrauličnih cilindara, posuda za skladištenje plina pod pritiskom i drugih dijelova u raznim industrijskim granama. Kao atraktivni materijal sadašnjosti i budućnosti, aluminijum zadovoljava većinu postavljenih zahtjeva, a posebno kada je u pitanju zahtjev za smanjenjem mase dijelova i komponenata u različitim industrijskim granama. Niža čvrstoćna svojstva aluminijskih dijelova moguće je poboljšati hladnim oblikovanjem. Na taj način se rotacioni dijelovi izrađeni iz Al, pored specifične kombinacije osobina (gustoće, korozione otpornosti, sposobnosti oblikovanja, cijene, karakterističnog metalnog sjaja, atraktivnosti, mogućnosti recikliranja i sl.) odlikuju i zadovoljavajućim čvrstoćnim osobinama. Tako se se oblast primjene Al pored proizvoda opšte upotrebe sve više širi na izradu dijelova u vojnoj, vazduhoplovoj i nuklearnoj industriji.

Upravo iz tih razloga, a zbog nepostojanja dovoljno pouzdanih informacija i literaturnih podataka o ponašanju i efektima ojačavanja aluminijuma pri hladnom deformisanju, predmet istraživanja u ovom radu je oblikovanje cjevastih izradaka iz tehnički čistog Al (99,5%) postupkom rotacionog oblikovanja. Predmetno istraživanje je provedeno s ciljem utvrđivanja efekata ojačavanja kroz analizu promjene tvrdoće po debljini i dužini stijenke oblikovanog materijala.

## 2. SPECIFIČNOSTI ROTACIONOG OBLIKOVANJA DIJELOVA

Rotaciono oblikovanje je proces oblikovanja metala obradom deformisanjem pri kome se ravna ploča ili cilindrični pripremak postavljen između trna i jedne ili više rolnica oblikuje u šuplji cilindar, konus ili drugi osnosimetrični dio sa pravolinijskom ili krivolinijskom izvodnicom. Postupak se odvija primjenom sile pritiska mašine koja se preko alata i složenog mehanizma rotacionog kretanja obratka i alata prenosi na obradak.

Razvoj tehnologije rotacionog oblikovanja je počeo razvojem procesa koji se danas najčešće naziva konvencionalno rotaciono oblikovanje. Pri ovom procesu ravna ploča se oblikuje u proizvod željenog oblika pri čemu se polazna debljina ploče vrlo malo ili nikako ne mjenja.

Therefore, its application creates preconditions for the application of cost-effective materials and parts with thin walls. It is very important for complex operating conditions of gas turbine parts, artillery ammunition, rocket motor housings, hydraulic cylinders, containers for storing gas under pressure and other parts in various industries.

As attractive material of the present and the future, aluminum meets most of the requirements imposed, especially when it comes to the requirement to reduce the weight of parts and components in different industries. Lower strength properties of aluminum parts can be improved by the cold forming. In this way, the rotary parts made of Al, in addition to the specific combination of properties (density, corrosion resistance, formability, cost, characteristic metallic luster, attractiveness, possibility of recycling and similar) are also characterized by satisfactory strength properties. Thus, the field of application of Al, in addition to the consumer products, is expanded to the production of parts in the military, aviation and the nuclear industry.

For these reasons, and because of the lack of sufficiently reliable information and the data about the behavior and effects of the strengthening of aluminum during cold deformation, the subject of research in this paper is the design of tubular workpieces from technically pure Al (99.5%) by rotational forming process. The research was conducted to determine the effect of strengthening through the analysis of changes in hardness along the thickness and the length of the wall of the deformed material.

## 2. CHARACTERISTICS OF THE ROTATIONAL FORMING OF PARTS

Rotational forming is a process of shaping metal in which the flat plate or cylindrical part placed between the mandrel and one or more rolls is formed in a hollow cylinder, cone or other axisymmetric part with the straight or curved generatrices. The process is performed by applying of pressure force by the machine, which is over tool and complex rotary movement of the workpiece and the tool transferred to the workpiece.

The development of technology of rotational forming began by the development of process, which is nowadays mostly known as conventional rotational forming. In this process a flat plate is formed into the desired product shape wherein the initial thickness of the plate is very little or not changed.

Nasuprot toga, procesi pri kojima se debljina stijenke pri oblikovanju smanjuje, predstavljeni su sa dva karakteristična procesa koji su opšte prihvaćeni kao:

- rotaciono oblikovanje elemenata konusnog, konveksnog ili konkavnog oblika i
- rotaciono oblikovanje elemenata cilindričnog oblika.

Postupkom rotacionog oblikovanja konusa izrađuju se osnosimetrični šuplji elementi sa pravolinijskom ili krivolinijskom izvodicom. Redukcija debljine zida je u strogoj funkcionalnoj zavisnosti i određena je odnosom između početne debljine ploče ili priprema i ugla konusnog trna. Ovaj postupak kao i postupak konvencionalnog rotacionog oblikovanja u literaturi se sreće pod nazivom rotaciono izvlačenje. Rotaciono oblikovanje elemenata cilindričnog oblika u praktičnoj primjeni i dostupnim literaturnim izvorima se najčešće susreće pod terminom rotaciono istiskivanje, iako se često u proizvodnim uslovima karakteriše i terminom rotaciono valjanje. U ovom radu će se koristiti termin rotaciono istiskivanje, a podrazumjeva postupak oblikovanja pri kome se cilindrični priprema oblikuje u cilindar sa unaprijed određenom redukcijom debljine zida. Shodno navedenom, osnovna razlika između ovih postupaka je da se kod rotacionog izvlačenja dobijaju dijelovi konstantne debljine oblikovanjem ravne ploče (platine) na šablonu koji rotira pomoću alata u obliku rolnice, dok se kod rotacionog istiskivanja vrši redukcija debljine stijenke cjevastog priprema na račun povećanja dužine izratka.

### 2.1. Tehnologija hladnog rotacionog istiskivanja

Sušтина postupka rotacionog istiskivanja je da se pod dejstvom pritiska rolnica (jedna ili više) materijal prevede u područje plastičnog tečenja i istiskuje u aksijalnom pravcu uz smanjenje prečnika i povećanje dužine izratka, kako je prikazano na slici 1. Na račun redukcije debljine stijenke dobija se veća dužina izratka, te se iz uslova konstantnosti zapremine radnog komada, dužina izratka može izračunati prema:

$$L_1 = L_0 s_0 (d_i + s_0) / [s_1 (d_i + s_1)] \quad (1)$$

Pri tome se ukupna logaritamska deformacija po debljini zida može izraziti kao:

$$\phi_s = \ln \frac{s_0}{s_1} \quad (2)$$

In contrast, the processes during which the wall thickness is decreased are represented by the two typical processes which are generally known as:

- rotational forming of elements with conical, convex and concave shape and
- rotational forming of elements with cylindrical shape.

By the process of rotational forming of the cone, axisymmetric hollow elements with a flat or curved generatrices are made. The reduction of the wall thickness is in strict functional dependence and is determined by the relationship between the initial thickness of the plate or workpiece and the angle of the conical mandrel. This process and the process of the conventional rotational forming are known in the literature as the rotational drawing processes. Rotational forming of cylindrical elements in the practice and in the available literature sources is most often known as rotational forward flow forming, although often under production conditions is characterized by the term rotational rolling. In this paper we will use the term rotational forward flow forming, implying forming process whereby a cylindrical workpiece is transformed into the cylinder with a predetermined reduction of the wall thickness. Accordingly, the main difference between these methods is that in the rotational drawing, parts with constant thickness are made by processing of flat panels (platinum) in a pattern that is rotated using a tool in the form of rolls, while by the rotational forward flow forming the reduction of the wall thickness of the tubular workpiece is performed causing the increase of the length of the workpiece.

