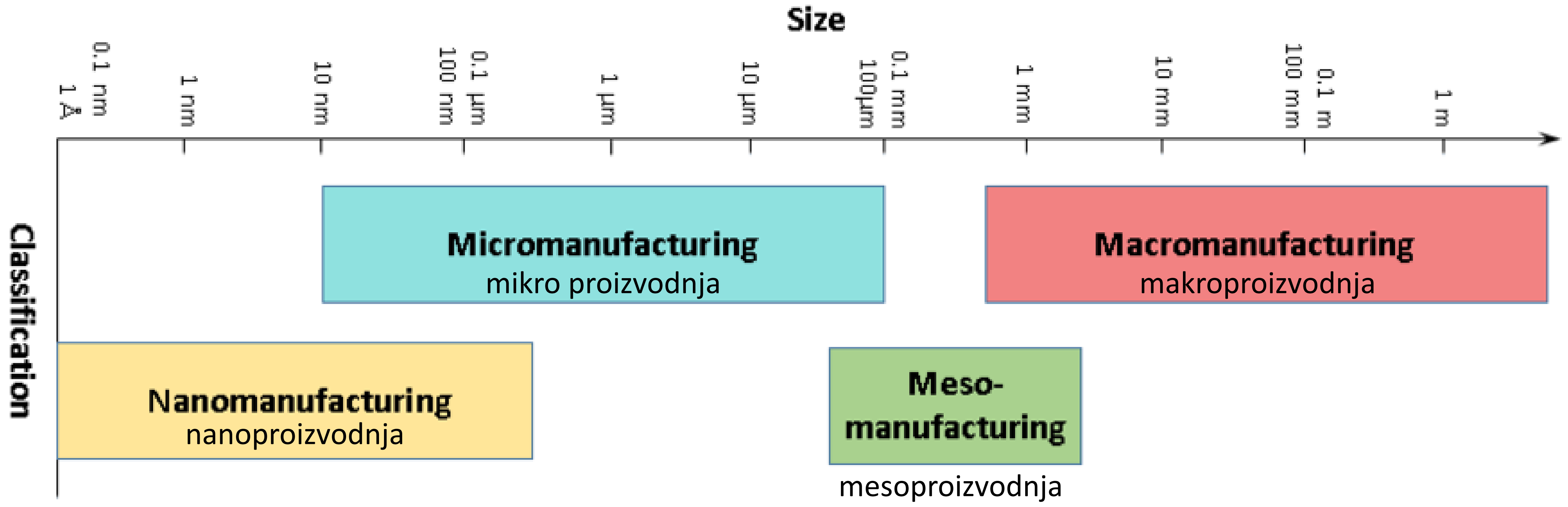
UNIVERZITET U NOVOM SADU - FAKULTET TEHNIČKIH NAUKA

MIKRO DEFORMISANJE

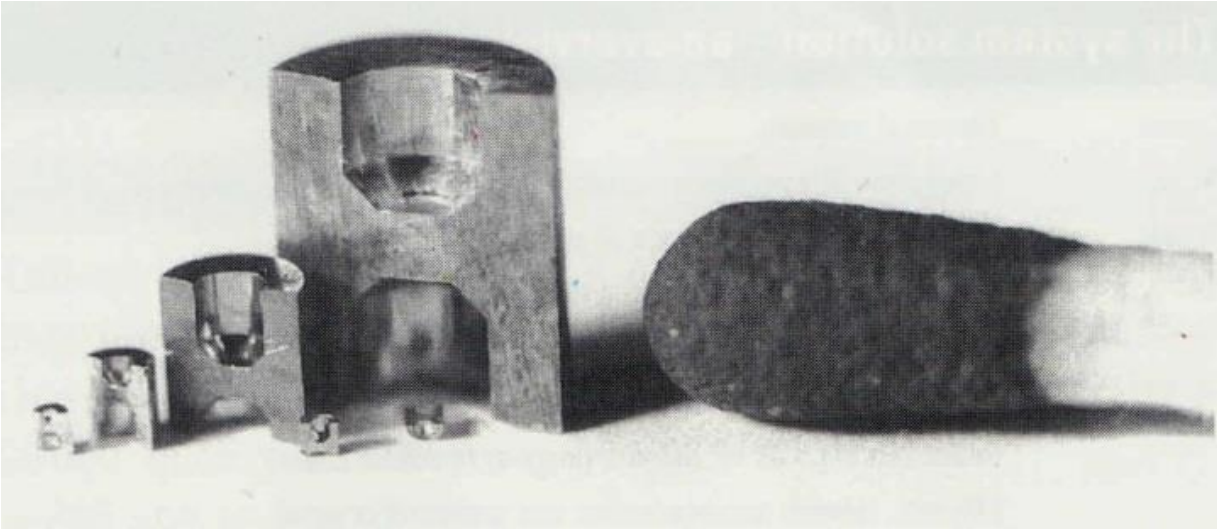
- Napredne metode tehnologije plastičnog deformisanja -

doc. dr Marko Vilotić

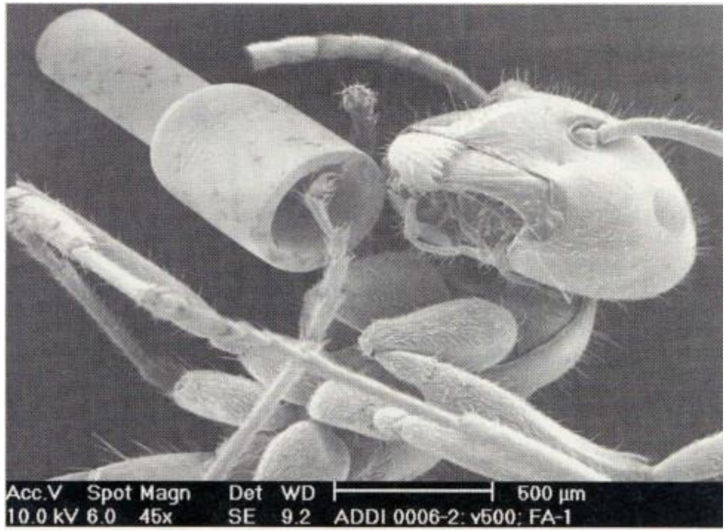


Klasifikacija proizvodnje

Mikro deformisanje je proces plastičnog deformisanja metala pri kojem se dobija obradak visokih mehaničkih osobina, čije su maksimalne dimenzije reda veličine ≤ od 0,1 mm.



Deo dobijen dvostrukim mikro suprotnosmernim istiskivanjem



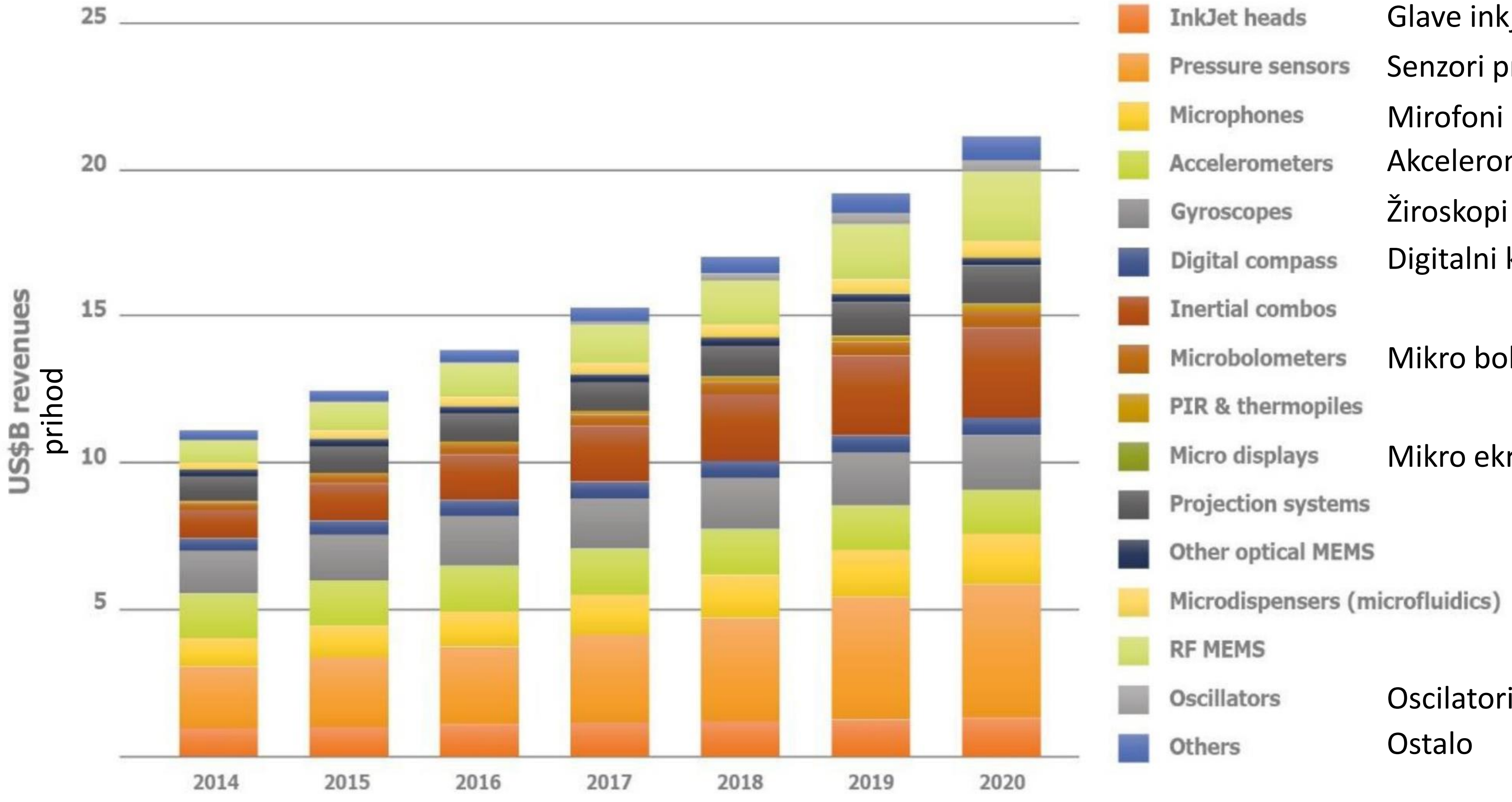
Deo dobijen kombinovanim mikro istiskivanjem u poređenju sa glavom mrava

MEMS MARKET FORECAST: 2014 – 2020 VALUE (IN B$)

Prognoza tržišta **M**ikro**E**lektro**M**ehaničkih **S**istema 2014-2020 (u milijardama američkih dolara)

(Source: Status of the MEMS Industry, Yole Développement, May 2015)

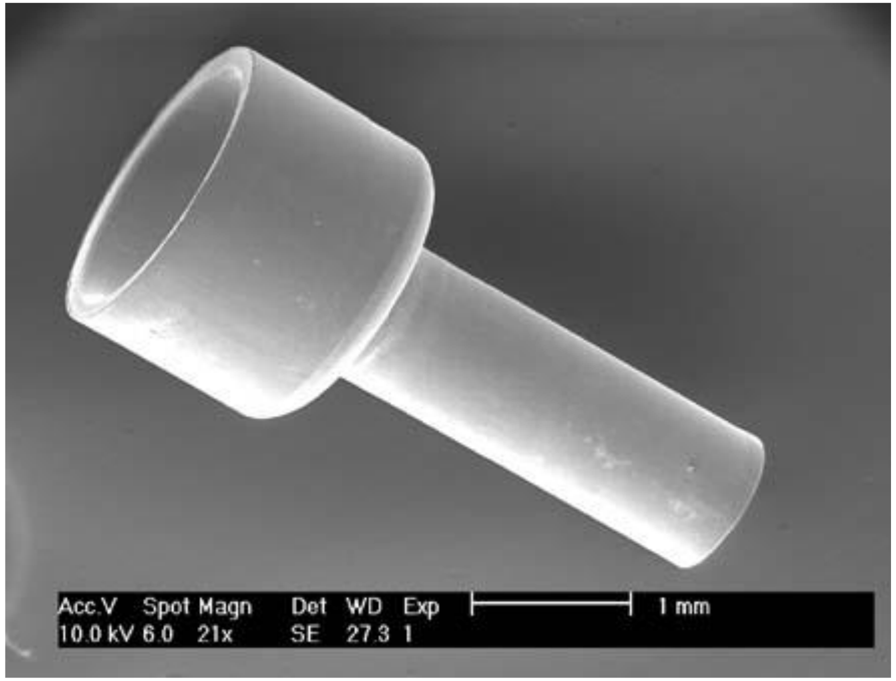
In 2014, the MEMS sector represented an $11.1B business for Si-based devices…
(Source: Yole Développement)



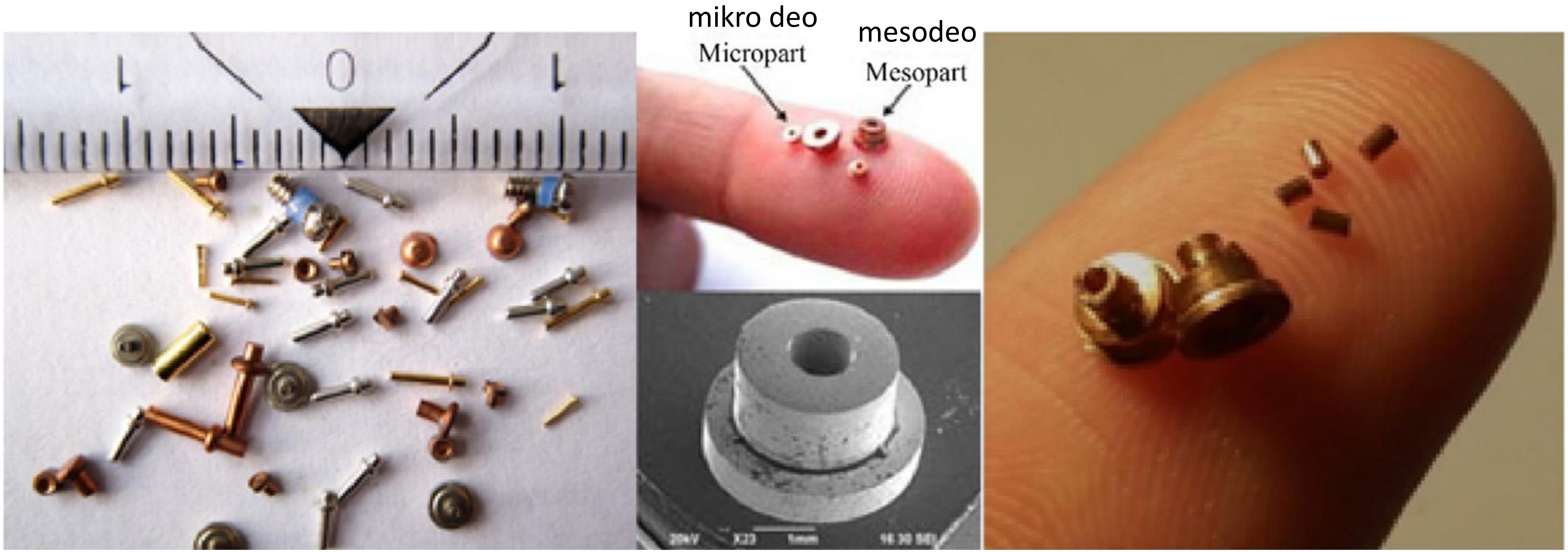
Glave inkjet štampača
Senzori pritiska
Mirofoni
Akcelerometar
Žiroskopi
Digitalni kompas
Mikro bolometar
Mikro ekrani
Oscilatori
Ostalo

Svi elektronski uređaji poseduju mehaničke delove poput igala, opruga, zavrtnjeva i dr.

Hard disk kapaciteta 1 TB

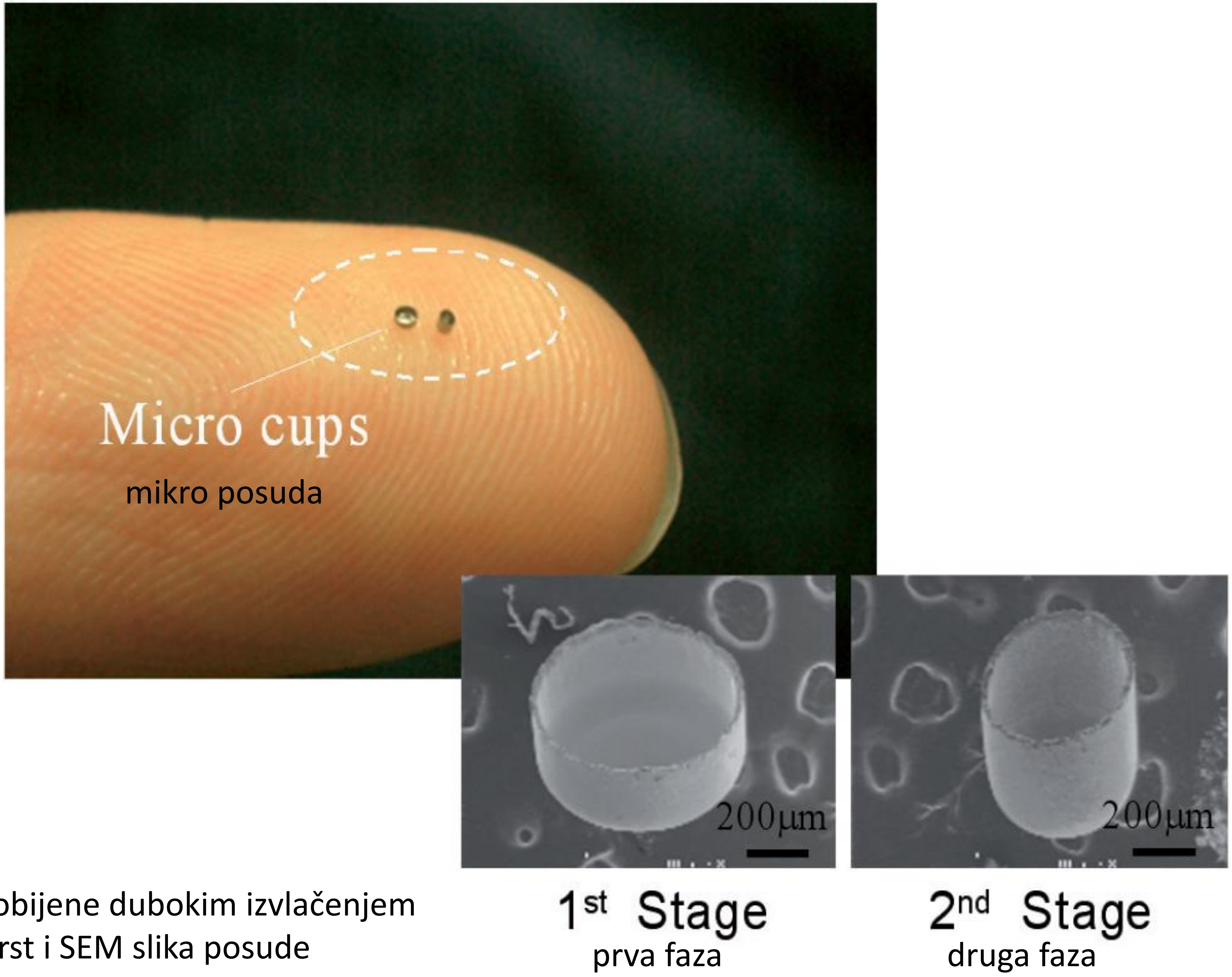


Vratilo mikro motora proizvedeno u 18 faza



Delovi dobijeni mikro deformisanjem

“Elektronske komponente i uređaji sadrže mehaničke delove kao što su igle konektora, minijaturne vijke, kontaktne opruge, olovne okvire i utičnice integrisanog kola”



Slika 6. Izgled posude dobijene dubokim izvlačenjem postavljene na prst i SEM slika posude

Figure 6. Appearance of drawn microcups on a forefinger and its SEM image

Mikro deformisanje je tehnologija veoma pogodna za izradu minijaturnih delova od metala pogotovo za slučaj velikih serija. (elektronika , mehanika, fizika, hemija, nauka o materijalnima, proizvodne tehnologije)

Prednosti u odnosu na druge proizvodne tehnologije:

- ušteda materijala, energije, visoka proizvodnost
- odlične mehaničke osobine izrađenih delova
- mogućnost ugradnje bez potrebe za naknadnom obradom
- ekologija

Tehnologija plastičnog deformisanja po svojim karakteristikama i mogućnostima veoma je pogodna za masovnu izradu mikro delova.

Razlozi što se takvi delovi još uvek rade pretežno metodama **skidanjem strugotine** leže u **nedostatku potrebnih teoretskih znanja u oblasti mikro deformisanja**.

Tek odnedavno intenzivno se radi na teoretski-eksperimentalnim istraživanjima, a dosadašnji rezultati su veoma ohrabrujući.

Microforming

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[1] Chair of Manufacturing Technology (LFT), University of Erlangen-Nuremberg, Germany
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*“Despite of this, there are only a **few typical products** known, justifying this development by an extremely successful dissemination, as e.g. inkjet printheads and airbag systems. The real breakthrough of micro system technology is still missing [4,5]. One of the reasons seems to be the fact that technologies, well known and established in the macroworld, cannot be simply scaled down to be applied on the microscale.”*

“Uprkos tome, trenutno postoji samo par proizvoda koji koriste prednosti mikro deformisanja, poput glave inkdžet štampača i airbag-ova. Značajan prodor tehnologije mikro sistema i dalje izostaje. Jedan od razloga može biti i taj što tehnologije koje su standard u makro svetu ne mogu biti samo umanjene za primenu u mikro svetu.”

Jedan od osnovnih problema u analizi i rešavanju konkretnih zadataka u oblasti mikro deformisanja jeste što se **teorijsko-praktična** saznanja koja postoje **u oblasti "makro" deformisanja ne mogu** jednostavno primenom teorije sličnosti **primeniti i u mikro deformisanju**.