### 2.1. Technology of the forward cold flow forming

The core of this procedure is to bring the material to the state of plastic flow and extrude it in the axial direction under the pressure of the rolls (one or more), resulting in the reduction of the diameter and increasing of the length of work piece, as shown in Figure 1. Because of the reduction of wall thickness, bigger length of the workpiece is obtained, and based on the conditions of the constancy of the volume of the work piece, the length of the workpiece can be calculated by:

$$L_1 = L_0 s_0 (d_i + s_0) / [s_1 (d_i + s_1)] \quad (1)$$

Thereby, the overall logarithmic strain through the thickness of the wall can be expressed as:

$$\phi_s = \ln \frac{s_0}{s_1} \quad (2)$$

gdje je:

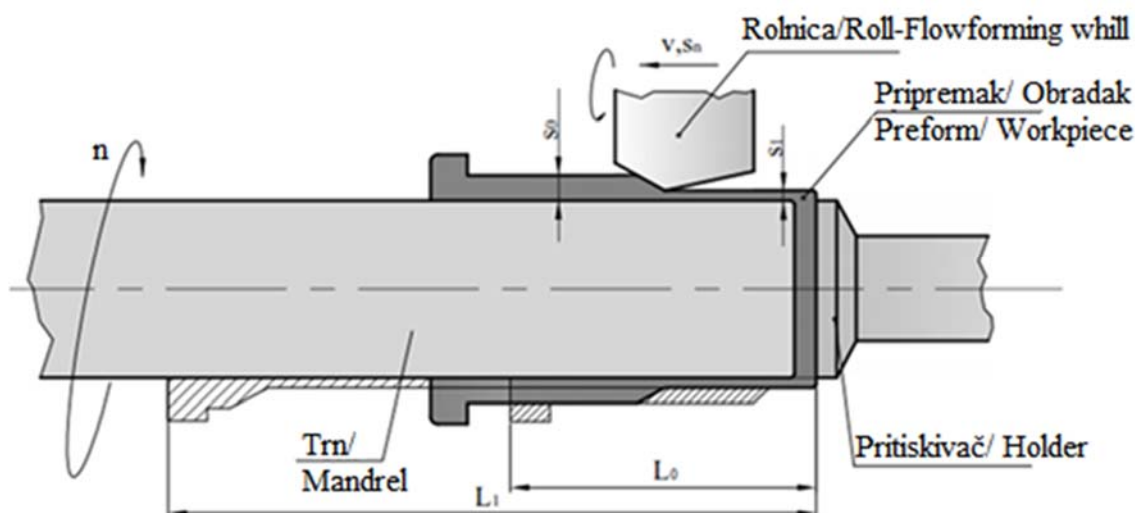
$L_1$ -dužina gotovog dijela,  $L_0$ -dužina početnog komada,  $s_0$ -početna debljina stijenke,  $s_1$ -konačna debljina stijenke,  $d_i$ -unutrašnji prečnik obratka/izratka

Deformisanje se odvija u uskoj dodirnoj zoni kontakta između rolnica (jedna ili više) i materijala.

where is:

$L_1$ -final length of the part,  $L_0$ -length of the preform,  $s_0$ -thickness of the preform,  $s_1$ -final thickness of the wall,  $d_i$ -inner diameter of the preform/final part

The deformation occurs in a narrow contact zone between the contact rolls (one or more) and the material.



*Slika 1. Šematski prikaz IHRI [2]*

*Figure 1. Schematic representation of the forward cold flow forming [2]*

Početni oblik - cjevasti pripreмки (toplo valjane cijevi, otkovci, puni profili i sl.) pritiskivačem se čeonu pritisnu uz trn da bi se obrtaji sa trna prenijeli na pripremkom. Cjevasti pripremkom se dodatno preko unutrašnjeg prečnika koji je jednak prečniku trna navuče na trn na kome se obavlja deformisanje. Pripremkom se prethodno izrađuje kovanjem ili dubokim izvlačenjem zavisno od debljine i oblika. Rolnice obično nemaju sopstveni pogon, već se obrtanje ostvaruje dejstvom kontaktnog trenja nastalog pri dodiru rolnice sa pripremkom. Pod dejstvom sile pritiska sa suporta mašine rolnice prodiru u metal uz obrtno kretanje trna i rolnica, te uz aksijalni posmak ostvaruju plastično tečenje - istiskivanje metala u aksijalnom smjeru. To dovodi do stanjenja stijenke i povećanja dužine izratka. Mala površina kontakta između alata (rolnica) i radnog komada, zahtijeva i malu silu oblikovanja, pa se zbog toga i mogu ostvariti veliki stepeni redukcije na mašinama male snage.

The initial forms - tubular preforms (hot-rolled pipes, forgings, rod systems, etc.) are frontal pressed against the mandrel by the pressing device, causing the transfer of the rotation from the mandrel to the preform. Further, the tubular preform with the inner diameter equal to the diameter of the mandrel is pulled over the mandrel where the deformation is performed. Preforms are previously prepared by forging or deep drawing, depending on the thickness and shape. Rolls usually do not have their own actuator, and their rotation is achieved through the effect of the friction generated by the contact between rolls and the work piece. Under the force of the pressure from the apron of machine, rolls penetrate the metal causing the rotary motion of the mandrel and rolls, and with axial feed realize flowing - extruding of metal in the axial direction. This leads to a thinning of the walls and increase the length of the work piece. A small contact zone between the tool (rolls) and the work piece, requires small force for processing, achieving a great degree of reduction in low-power machines.

Pod uticajem tako visokih pritisaka zrno materijala se drobi i razvlači u pravcu toka materijala, te se intenzivno mijenja struktura i mehaničke osobine. Obilnim hlađenjem zone zahvata materijala, najčešće uljnom emulzijom koja se pod pritiskom, putem odgovarajućih mlaznica raspršava u zoni deformisanja, sprječava se zagrijavanje materijala i zadržavaju efekti hladnog deformisanja. Po završetku obrade, skidanje izratka se obavlja primjenom izbijača smještenog u unutrašnjosti trna ili svlačenjem izratka sa trna primjenom neke vanjske sile.

Postoji nekoliko metoda HRI cjevastih dijelova, a dvije osnovne vrste tehnološkog postupka HRI su:

- Istosmjerno (I) ili direktno i
- Suprotnosmjerno (S), odnosno indirektno.

Varijante se uglavnom razlikuju prema načinu tečenja materijala u odnosu na pravac kretanja rollica, dok je deformisanje metala u obje varijante lokalizovano na usku dodirnu zonu kontakta alata-rollice i materijala obradka.

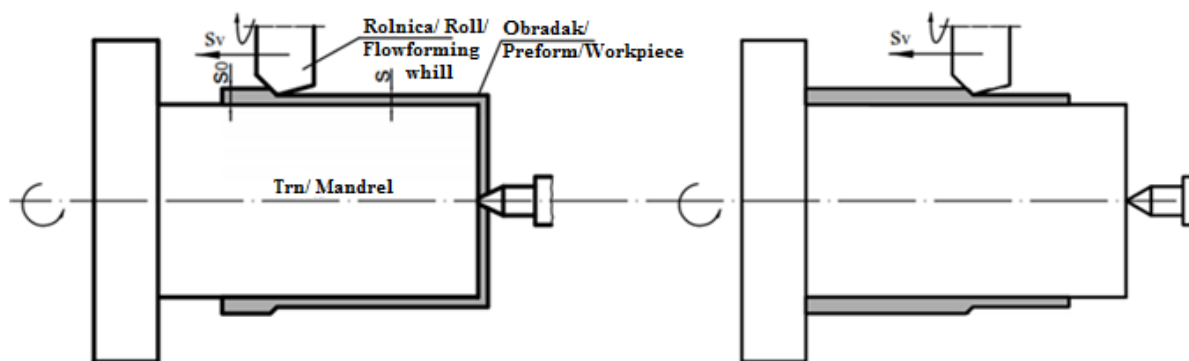
Na slici 2. je šematskim prikazom predstavljen princip oblikovanja predmetnim varijantama HRI sa prikazom radnih elemenata alata.