Razlog je što se određeni fenomeni koji se pojavljuju pri plastičnom deformisanju **ne ponašaju prema toj teoriji**. Tu se misli, pre svega, na **ponašanje materijala** (napon tečenja, anizotropija, deformabilnost) i **procese trenja** (odnosi u kontaktu alat – materijal). Ovaj problemski kompleks naziva se jednim imenom "**efekat veličine**" (eng. size effect).

Parametari koji zavise od veličine

Size related parameters

- Workpiece size vel. obratka
- Grain size vel. kristalnog zrna
- Feature size vel. svojstva/geometrije
- Asperity size vel. jedne čestice/jedinice hrapavosti

Ponašanje/karakteristike koje zavise od veličine

Size effect related behaviors

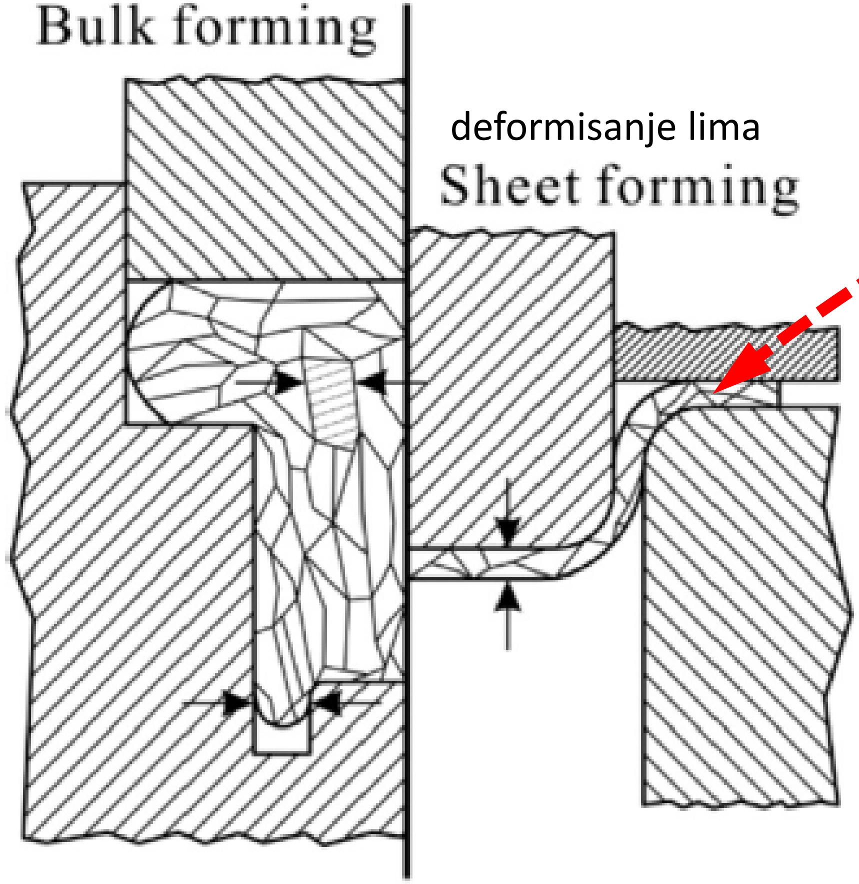
- Flow stress napon tečenja
- Fracture behavior ponašanje pri prelomu materijala
- Flow behavior ponašanje pri tečenju materijala
- Elastic recovery elastično vraćanje
- Friction trenje
- Surface roughening povećavanje hrapavosti površine

zapreminsko deformisanje

Bulk forming

deformisanje lima

Sheet forming



- kristalna zrna u opsegu 10 do 100 μm
- anizotropija

Process performances povećavanje hrapavosti površine

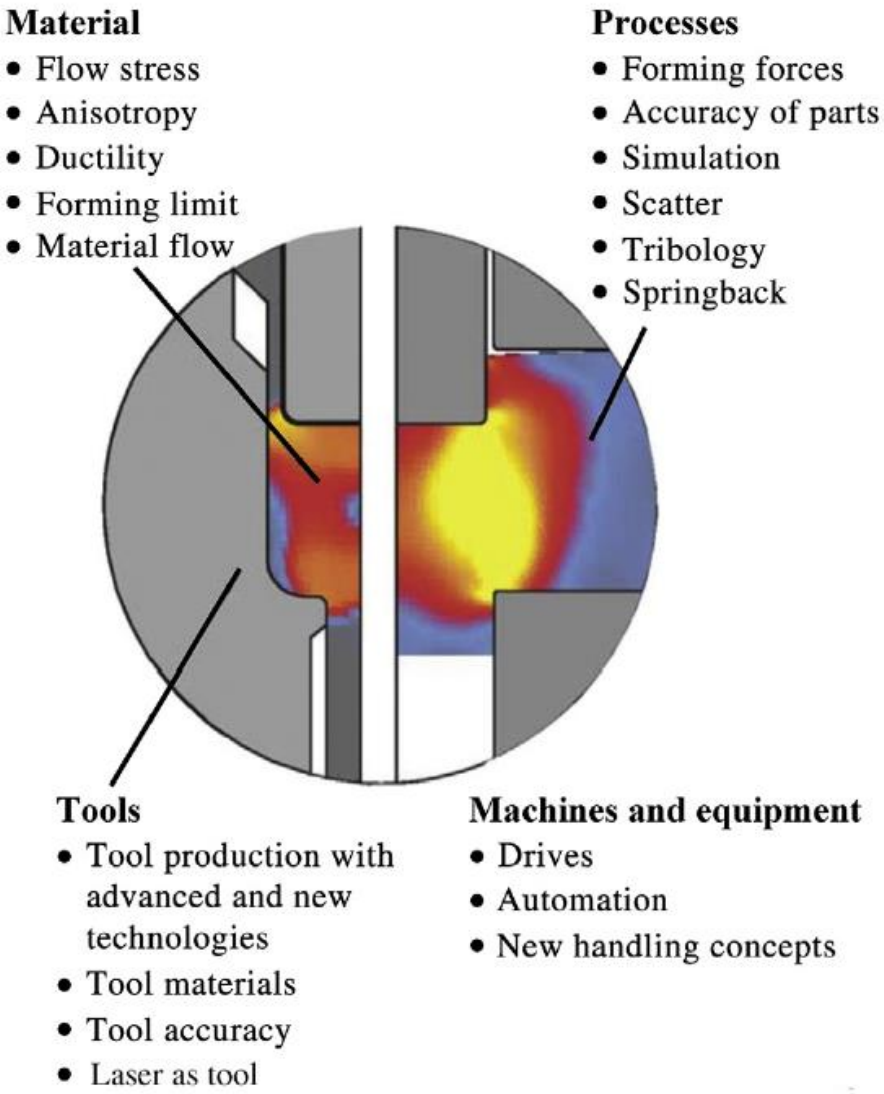
- Deformation load deformaciono opterećenje
- Defects (i.e. Underfilling, earing, cracking, etc.) Defekti (nepotpuno popunjavanje gravure, gužvanje, pucanje)
- Dimensional accuracy Tačnost dimenzija
- Formed part properties osobine delova dobijenih deformisanjem
- Scattering rasipanje
- Surface finish kvalitet površine

Problemi u mikro deformisanju vezani za "efekat veličine"

Sistem za mikrodeformisanje

A microforming system can be divided into four primary groups including material, processes, tools, and machines/equipment [6], as shown in Fig. 1.2.

Material. When a forming process is scaled down to microscale, the material to be deformed cannot be considered as a continuum due to the large share of volume occupied by an individual grain. Different from the conventional forming process, only limited grains are located in the forming area during microforming. Fig. 1.3 shows an example of the difference of a material between macroscale and microscale compressions. Grain and grain boundaries, which may have less impact on the material's mechanical behavior in macroscale compression, will have more significant impact on the mechanical behavior with the scaling down of dimensions. With miniaturization, the characteristics of an individual grain, including its size, shape, orientation, and position, and as well as other microstructural characteristics including grain boundaries, precipitations, and other phase constituents will have a close relevance to the material's mechanical conversion processes. The type of the material usable for microforming process is still