Under the influence of such a high pressure grain of material is crushed and extends in the direction of material flow, causing the intensive change in structure and mechanical properties. By intensive cooling of the contact zone, usually with an oil emulsion which is under pressure, through the appropriate nozzle sprayed into the zone of deformation, the heating of material is prevented and the effects of cold deformation are retained. Upon completion of processing, the removal of the work piece is performed using the punches located in the interior of the mandrel or stripping of the work piece from the mandrel by applying some external force.

There are several methods FCFF of tubular parts, and two basic types of technological process of FCFF are:

- direct and
- oppositional.

Variants differ mainly in the direction of material flow in relation to the direction of the rotation of rolls, while the deformation of metal in both variants is localized in a narrow contact zone between tool-roll and the work piece material. In Figure 2 is given a schematic representation of the principle of forming by the mentioned FCFF variants showing the operational elements of the tool.



**Slika 2.** Šematski prikaz postupka istosmjernog (lijevo) i suprotnosmjernog (desno) HRI [1]  
**Figure 2.** Scheme of procedure of direct (left) and oppositional (right) CFF [1]

Pri istosmjernom (direktnom) HRI (slika 1, lijevo) tečenje nedeformisanog materijala priprema/predoblika i kretanje rollica (alata) je u istom smjeru, dok je kod suprotnosmjernog (indirektnog) HRI (slika 1, desno) tečenje materijala u suprotnom smjeru u odnosu na smjer kretanja rollica.

In direct CFF (Figure 1, left) the flow of unformed material of preparation/preform and the rotation of rolls (tool) is in the same direction, while in the indirect CFF (Figure 1, right) material flow is in the opposite direction compared to the direction of the roll's rotation.

Na taj način se mogu oblikovati otvoreni cilindrični dijelovi veće dužine, dok se kod IHRI primjenom alata najčešće u obliku rolnica na specijalnim trnovima dobijaju šuplji cilindrični dijelovi stalne ili promjenjive debljine stijenke sa jednom zatvorenom stranom cilindra.

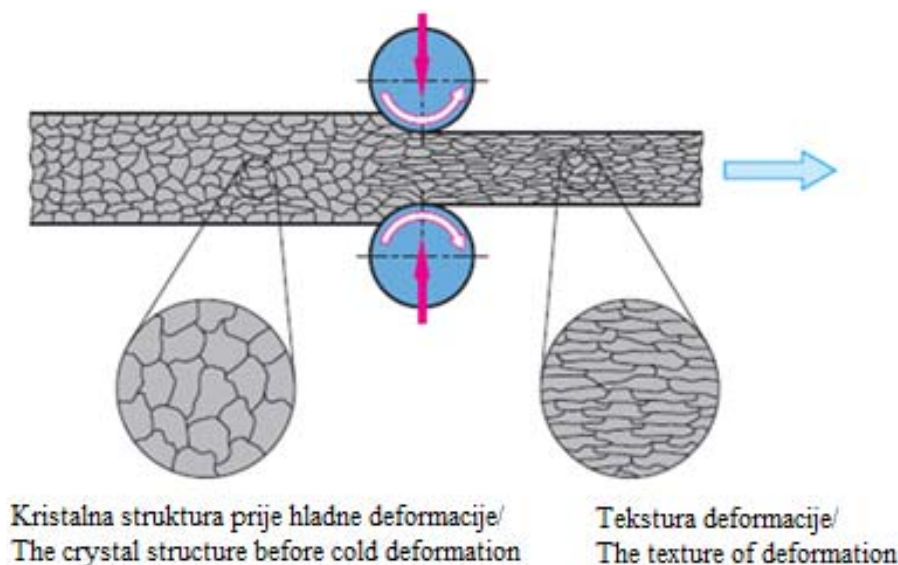
In this way, open cylindrical parts with larger length can be formed, while in FCFF using tools, most commonly in the form of rolls on special mandrels, special hollow cylindrical parts with constant or variable wall thickness with one closed side of the cylinder can be produced.

## 2.2. Ojačavanje materijala postupcima obrade deformisanjem u hladnom stanju

Najvažnija promjena koja se dešava kao posljedica hladne plastične deformacije je ojačavanje materijala. Iako još uvijek nije do kraja razjašnjena, prema većini teorija koje objašnjavaju ovu pojavu, ona je uzrokovano gomilanjem dislokacija i njihovim otežanim kretanjem. Usljed dejstva spoljašnjih sila određenim stepenom deformacije dolazi do ravnomjernog izravnavanja kristalografskih zrna u aksijalnom smjeru paralelno sa pravcima tečenja metala i formiranja homogene kristalografske orijentacije zrna koja se naziva tekstura deformacije (slika 3).

## 2.2. Strengthening of material using the procedures of cold deformation

The most important change that occurs as a result of cold plastic deformation is the strengthening of material. Although not yet fully clarified, according to most theories that explain this phenomenon, it is caused by the accumulation of dislocations and their mobility limitations. Due to the effects of external forces some degree of deformation leads to a uniform leveling of the crystallographic grains in the axial direction, parallel to the direction of metal flowing and forming of a homogeneous crystallographic orientation of grains, which is called texture of deformation (Figure 3).



Slika 3. Ilustracija nastanka deformacione teksture pri hladnoj obradi deformisanjem  
Figure 3. The emergence texture of deformation in the cold metal forming

Pojava deformacione teksture je praćena značajnim promjenama fizičko mehaničkih svojstava metala. Te promjene se odnose na znatno povećanje mehaničkih osobina, kvaliteta površine i povećanje dimenzijske tačnosti izradaka uz istovremeno smanjenje plastičnosti. Pored toga, nastupaju i druge promjene koje su povezane sa povećanjem elektrootpornosti, smanjenjem magnetnih karakteristika, toplote provodnosti i drugih fizičko hemijskih svojstava oblikovanih dijelova.

The occurrence of deformation texture is accompanied by significant changes in physical and mechanical properties of metals. These changes are related to an extensive increase in mechanical properties, surface quality and dimensional accuracy of work pieces while the plasticity is reduced. In addition, other changes occur which are associated with an increase in electrical resistance, decrease of magnetic characteristics, thermal conductivity and other physical and chemical properties of formed parts.

Ilustrativan prikaz promjene fizičko-mehaničkih osobina u zavisnosti od stepena deformacije pri plastičnom deformisanju u hladnom stanju prikazan je na slici 4.

U nastavku je na primjeru oblikovanja cilindričnih izradaka iz tehnički čistog aluminijuma analiziran porast tvrdoće materijala kao jednog od najznačajnijih mjerljivih parametara kojim se pojava deformacionog ojačavanja može identificirati.

### 3. EKSPERIMENTALNI RAD

#### 3.1. Tehnologija oblikovanja izradaka

S ciljem analize ponašanja tehnički čistog aluminijuma i efekata njegovog ojačavanja tokom hladne obrade deformisanjem izvršeno je oblikovanje Al 99,5 komore u dvije faze IHRI. U tabeli 1. su predstavljene karakteristike priprema koji su korišteni za IHRI. Vrijednosti predstavljaju prosječne veličine parametara dobijenih ispitivanjem epruveta iz deset slučajno odabranih priprema.