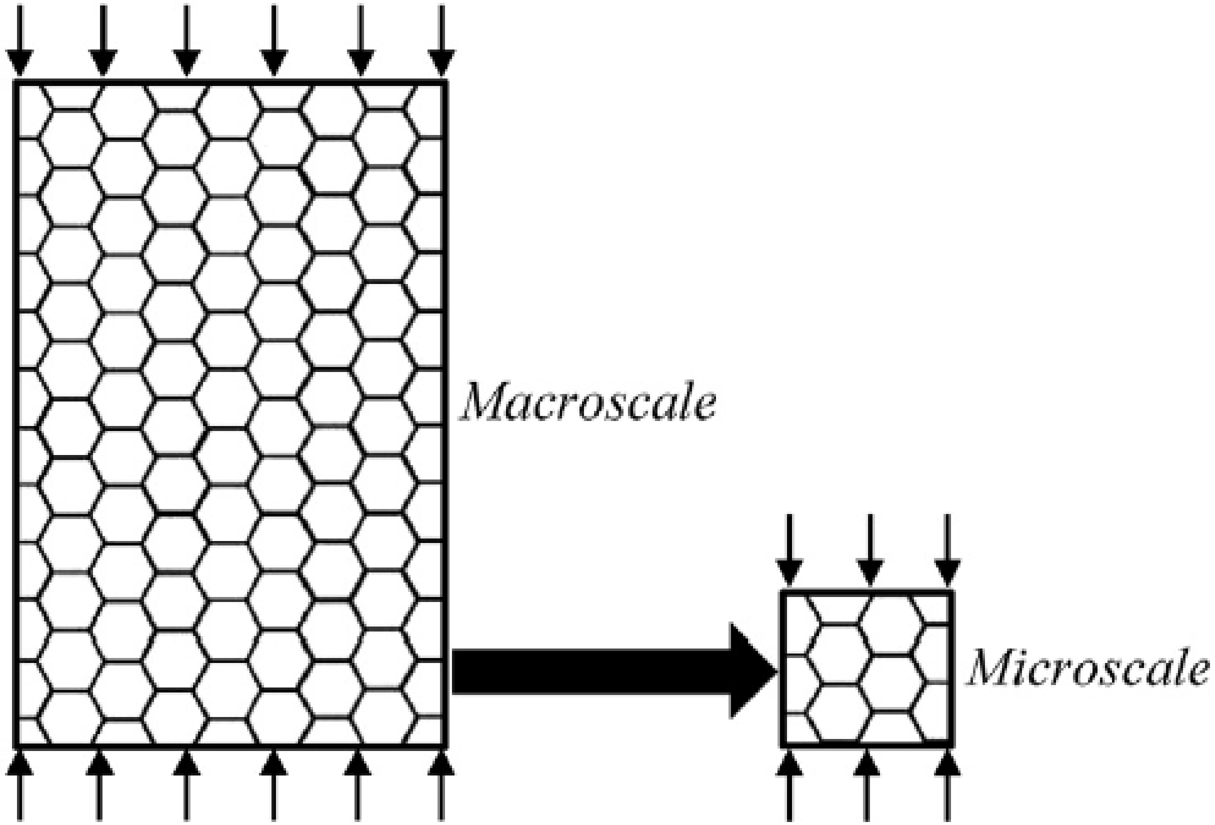
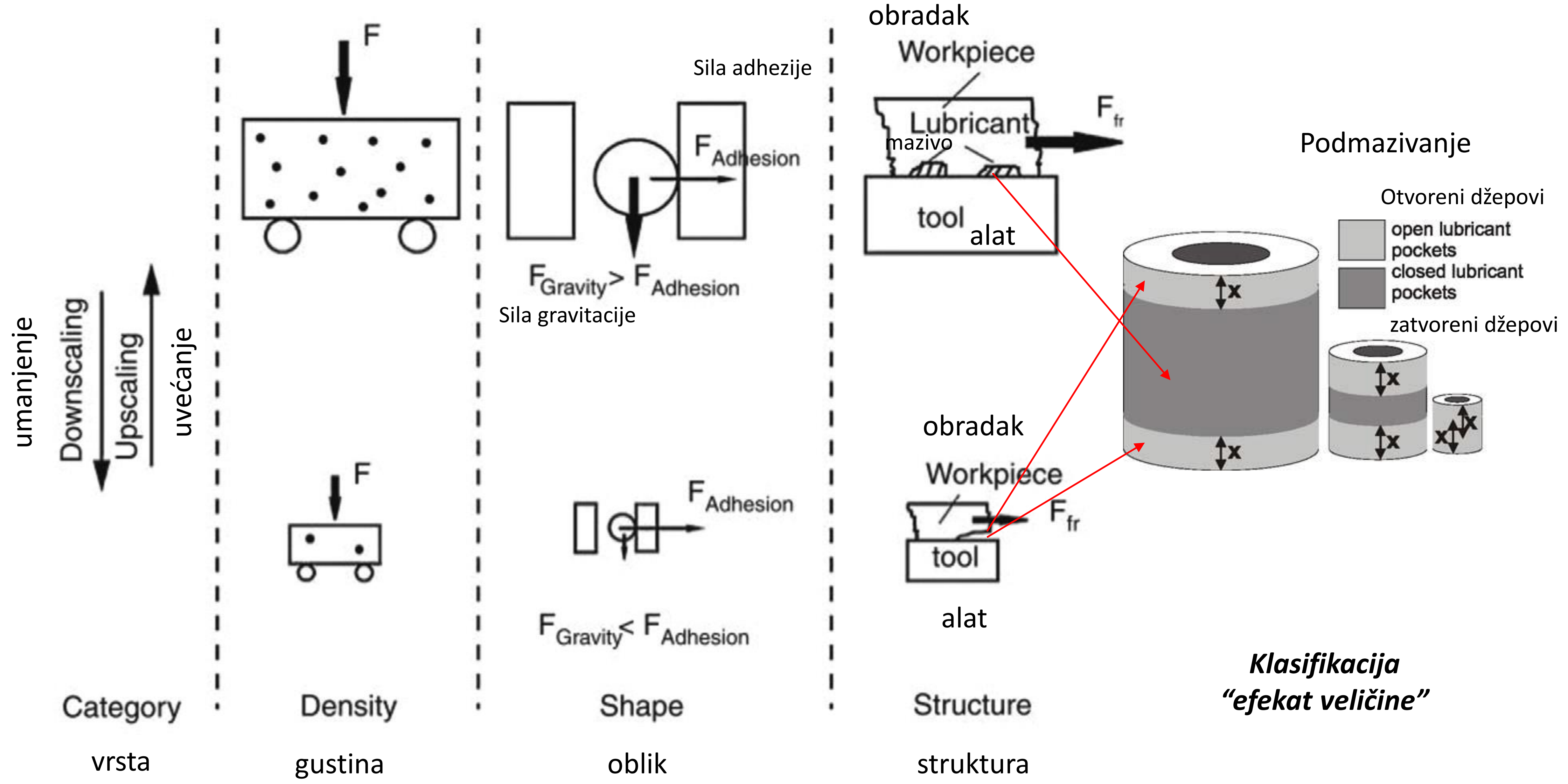


FIGURE 1.3 Schematic illustration of the difference between macroscale and microscale compressions.

Processes. In the conventional metal forming, appropriate design of forming processes is essential for economical and reliable manufacturing of high-quality products. At present, it is possible to form complex-shaped parts with different geometrical features by combining optimized forming processes with appropriate tools and machines/equipment in large-scale production in industry. However, the conventional metal forming methods and strategies are not applicable to the reliable forming processes in microscale. Microforming largely uses nonconventional processes or scaling down or modifying the conventional processes, as appropriate, to fully address the issues related to the forming in the micro world. The microforming processes are, of course, strongly coupled with the material to be formed. Further, other factors, including forming forces, tribology, springback, scatter of the results, and accuracy of formed parts, should be considered in the design of microforming processes. Also, due to the differences between the conventional forming and microforming, simulation models should be improved by addressing as many issues as possible involved in the modeling of microforming processes. An optimized design of microforming processes is the premise of successful manufacturing of high-quality micro products.

Tools. Forming tools are core parts of the metal forming processes. As the size of a component is reduced to microscale, the demands for precise tools with high surface quality and close tolerance are increased. Unlike the manufacturing of tools for the conventional metal forming, the manufacturing processes of microforming tools are quite complex due to the difficulties in the creation of very small contour with high accuracy, which is, however, necessary for microforming operations. Especially, the tools with complex inner shapes, e.g., extrusion dies, are difficult to manufacture because close tolerance and adequate surface quality are simultaneously required [7]. In order to overcome these difficulties, development of advanced and new manufacturing technologies of microforming tools becomes essential. In the manufacturing of microforming tools, two main factors including tool materials and tool accuracy must be taken into account. The materials for tools should have superior performance so that the service life of tools can be prolonged. A guarantee of the tool accuracy is essential for the manufacturing of high precision micro products in the following microformig process. In addition, flexibility of tools is also a very important factor that should be considered in the development of tooling system in order to achieve efficient microforming processes. With the ongoing trend toward miniaturization, forming of micro products with more complex contours and shapes will become more common, and therefore advanced technologies involving innovative manufacturing methods of high-quality microforming tools are always expected.

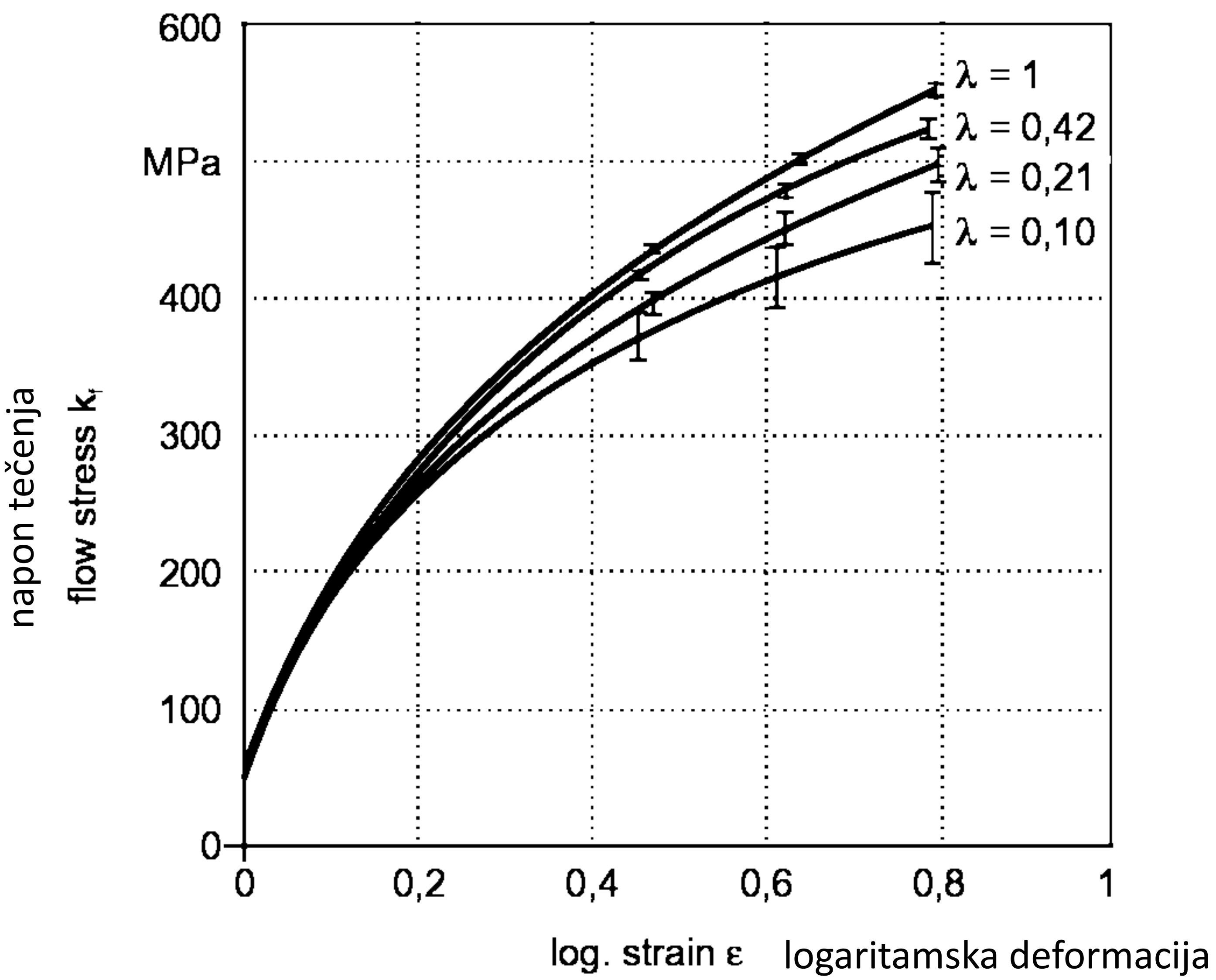
Machines and equipment. Many problems occurred in microforming process are associated with machines and equipment with miniaturization. In the conventional forming processes, the clearance or backlash between machine parts can be negligible, which, however, may have a detrimental influence on the accuracy of the produced products in the range of a few 100 μm [6,7]. Therefore, it is necessary to develop machines and equipment that are particularly suitable for the microforming processes. Currently, the main trend in the development of machines and equipment for microforming is to reduce their scales which could, in turn, result in reduced energy consumption, pollution, and equipment cost due to the use of fewer materials for the miniaturized forming system. Also, as the scales of machines and equipment are reduced, the weight of the mechanical parts will be markedly reduced. As a result, the speed of the forming tools and the rate of production could be increased. However, as the size of micro part is very small and the part weight is quite low as compared with adhesion forces, appropriate strategies should be developed to separate the part from a gripper when handling. Driving, automation control, and measurement systems should also be considered in the development of machines and equipment in order to achieve a high productivity, ensure the product quality and enable an easy



Klasifikacija
"efekat veličine"

U tehnologiji obrade metala deformisanjem parametri koji najpriklladnije opisuju ponašanje materijala jesu **napon tečenja** i **kriva tečenja**. Oni utiču na proces deformisanja, opterećenje alata, lokalno tečenje materijala i popunjavanje gravure alata.

Umanjenje standardnih testova za određivanje krive tečenja ukazuje da je prisutan “efekat veličine”: sa smanjenjem dimenzija uzorka najčešće se javlja i sniženje krive tečenja.