Tabela 1. Mehaničke karakteristike priprema za IHRI  
Table 1. Mechanical characteristics of the preforms for FCFF

Materijal Material	Prosječne vrijednosti parametara - Mean values of parameters				
	$m_{pr}$ [gr]	$R_{p0,2}$ [N/mm <sup>2</sup> ]	$R_m$ [N/mm <sup>2</sup> ]	A [%]	Z [%]
Al 99,5 %	2268	80	98	28,0	86

Tokom oblikovanja su korištene ranije utvrđene optimalne vrijednosti geometrijskih karakteristika alata i tehnoloških parametara procesa, a odnose se na sljedeće:

- Tehnološki proces oblikovanja se odvija alatom u obliku rolnica prečnika  $D_1=D_2=D_3=250$  mm, radijusom  $R_1=R_2=4$  mm,  $R_3=2$  mm, napadnim uglom  $\alpha=20^\circ$  i aksijalnim podešenjem rolnica u tri ravnine na udaljenosti  $a_1=7$  mm,  $a_2=4$  mm i  $a_3=3$  mm,
- Pritisak na rolnice:  $p_1=p_2=p_3=6$  [N/mm<sup>2</sup>],
- Intenzivno hlađenje vanjske površine izradaka emulzijom 1:10 (voda/ulje),
- Podmazivanje trna (unutrašnja površina izratka) mješavinom masti i grafitnog praha u omjeru: 1 kg masti na 100 gr. grafita.

Na slici 5. su predstavljene dimenzije priprema i izradaka po fazama IHRI.

Illustrative representation of changes in physical and mechanical characteristics in dependence of the degree of deformation by the cold plastic deformation is shown in Figure 4.

The analysis of the increase in the hardness of the material as one of the most important measurable parameters, by which the strain hardening phenomenon can be identified, on the example of forming of cylindrical work pieces which are made of technically pure aluminum is given below.

### 3. EXPERIMENTAL WORK

#### 3.1. Technology of the forming of work pieces

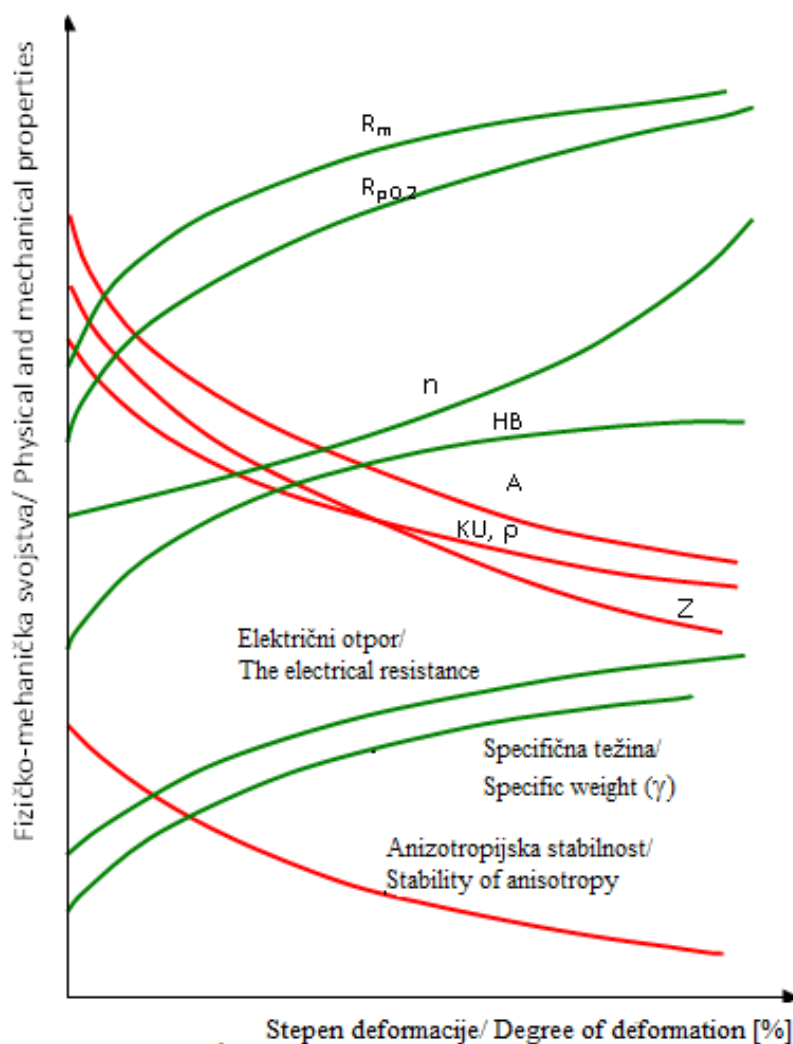
For the purposes of the analysis of the behavior of technically pure aluminum and its effects strengthening during the cold metal forming, processing of Al 99.5 chamber in two phases of FCFF was carried out.

Table 1 presents the characteristics of preforms which are used for FCFF. Values represent the mean values of the parameters obtained from specimens from ten randomly selected preforms.

During the forming have been used previously determined optimal values of geometric characteristics of tool and technological parameters of the process, that refer to the following:

- Technological process of the forming is performed by the tool in the form of rolls with the diameters  $D_1=D_2=D_3=250$  mm, radii  $R_1=R_2=4$  mm,  $R_3=2$  mm, incidence angle  $\alpha=20^\circ$  and axial adjustment of the rolls in the three planes at the distances  $a_1=7$  mm,  $a_2=4$  mm i  $a_3=3$  mm,
- Pressure to the rolls:  $p_1=p_2=p_3=6$  [N/mm<sup>2</sup>],
- Intensive cooling of the outer surface of work piece by emulsion 1:10 (water/oil),
- Lubrication of the mandrel (inner surface of work piece) by the mixture of grease and graphite powder with the ratio: 1 kg grease to 100 gr. graphite.

In Figure 5 are presented dimensions of preforms and work pieces in the different stages of the FCFF.



Slika 4. Promjene fizičko-mehaničkih svojstava u zavisnosti od stepena deformacije pri plastičnom deformisanju u hladnom stanju [4, 5]

Figure 4. Changes physical and mechanical properties depending on the degree of deformation in cold metal forming

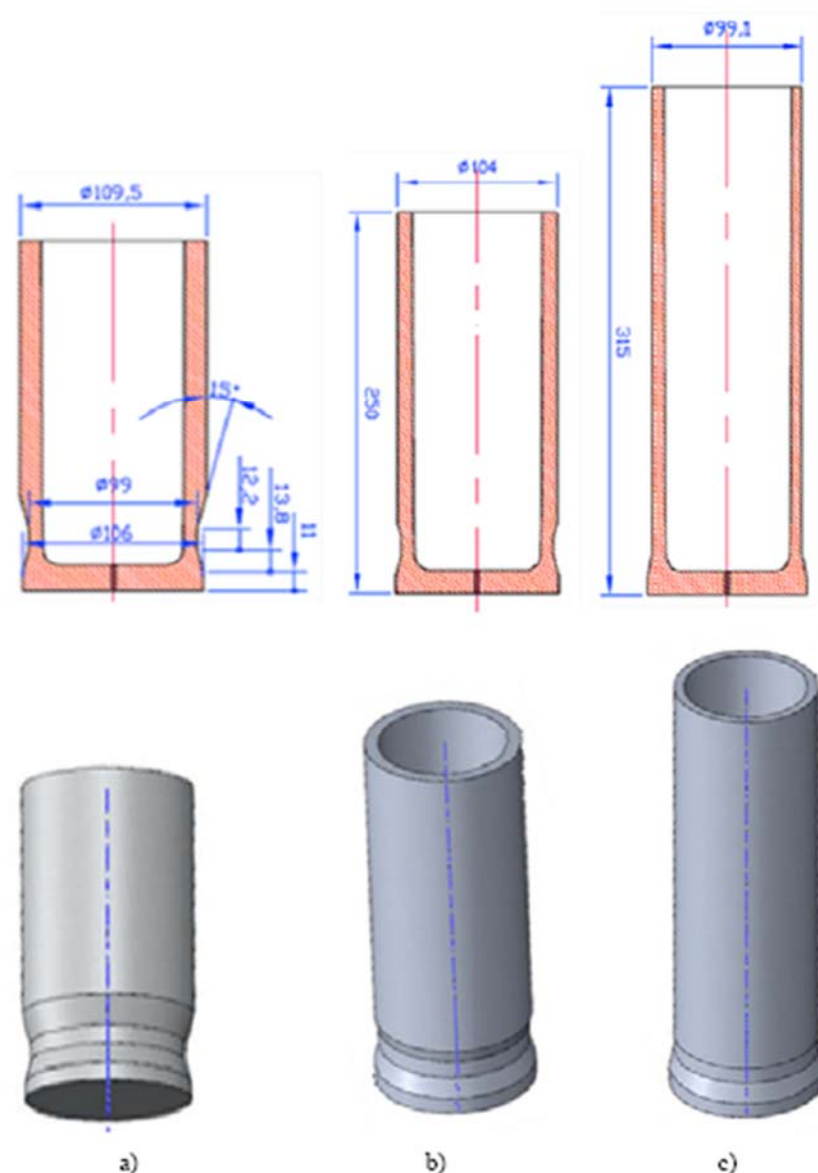
Prilikom provođenja eksperimenta, a u svrhu istraživanja uticaja tehnoloških parametara na pojavu ojačavanja materijala tokom hladne plastične deformacije vršena su preliminarna i glavna istraživanja. Preliminarnim istraživanjima su utvrđene optimalne vrijednosti tehnoloških parametara oblikovanja: broj obrtaja trna  $n$  [°/min], minutni posmak rolnica  $s_v$  [mm/min] i ukupna dubina prodiranja rolnica:  $\Delta s = \Delta s_1 + \Delta s_2 + \Delta s_3$  [mm] sa aspekta efikasnosti oblikovanja i dobijanja potrebnih dimenzija izradaka. Glavnim istraživanjem kroz primjenu metodologije planiranog eksperimenta utvrđene su ključne zakonitosti izbora tehnoloških parametara oblikovanja za dobijanje izradaka određenih karakteristika.