Opadanje krive tečenja

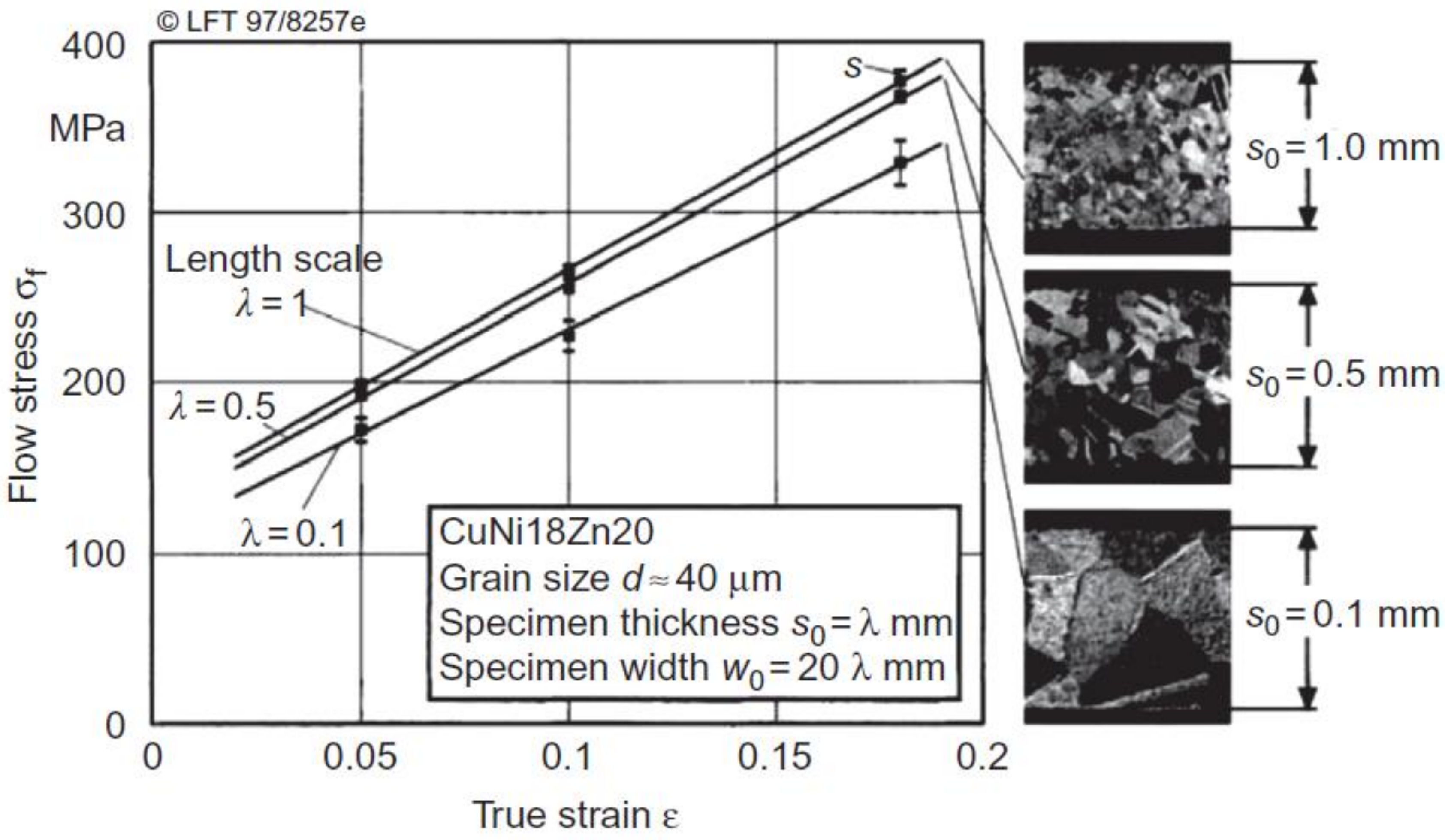
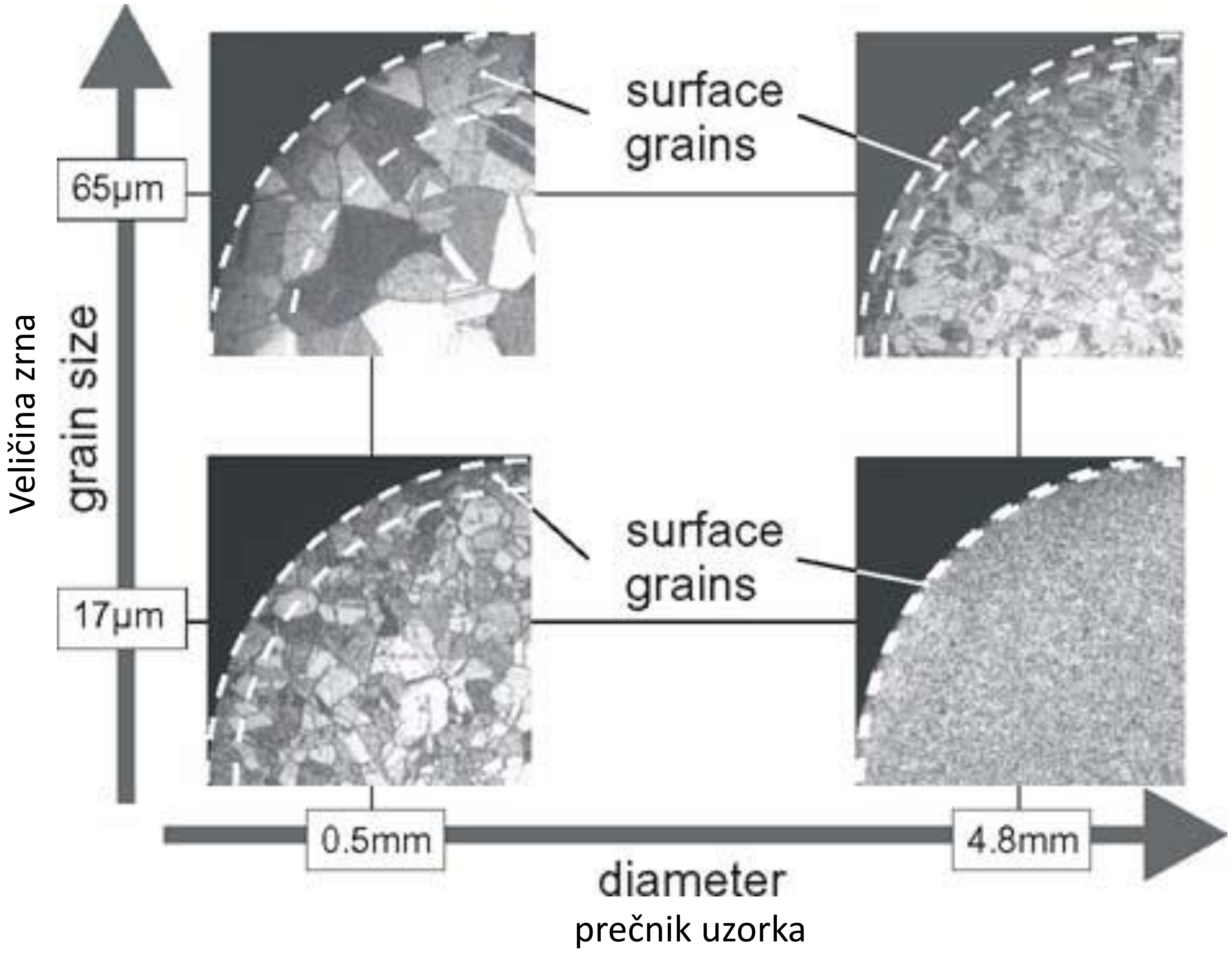


FIGURE 2.2 Flow curves of CuNi18Zn20 for different values of the length scale λ [4].



Povećanje procenta kristalnih zrna na slobodnoj površini

Tokom procesa deformisanja dislokacije se kreću kroz kristalno zrno i zaustavljaju se na granicama zrna, ali ne i na slobodnoj površini uzorka (zrna).

To dovodi do slabijeg ojačavanja i manjeg otpora deformisanju na površini uzorka.

Sa smanjenjem dimenzija uzorka, procenat zrna na površini uzorka se povećava, što vodi do niže krive tečenja.

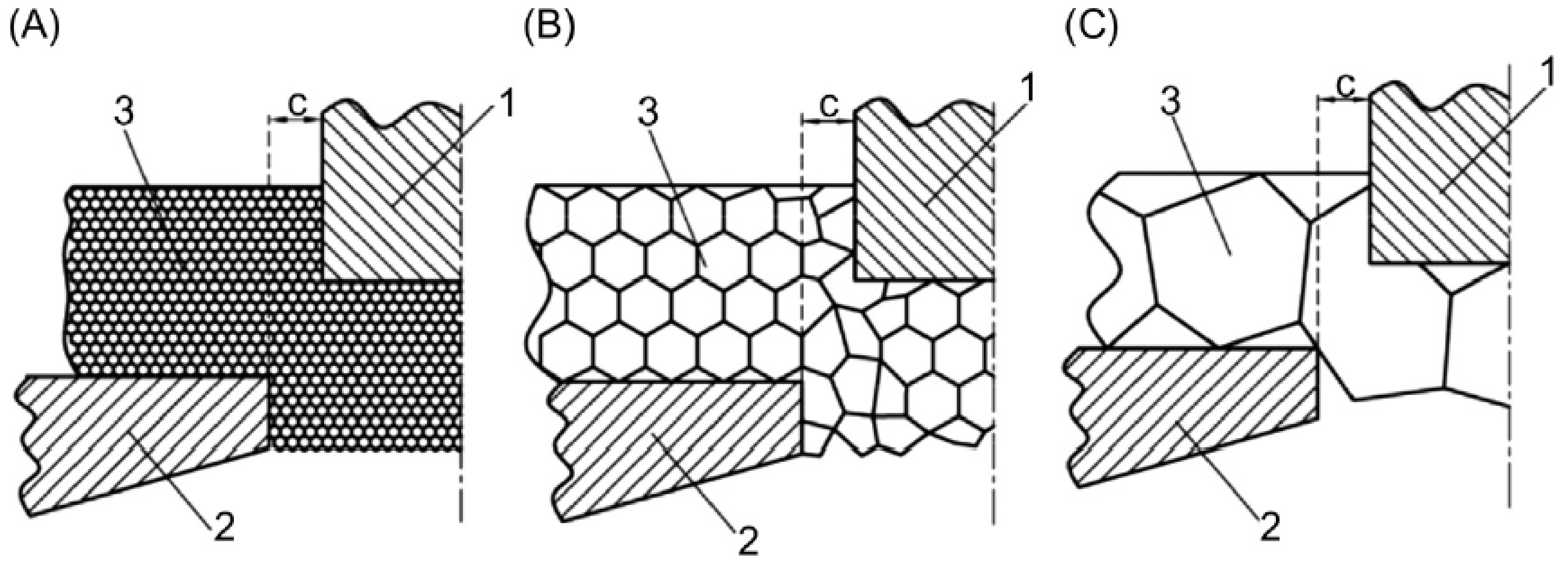


FIGURE 2.6 Size effects model of grain size in micro blanking: (A) $C/D > 1$, (B) $C/D \approx 1$, and (C) $C/D < 1$. 1—micro punch, 2—micro die, and 3—metal foil [11].