By the experiment, in order to research the impact of technological parameters on the occurrence of the strengthening of material during the cold plastic deformation, preliminary and main investigation were carried out. Preliminary investigations have determined optimal technological parameters of forming: speed of mandrel  $n$  [°/min], minute in-feed of rolls  $s_v$  [mm/min] and total depth of the penetration of rolls:  $\Delta s = \Delta s_1 + \Delta s_2 + \Delta s_3$  [mm] in terms of the efficiency of forming and obtaining of the required dimensions of work pieces. Through the application of the methodology of planned experiment in the main investigation are identified key rules for the choice of technological parameters of forming for obtaining work pieces with certain characteristics.



U ovom radu predstavljeni su dobijeni rezultati i izvedene zakonitosti promjene tvrdoće izradaka nakon prve operacije IHRI tokom preliminarnih i glavnih istraživanja koja su vršena u Laboratoriji za obradu rezanje i alatne mašine- LORAM na Mašinskom fakultetu i Laboratorijama Metalurškog instituta Univerziteta u Zenici. Tvrdoća izradaka nakon druge faze kod preliminarnih i glavnih istraživanja zbog žarenja i oporavljanja strukture ne odražava efekte hladne obrade deformisanjem zbog čega ovi rezultati nisu ni analizirani.

This paper presents obtained results and derived principles for the change in hardness of work pieces after the first operation by FCFF during the preliminary and the main research conducted in the Laboratory for cutting and cutting tool machines - LORAM at the Faculty of Mechanical Engineering and in the laboratories of the Institute of Metallurgy at the University of Zenica. The hardness of work pieces after the second stage of forming in the preliminary and main research does not reflect the effects of cold metal forming because of tempering and the recovery of structure and that is the reason why these results have not been analyzed.



Slika 5. Izgled i dimenzije priprema i izradaka po fazama IHRI a) Pripremak b) Izradak poslije I faze c) Izradak poslije II faze [2]

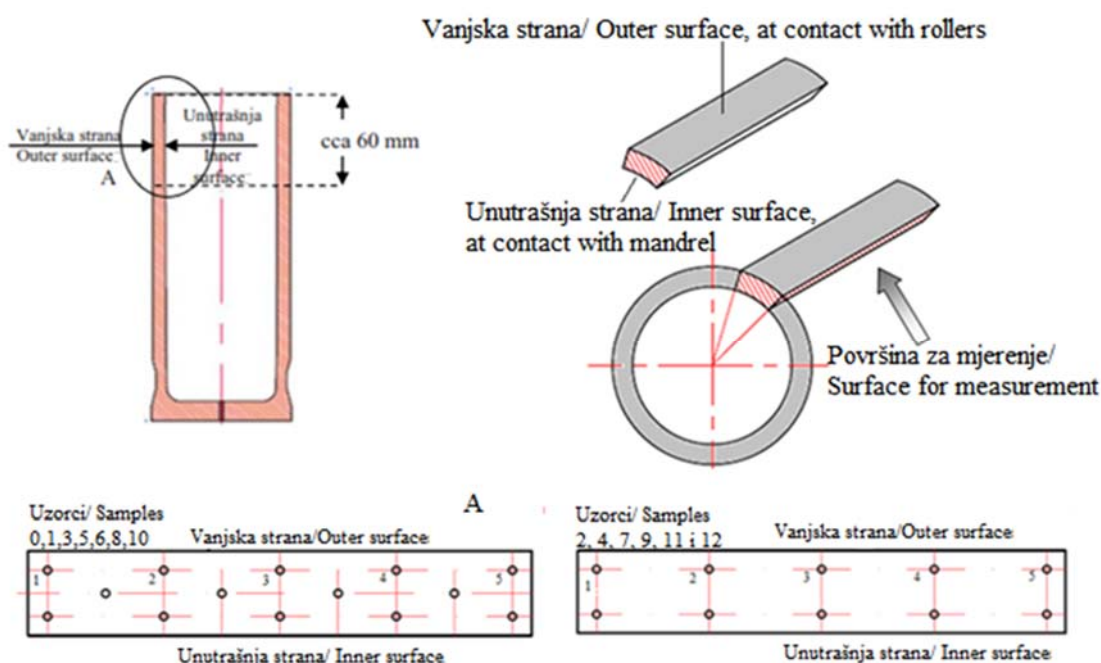
Figure 5. The workpiece in the different stages of processing a) Preform; b) Workpiece after the phase I; c) Workpiece after the phase II [2]

### 3.2. Mjerenje i analiza tvrdoće oblikovanih uzoraka

U cilju izvođenja zaključaka u vezi sa ojačavanjem materijala tokom hladne obrade deformisanjem tehnologijom IHRI ispitivanje tvrdoće je vršeno po debljini stijenke pri vrhu cilindričnog dijela izradaka (zona intenzivne deformacije) i po njihovoj dužini. Za ispitivanje tvrdoće korišteni su uzorci dužine 60 mm sa debljinom koja odgovara debljini izradaka. Mjerenje tvrdoće kod preliminarnih istraživanja (izradci oblikovani sa međufaznim žarenjem) je vršeno Vickersovom metodom ispitivanja, dok je Brinellova metoda mjerenja tvrdoće korištena kod glavnih istraživanja (oblikovanje izradaka bez međufaznog žarenja). U oba slučaja su na svakom uzorku definisana mjerna mjesta i to na unutrašnjoj (površina prema trnu tokom oblikovanja) i vanjskoj (površina ispod rollica tokom oblikovanja) strani izratka. Na slici 6. su predstavljene lokacije mjernih mjesta.

### 3.2. Measurement and analysis of the hardness of processed specimens

In order to draw conclusions with regard to strengthening of the material during the cold metal forming technology FCFF, hardness measurement was performed along the wall thickness at the top of the cylindrical section of work pieces (zone of intense deformation) and along their length. For hardness measurement are used specimens with the length of 60 mm with a thickness corresponding to the thickness of the work piece. Hardness measurement in preliminary studies (the specimens formed with interphase tempering) was performed using Vickers test method, while the Brinell hardness measurement methods were used in the main study (forming of work pieces without interphase tempering). In both cases were defined measuring points on each sample on the inner (the surface facing mandrel during forming) and the outer (the area under the rolls during the forming) side of the workpiece. In Figure 6 are presented locations of measurement points.