In the micro tensile tests of brass foils with different thicknesses and two cases of grain sizes, Li et al. [10] found that the samples with fine grains exhibited a higher flow stress than those with coarse grains, as shown in Fig. 2.5. In the figure, the numbers represent foil thickness while "Fine" and "Coarse" refer to the fine- and coarse-grained samples, respectively. They also found that the elongation of foils decreased with decreasing the foil thickness, and fracture occurred along the grain boundary in the thickness direction when the samples were subjected to tensile loads in the plane of the sheet. For thinner foils, these fractures were penetrated across the entire foil thickness, but for thicker foils the microcracks were stopped by inner grains, resulting in longer elongation. These results indicate that higher strain gradient and more inhomogeneous deformation have occurred in thinner foils than those in thicker foils. The deformation behavior in micro blanking is related not only to the blanking clearance, but also to the grain size of metal foil. The ratio of blanking clearance (C) to grain size (D) is one of the main factors affecting micro deformation behavior in micro blanking, and the ultimate shearing strength will reach an extreme value when C/D is equal to one [11]. A model for explaining size effects in micro blanking is illustrated in Fig. 2.6 [11].

Problem sa trenjem/podmazivanjem

- mali broj džepova koji će zadržati sredstvo za podmazivanje
- zagađenost/prljanje gotovih delova malih dimenzija
- sredstvo ne može da prodre u mikro-procepe/zazore
- nestabilan proces deformisanja – neravnomerna raspodela sredstava za podmazivanje – neravnomerno trenje

Izbegavanje korišćenja sredstava za podmazivanje u mikro deformisanju

Primena prevlaka (CVD ili PVD) za smanjenje koef. trenja.

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Diamond and Related Materials 12 (2003) 757–761

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Proizvodnja dijamantskih alata za mikro deformisanje

Fabrication of diamond dies for microforming

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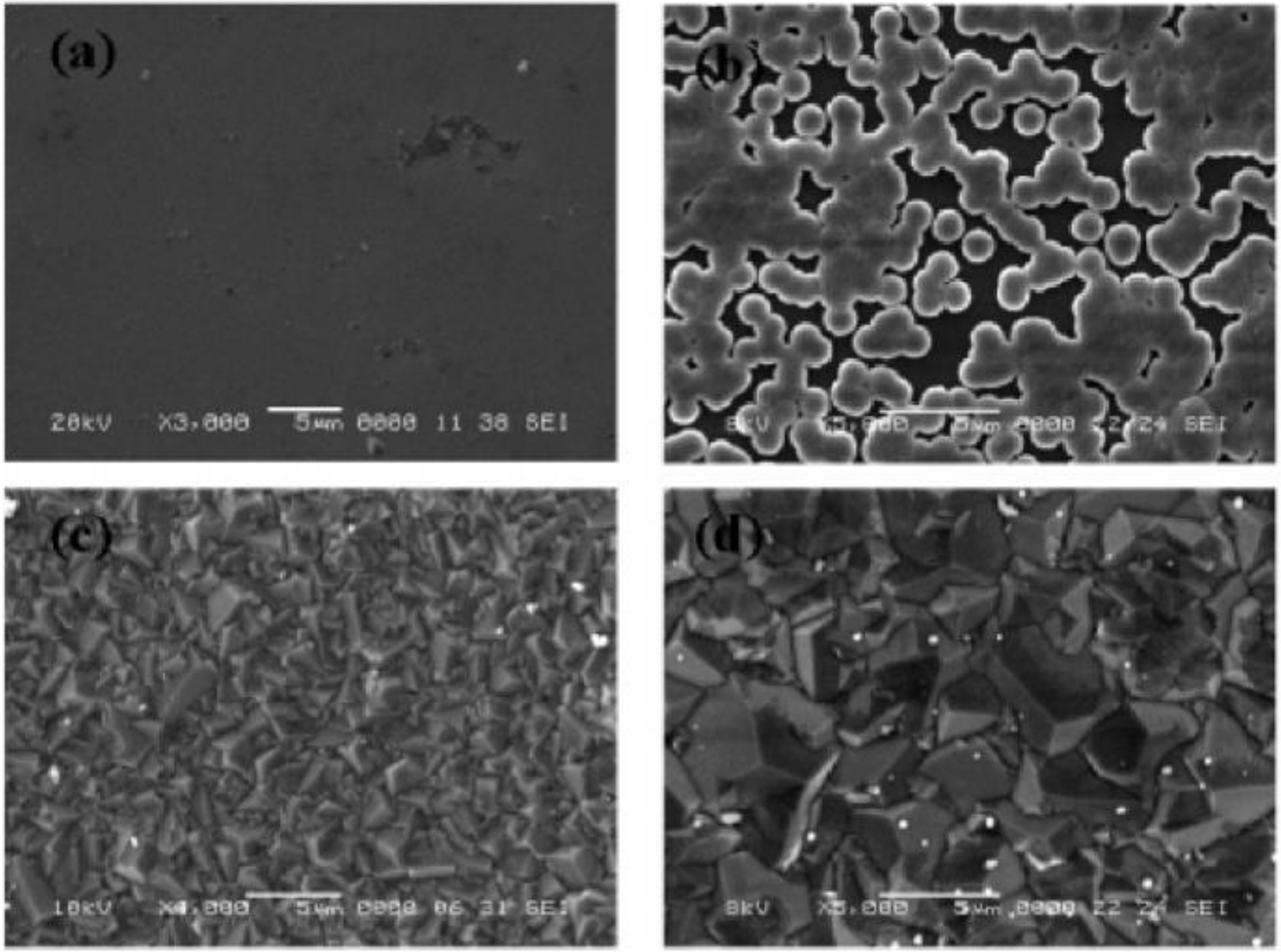


(a) početno stanje

Fig. 1. SEM micrographs of diamond films deposited for various deposition times: (a) as-seeded; (b) 5; (c) 10; and (d) 30 h.

SEM slika dijamantskih filmova nanesenih u različitim vremenskim intervalima

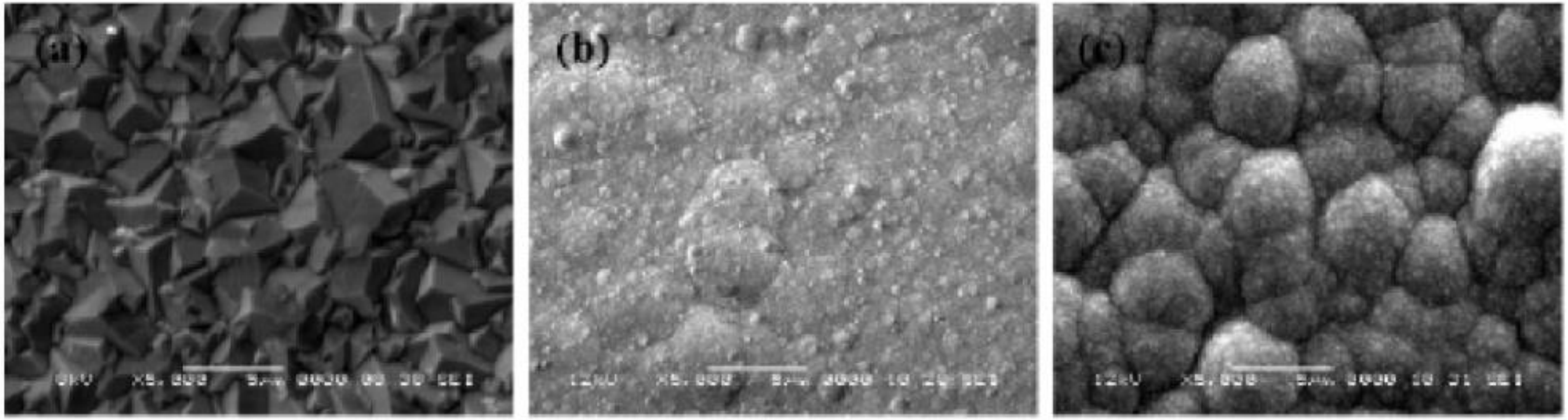


Fig. 3. SEM micrographs of diamond films deposited at various methane concentrations: (a) 1; (b) 2; and (c) 3%.