Slika 6. Mjesto uzorkovanja (gore) i lokacije mjernih mjesta po debljini stijenke (dolje)

Figure 6. Sampling location (up) and the location of measurement points per the wall thickness of the workpiece (down)

U tabeli 2. su predstavljene prosječne vrijednosti tvrdoće izradaka na lociranim mjernim mjestima u funkciji tehnoloških režima oblikovanja i izvršenog stepena deformacije.

In Table 2 are presented mean values of the hardness of work pieces at the located measuring points in dependence on the technological regimes of forming and the obtained degree of deformation.

Tabela 2. Rezultati mjerenja tvrdoće nakon prve faze IHRI

Table 2. Results of the hardness measurement after the first stage of FCFE

No.	Režimi oblikovanja Regimes of forming			$\varphi$ [%]	HB uzorka na* HB of specimen on*			Prosječna Mean [HB]	Porast Increase in hardness [%]
	n [o/min]	$s_v$ [mm/o]	$\Delta s$ [mm]		a	b	c		
0	-	-	-	-	32,42	32,52	33,1	32,68	-
1	140	60	2	18,1	33,78	34,92	39,36	36,02	10
2	240	60	2	17,6	31,02		35,46	33,24	2
3	140	100	2	15,3	32,08	32,2	37,9	34,06	4
4	240	100	2	21,0	33,78		38,28	36,03	10
5	140	60	3,5	35,4	36,44	34,4	34,44	35,09	7
6	240	60	3,5	35,2	36,9	33,94	34,24	35,03	7
7	140	100	3,5	32,9	32,4		36,3	34,35	5
8	240	100	3,5	33,6	33,04	32,16	34,5	33,23	2
9	190	80	2,75	23,15	34,04		37,64	35,84	10
10	190	80	2,75	22,9	35,7	34,92	36,96	35,86	10
11	190	80	2,75	23,5	35,04		36,98	36,01	10
12	190	80	2,75	25,1	33,56		36,64	35,10	7

\*a-unutrašnja strana/inner surface; b-polovina debljine/half thickness; c- vanjska strana/ outer surface

Dobijeni rezultati mjerenja tvrdoće nakon prve faze oblikovanja i kod preliminarnih i kod glavnih istraživanja ukazuju na sljedeće zaključke:

- Rezultati mjerenja tvrdoće nakon prve operacije IHRI su u granicama očekivanih jer je na svim uzorcima došlo do povećanja tvrdoće u odnosu na tvrdoću priprema. Prosječne vrijednosti tvrdoće na izradcima koji su dobijeni tehnologijom IHRI su u rasponu od 33,23 do 36,03 HB. S obzirom da je srednja vrijednost izmjerene tvrdoće na pripremcima bila 32,68 HB to je maksimalni porast tvrdoće u rasponu od 2 do 10 %.
- Pošto je Al 99,5 materijal koji, pored niza izuzetno dobrih karakteristika, ima dobra plastična svojstva, a male čvrstoćne karakteristike ( $R_{p0,2}$ ,  $R_m$  i HB) u odnosu na druge materijale (npr. čelike) očekivano se kod oblikovanja tehnički čistog Al 99,5 nemogu dobiti njihove značajno veće vrijednosti obradom deformisanjem u hladnom stanju. Dobijeni rezultati su u skladu sa dosadašnjim objavljenim rezultatima u vezi sa porastom tvrdoće tehnički čistog aluminijuma deformisanjem na hladno [5,7].

The results of measurement of hardness after the first phase of forming in both studies (preliminary and main) suggest the following conclusions:

- Results of measurement of hardness after the first stage of FCFE were expected because in all samples, hardness was increased compared to the hardness of the preform. Mean values of hardness of the work pieces obtained by FCFE technology are in the range from 33.23 to 36.03 HB. Since the mean value of the hardness of preforms was 32.68 HB, the maximum increase of hardness was in the range from 2 to 10%.
- Since the Al 99,5 is a material, which, besides a number of extremely good properties, compared to other materials (e.g., steel) has good forming properties and low strength characteristics ( $R_{p0,2}$ ,  $R_m$  and HB), their significantly higher levels, as expected, can not be obtained by cold forming of technically pure Al 99,5. The results are comparable with previous published results regarding the increase in the hardness of technically pure aluminum by cold forming [5,7].

- Procentualni porast tvrdoće je maksimalan na uzorcima koji su oblikovani sa srednjim vrijednostima tehnoloških režima rada ( $n=190$  [o/min];  $s_v=80$  [mm/o] i  $\Delta s=2,75$  [mm]) kako je prikazano i dijagramima na slici 7.

Na osnovu približnog obrasca ruskih istraživača H.V. Tretjakova i V.J. Zjuzina do kojih su došli ispitujući oko 133 vrste metala i legura moguće je izvesti i zakonitost promjene tvrdoće ovisno o stepenu deformacije drugog reda ( $\Psi$ ) sljedećim izrazom:

$$J=J_0 + a x^n \text{ (za HB)} \quad (3)$$

Uvrštavajući eksperimentalno dobijene vrijednosti tvrdoće, u sklopu predmetnih istraživanja izračunati su koeficijenti  $a$  i  $n$ , te se promjena tvrdoće pri oblikovanju Al 99,5 postupkom IHRI može predstaviti sljedećim izrazom:

$$HB=32,68 + 1,0977 \psi^{-0,37472} \quad (4)$$

Ono što se takođe može izvesti kao zaključak provedenih istraživanja, a na osnovu mjerenja tvrdoće izradaka odnosi se na činjenicu da postoji razlika u tvrdoći kako po debljini stijenke tako i po dužini izradaka. Očigledno je da se kod dijelova oblikovanih IHRI javlja anizotropija mehaničkih osobina, kao posljedica obrazovanja tekture deformacije. S tim u vezi, mehaničke osobine izradaka se mijenjaju od spoljašnjeg ka unutrašnjem zidu oblikovanog elementa. To je potvrđeno mjerenjem tvrdoće na uzdužnom presjeku deformisanog cilindričnog izratka.

Položaj i broj mjernih mjesta na specifičnim dijelovima oblikovanog cilindričnog izratka prikazan je na slici 8 (0-dno izratka sa tri mjerna mjesta na unutrašnjoj i vanjskoj površini i dijelovi oblikovanog cilindra 1, 2, 3, 4 sa po tri mjerna mjesta na unutrašnjoj i spoljnoj površini).

Sistematizovani rezultati ovih mjerenja sa prosječnim vrijednostima tvrdoće na unutrašnjoj i vanjskoj strani izradaka predstavljeni su u tabeli 3 i dijagramom na slici 9. Isti pokazuju da je tvrdoća na vanjskoj strani (ispod rolnica) veća nego na unutrašnjoj strani uzoraka (površina prema trnu tokom izrade). Do istog zaključka došlo se i u istraživanjima [6] tokom oblikovanja konusa od Cu.

- The percentage increase in hardness has its maximum by the samples which are formed with medium values of technological parameters ( $n=190$  [o/min];  $sv=80$  [mm/o] and  $\Delta s=2,75$  [mm]) as shown in the diagrams in Figure 7.