SEM slika dijamantskih filmova sa različitom koncetracijom metana

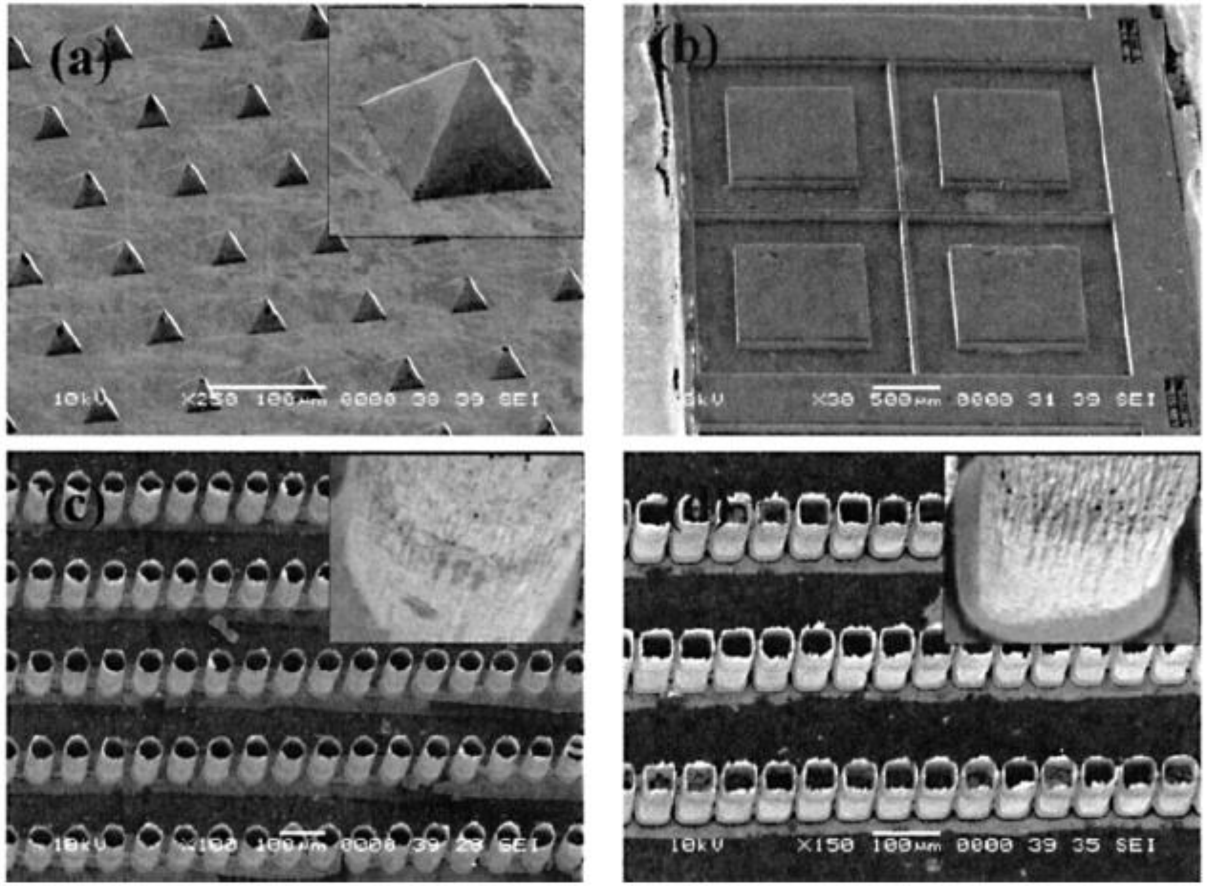
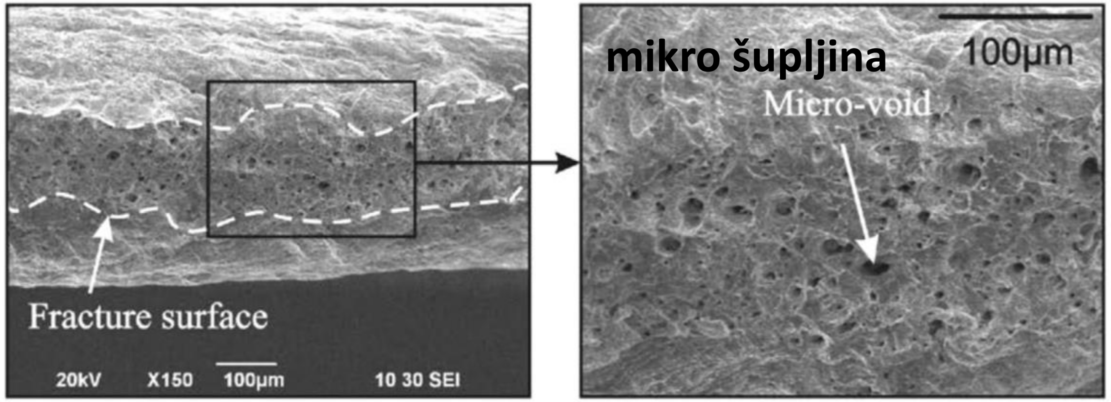
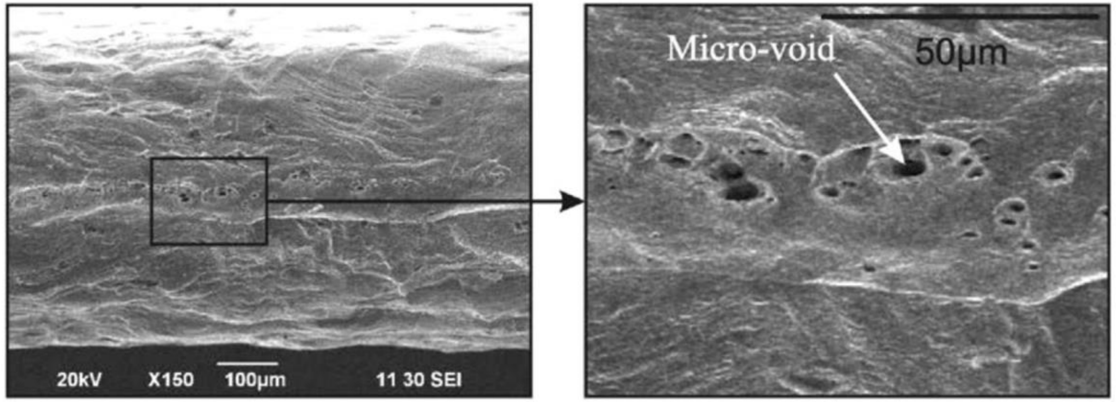


Fig. 6. SEM micrographs of the fabricated diamond dies: (a) pyramids; (b) square poles and crossed wall; (c) round; and (d) square hollow poles.

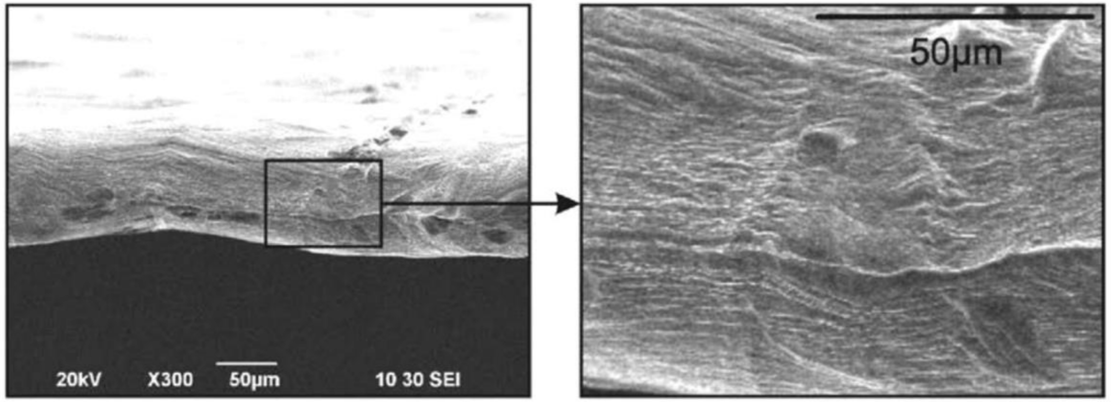
SEM slika proizvedenih dijamantskih alata (a) piramida, (b) kvadratni stubi ukršteni zid, (c) kružni i (d) kvadratni šuplji stubovi



(a) t=600µm, d=36µm, $N=t/d$=16.7

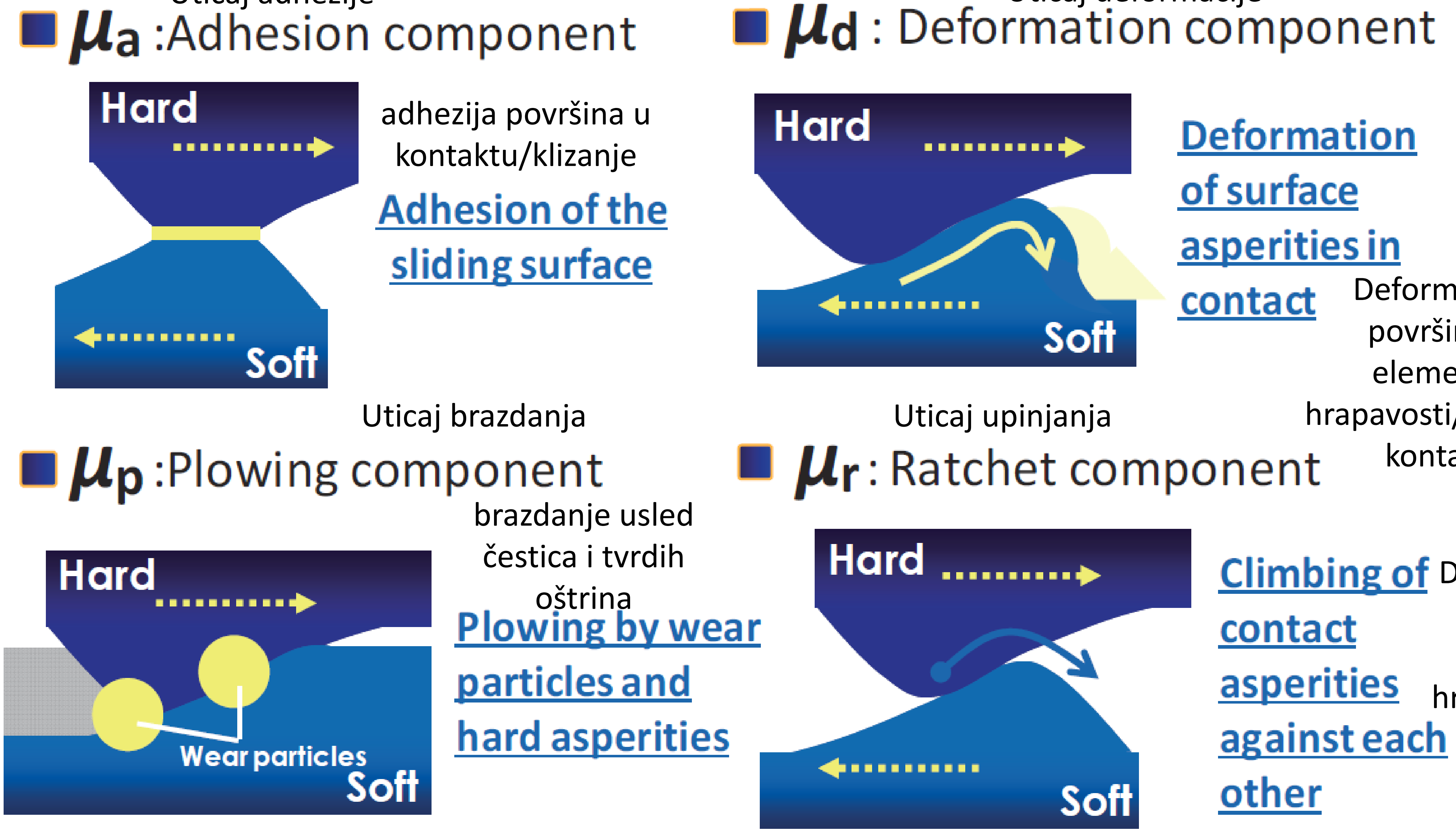


(b) t=600µm, d=286µm, $N=t/d$=2.1



(c) t=100µm, d=83µm, $N=t/d$=1.2

Uticaj odnosa debljine materijala i veličine kristalnog zrna na količinu mikro jamica



Uticaj adhezije

adhezija površina u kontaktu/klizanje

Uticaj deformacije

Deformisanje površinskih elemenata hrapavosti/oštrine u kontaktu

Uticaj brazdanja

brazdanje usled čestica i tvrdih oština

Uticaj upinjanja

Deformisanje površinskih elemenata hrapavosti/oštrine u kontaktu

Figure 1. Contributions of the four different components of friction coefficient under dry friction