Based on the approximate equation of Russian researchers H.V. Tretjakov and V.J. Zjuzin which was obtained by examining of about 133 kinds of metals and alloys, the law of the change in hardness depending on the degree of deformation of the second order ( $\Psi$ ) can be described by the following expression:

$$J=J_0 + a x^n \text{ (za HB)} \quad (3)$$

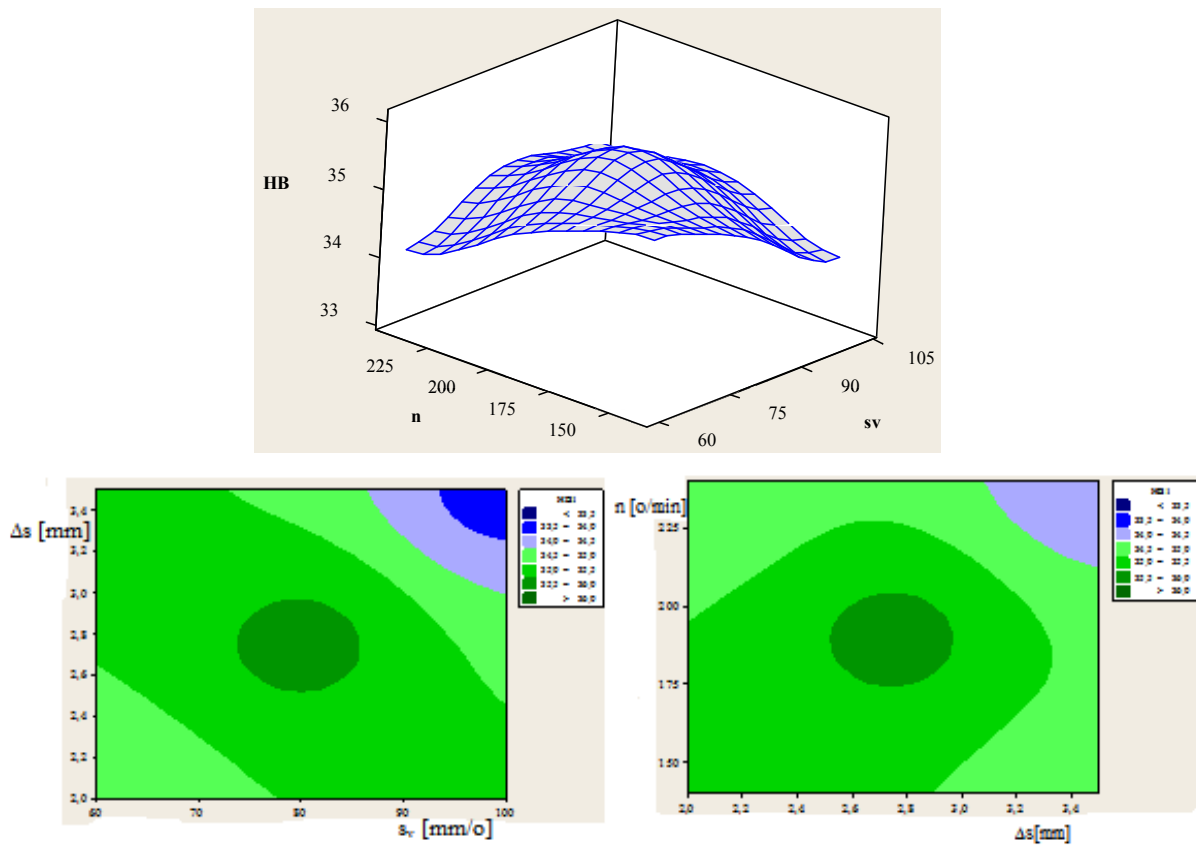
Incorporating the experimentally obtained values of hardness, as part of the underlying research, coefficients  $a$  and  $n$  were determined, and changes in hardness by the forming of Al 99.5 by FCFE procedure can be presented by the following expression:

$$HB=32,68 + 1,0977 \psi^{-0,37472} \quad (4)$$

The point that can also be defined as a conclusion of the research based on measuring the hardness of workpiece, refers to the fact that there is a difference in the hardness both in the wall thickness and the length of the work piece. It is obvious that in parts formed by FCFE occurs anisotropy of mechanical properties, as a result of forming of deformation texture. According to that, the mechanical properties of work pieces are changed from the outer to the inner wall of the formed element. It was confirmed by the measuring of hardness of the longitudinal section of a deformed cylindrical work piece.

The position and number of measuring points on the specific parts of the formed cylindrical work piece is shown in Figure 8 (0-bottom of the work piece with three measuring points on the inner and outer surface and the parts of formed cylinder 1, 2, 3, 4 with three measuring points on the inner and outer surface).

Systematized results of these measurements with mean values of hardness on the inside and outside of work pieces are presented in Table 3 and Figure 9. These results show that the hardness on the outside (below rolls) is higher than on the inner side of samples (surface toward the mandrel during the processing). The same was concluded also in research [6] during the forming of the cone of Cu.



Slika 7. Tvrdoća izradaka u funkciji  $n$ ,  $\Delta s$  i  $s_v$  nakon prve faze IHRI  
 Figure 7. Hardness of workpieces in the function  $n$ ,  $\Delta s$  and  $s_v$  after the first phase FCFE

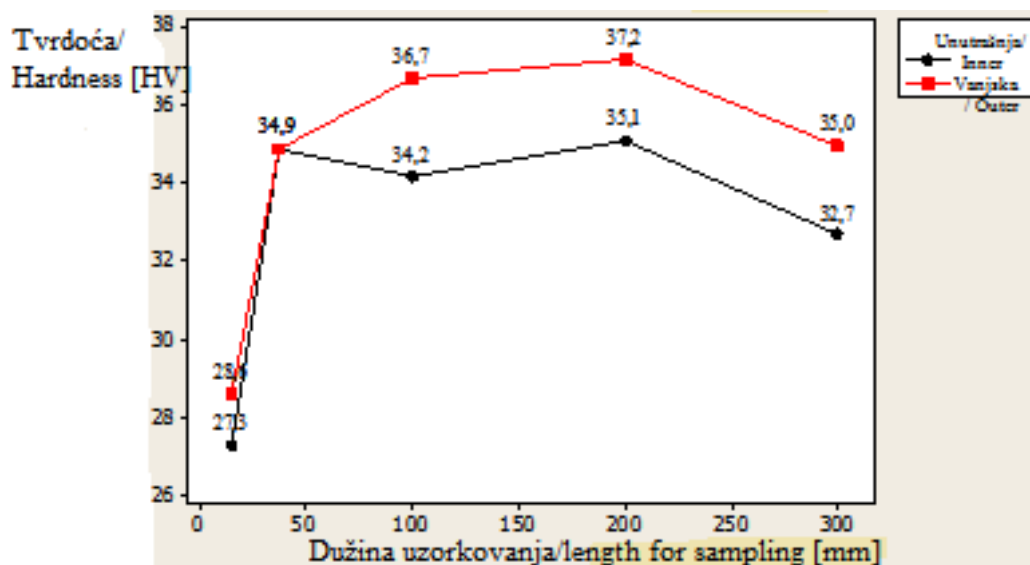
Tabela 3 Rezultati mjerenja tvrdoće po dužini izratka

Table 3 Results of the measurement of hardness along the length of work piece

Uzorak Sample	Tvrdoća HV 1 - Hardness HV 1							
	Mjerna mjesta na unutrašnjoj strain Measurement points on the inner surface				Mjerna mjesta na vanjskoj strain Measurement points on the outer surface			
	1	2	3	HV1 <sub>sr</sub>	1	2	3	HV1 <sub>sr</sub>
0- Dno/Bottom	27,4	27,4	27,0	27,3	28,3	28,3	29,2	28,6
1	35,1	34,5	35,1	34,9	35,1	35,1	35,1	35,1
2	33,9	33,9	34,8	34,2	37,0	37,0	36,3	36,7
3	35,1	35,1	35,1	35,1	37,0	37,0	37,6	37,2
4	32,7	32,7	32,7	32,7	35,1	34,8	35,1	35,0



Slika 8. Položaj mjernih mjesta za mjerenje tvrdoće po dužini izradaka  
Figure 8. Location of measurement points for measuring the hardness lengthwise of workpieces



Slika 9. Promjena tvrdoće po dužini izratka  
Figure 9. Change of hardness along the length of the workpiece

Navedeni zaključak ukazuje na *nehomogenost deformacije po presjeku komada*, tj. na nehomogeno tečenje materijala. Nehomogeno tečenje materijala može prouzrokovati pojavu ljuspi, prevaljanosti, pa čak i mikropukotina na površini [6]. Pojava ljuspičenja i odvajanje sitnih čestica na površini izradaka po cijeloj dužini izradaka izuzev na 30-40 mm dužine od početka zahvata rolnica, potvrđena je i kod provođenja vlastitog eksperimenta.

This conclusion indicates the *inhomogeneity of deformation in cross-section of work pieces*, i.e. the inhomogeneous material flow. Inhomogeneous material flow can cause the appearance of flakes, over-rolling and even microcracks on the surface [6]. The appearance of flakes and separation of fine particles on the surface of work pieces along the entire length of work pieces except on the first 30-40 mm from the starting point of procedure, has been confirmed by own experiment.

Slika 10. prikazuje pojavu ljuštenja Al 99,5 pri oblikovanju svih eksperimentalnih uzoraka.

Generalno se, sa aspekta ovog tehnološkog postupka oblikovanja može konstatirati da se najviše vrijednosti mehaničkih karakteristika, zbog tečenja metala u aksijalnom i tangencijalnom pravcu, dobijaju na strani do rolni, dok je jačina materijala na unutrašnjem sloju - do trna manja.



*Slika 10. Odvajanje sitnih čestica od izradaka iz Al 99,5 pri IHRI*  
*Slika 10. Separation of small particles of workpieces from Al 99.5 during the FCFF*

#### 4. ZAKLJUČAK

Tehnologijom IHRI uz adekvatne geometrijske karakteristike alata (prečnik, radijus, napadni ugao, radijalno i aksijalno podešavanje i dr.), tehnološke (n i s) i druge procesne parametre (pritisak rolnica, sredstvo za hlađenje i podmazivanje i sl.), te ostvarene stepene deformacije tokom oblikovanja u rasponu 51 do 58 % efikasno se mogu oblikovati osnosimetrični izradci zadovoljavajuće tačnosti oblika, dimenzija, kvaliteta (glatkosti) unutrašnje i vanjske površine izratka i sa poboljšanim čvrstoćnim karakteristikama u odnosu na materijal priprema. Iako su efekti ojačavanja kroz povećanje tvrdoće za Al 99,5 koji su identificirani u ovom radu dosta manji u odnosu na oblikovanje različitih vrsta čelika i legura obojenih metala na isti način ipak su, s obzirom na druge pozitivne aspekte primjene aluminijuma oni jako značajni.

Nivo povećanja tvrdoće na primjeru oblikovanja cjevastih izradaka od Al 99,5 u ovom radu se kreće u rasponu 2 do 10 % što zajedno sa porastom zatezne čvrstoće može značajno povećati čvrstoćna svojstva rotaciono simetričnih izradaka. Time se postiže efekat ojačavanja tehnološkim postupkom oblikovanja, a ne nekom naknadnom termičkom ili drugom vrstom obrade.

Figure 10 shows the appearance of flakes on Al 99,5 by the forming of all experimental samples.

Generally, in terms of the technological process of forming can be concluded that the highest values of mechanical properties, due to the flow of metal in the axial and tangential direction, are obtained on the side of the roll, while the strength of the material in the inner layer (mandrel side) is lower.

#### 4. CONCLUSION

Using FCFF technology with adequate geometric characteristics of the tool (diameter, radius, angle of attack, radial and axial adjustment, etc.), technological (n and s) and other process parameters (pressure of rolls, means for cooling and lubrication and so on) and achieved degrees of deformation during the forming in the range 51 to 58%, can be efficiently formed axisymmetric work pieces with satisfactory accuracy in shape, dimensions, the quality (smoothness) and the inner and outer surface of a work piece with improved strength characteristics compared to the preform material. Although the effects of strengthening through the increase of hardness of Al 99,5 identified in this study are much lower compared to the effects by the forming of different types of steel and non-ferrous alloys in the same way, they are, however, very important because of the other positive aspects of the use of aluminum.

The level of increase in hardness in the case of forming of tubular work pieces of Al 99,5 in this study ranges from 2 to 10%, which together with the increase in tensile strength can significantly increase strength properties of rotationally symmetrical work pieces. This allows the effect of strengthening by the technological process of forming itself, and not by an additional thermal or other type of treatment.

Ovo su razlozi primjene navedene tehnologije oblikovanja za izradu dijelova visoke tačnosti, kvaliteta obrađene površine i dobrih čvrstoćnih karakteristika u najzahtjevnijim privrednim granama poput nuklearne, vazduhoplovne i vojne industrije. U tom smislu provedena metodologija i dobijeni rezultati u ovom radu mogu da posluže kao dobra osnova za nastavak istraživanja usmjerenih na proizvodnju uređaja i konstrukcija manje težine, a iste ili povećane čvrstoće primjenom tehnički čistog aluminijuma.

These are the reasons for application of this forming technology for producing parts with high accuracy, high surface quality and good strength characteristics in the most demanding industries such as nuclear, aviation and defense industries. In that sense, the methodology and the results obtained in this study can serve as a good basis for the further research work focused on the production of equipment and constructions of less weight, and the same or increased strength by using technically pure aluminum.

## 5. LITERATURA - REFERENCES

- [1] I. Plančić, M. Čabaravdić, E. Begović, S. Härtel, S. Kleditzsch: *Simulation Of The Heat Distribution By The Forward Cold Flow Forming*, Journal of Trends in the Development of Machinery and Associated Technology Vol. 18, No. 1, 2014, ISSN 2303-4009 (online), p.p. 71-74, 2014.
- [2] S. Ekinovic, H. Đukic, I. Plancic, E. Begovic: *Assessment of the surface topography of Al 99.5% tubular products formed by cold flow forming technology*, Proceedings of the 6<sup>th</sup> Manufacturing Engineering Society International Conference – MESIC Conference 2015 Topic 2 Forming Processes, 127-133, ISBN: 978-84-1568863-1, Barcelona, 22<sup>nd</sup> to 24<sup>th</sup> July 2015.
- [3] I. Plančić, D. Petković, S. Lemeš, H. Bašić: *Research on impact factors influencing roundness of products made of Al 99.5 % formed by flow forming technology*, ANNALS of Faculty Engineering Hunedoara, – International Journal of Engineering, Tome XIII [2015] UNIVERSITY Politehnica Timisoara, Faculty Of Engineering Hunedoara, 5, Revolutiei, 331128, Hunedoara, Romania, <http://annals.fih.upt.ro>
- [4] S. Ekinović, I. Plančić, E. Begović, H. Đukić, B. Muminović: *Očvršćavanje materijala pri oblikovanju cjevastih izradaka iz Al 99,5 % kod istosmjernog hladnog rotacionog istiskivanja*, X Naučno/stručni simpozij sa međunarodnim učešćem, "Metalni i nemetalni materijali" Bugojno, BiH, 21-22. april 2014.
- [5] V. Pavelić: *Specifične tehnologije u proizvodnji oružja*, Novi Travnik-Zagreb, MORH-TP-4/95 1995.
- [6] M. Nikačević, Lj. Radović: *Rotaciono valjanje: specifična tehnologija za izradu delova raketa*, - kumulativna naučnotehnička informacija-, Vojnotehnički institut - Beograd, Naučno tehničke informacije, ISSN 1820-3418, Volume XLIV Broj 2, 2010.
- [7] C.C. Wong, T.A. Dean, J. Lin: *Incremental forming of solid cylindrical components using flow forming principles*, Journal of Materials Processing Technology 153–154, 60–66, 2004.

### Corresponding author:

**Plančić Ibrahim**

**University of Zenica**

**Faculty of Mechanical Engineering**

**Email: [iplancic@mf.unze.ba](mailto:iplancic@mf.unze.ba)**

**Phone: +387 32 449 120**