Doprinos četiri različita elementa koeficijenta trenja pri suvom trenju

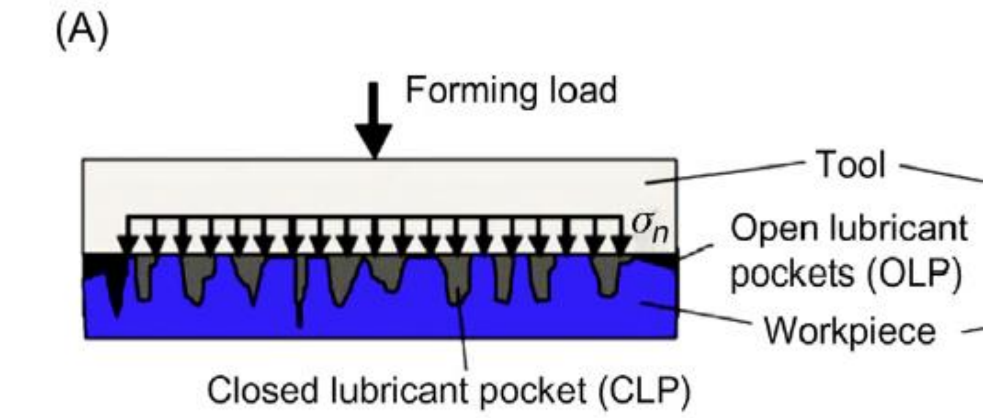
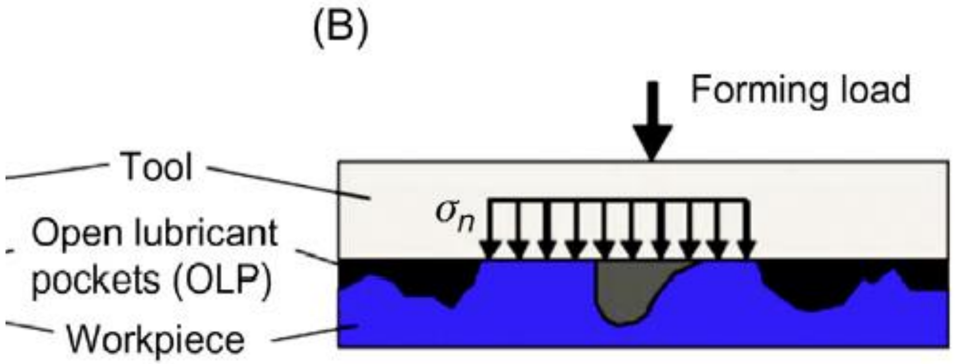


FIGURE 2.10 (A) Contact state at conventional lengtl
forming processes [22].



nventional length scale and (B) contact state in micro-

The size effects on lubricant friction behavior can be explained by the model of open and closed lubricant pockets (CLPs), also known as dynamic and static lubricant pockets, respectively. When a forming load is applied to a lubricated workpiece surface, the asperities (roughness peaks) start to deform plastically, thus increasing the pressure of the lubricant, which is trapped in the roughness valleys or squeezed out. In the case of roughness valleys that have a connection to the edge of the surface and cannot keep the lubricant, these are called open lubricant pockets (OLPs). With increasing normal pressure, the lubricant escapes and is not able to support or transmit the forming load. The forming load acts only on the asperities which results in a higher normal pressure, a higher degree of surface flattening and thus, a higher friction. CLPs, on the contrary, do not have a connection to the edge of the surface. The lubricant becomes trapped in those pockets and is pressurized during forming. The developing hydrostatic pressure will take a part of the external load, thus reducing the normal pressure on the asperities, which results in lower friction [7,21]. When scaling down a forming process, the contact area is reduced significantly while the size of single topography features remains approximately constant. Therefore, the ratio of CLPs is reduced drastically and the external load will be transmitted more and more by the real contact area which will consequently increase, leading to an increase in friction, as shown in Fig. 2.10 [22].

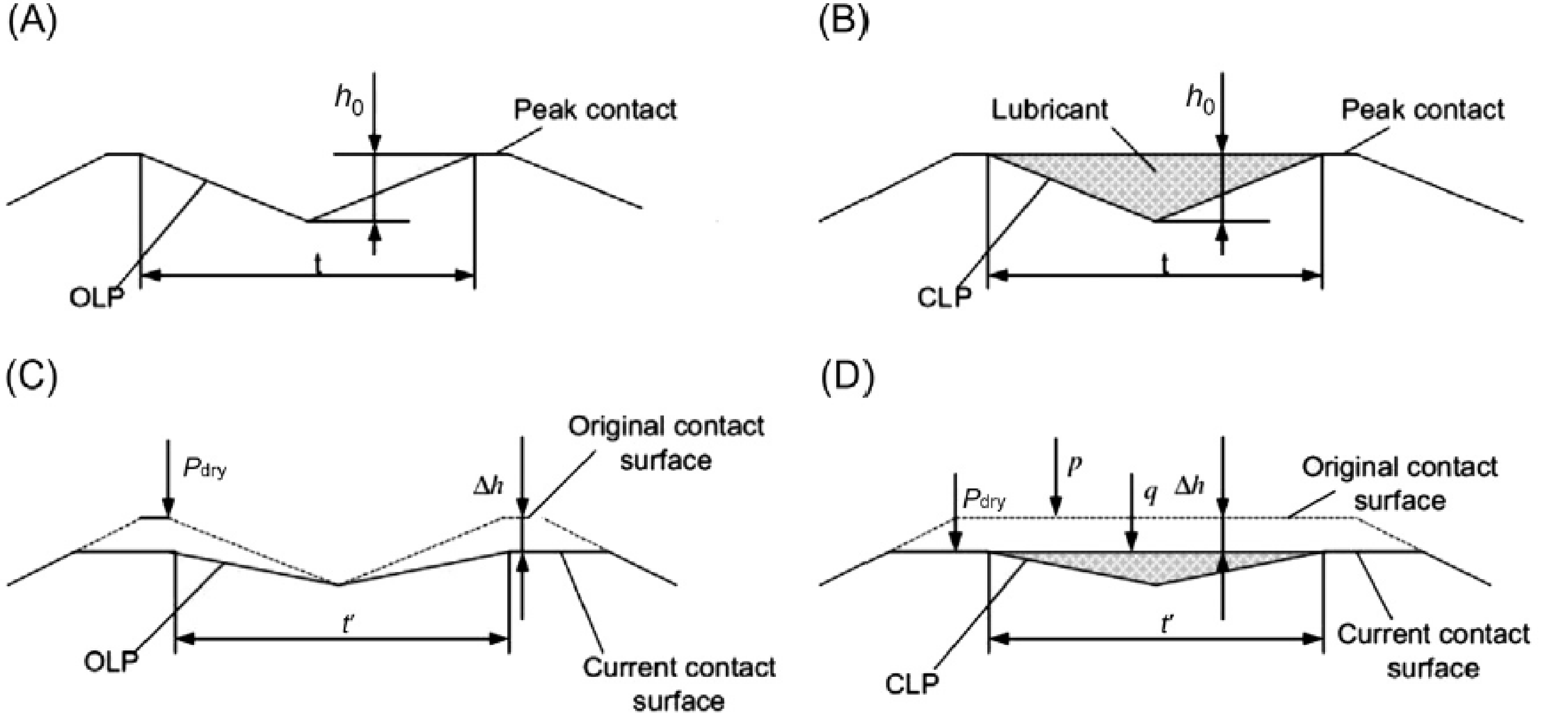


FIGURE 2.12 The deformation of materials in microscopic view: (A) initial contact surface without lubricant, (B) initial contact surface with lubricant applied, (C) current contact surface without lubricant, and (D) current contact surface with lubricant applied [23].

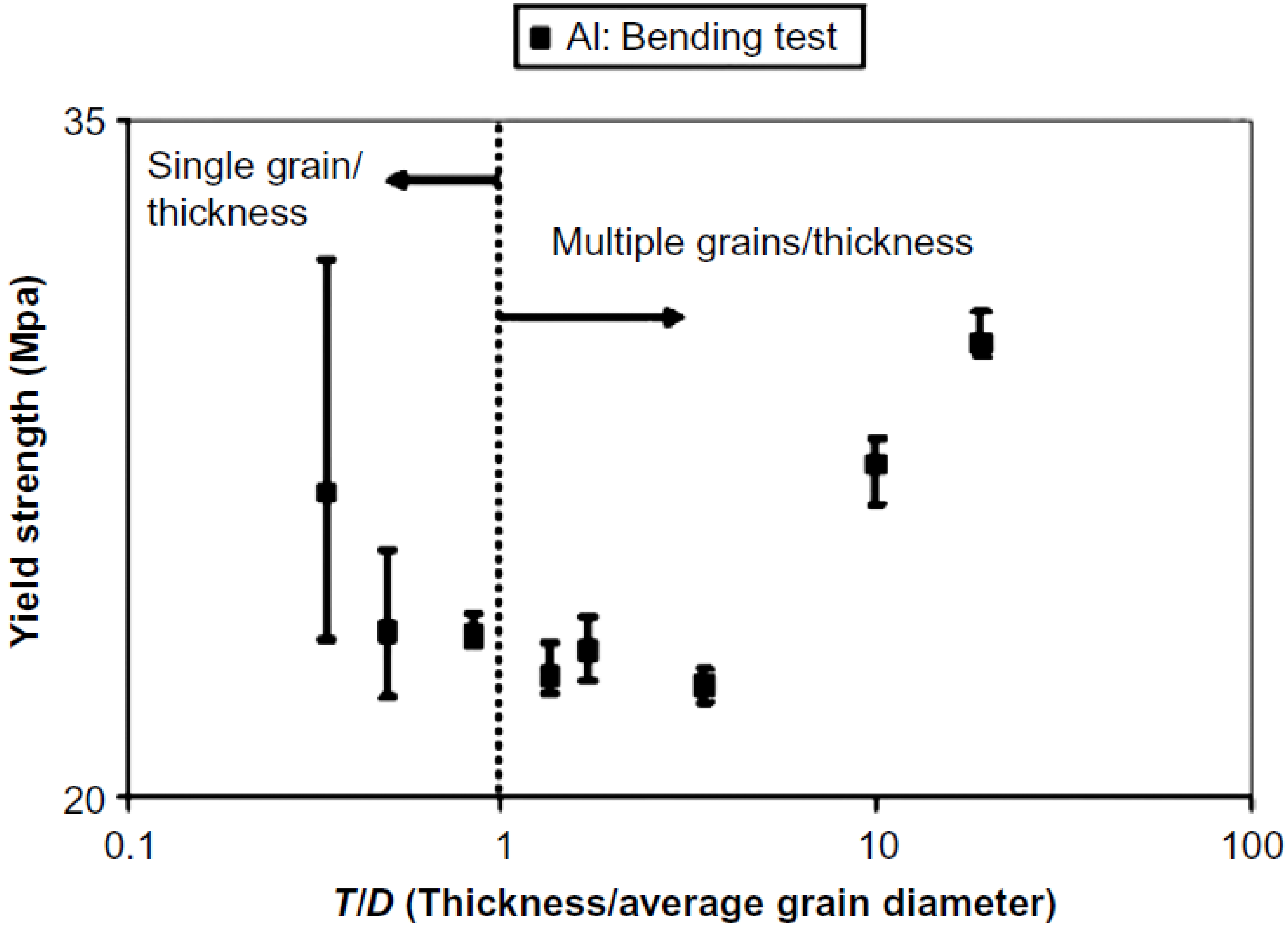


FIGURE 2.13 Yield strength of aluminum obtained from bending tests [24].

2.3.2 Microstructural Refinement

An alternative approach for reducing the influence of size effects is to refine the microstructure of deformed part. Microstructure has been identified to be one of the main reasons for process scatter, as well as the uneven shape evolution in microforming processes [39,40]. A typical work on micro extrusion indicates that grain size effects on deformation load are sensitive to the friction force at tooling–workpiece interface in micro extrusion process [41]. Inhomogeneous deformation occurs in the case of material with coarse grains in micro extrusion, as shown in Fig. 2.20. This phenomenon is thought to be caused by the fact that anisotropy grain properties become significant when only a few grains flow into the microsized cavity, resulting in an irrational local deformation. A large number of slips pass through the grain boundary

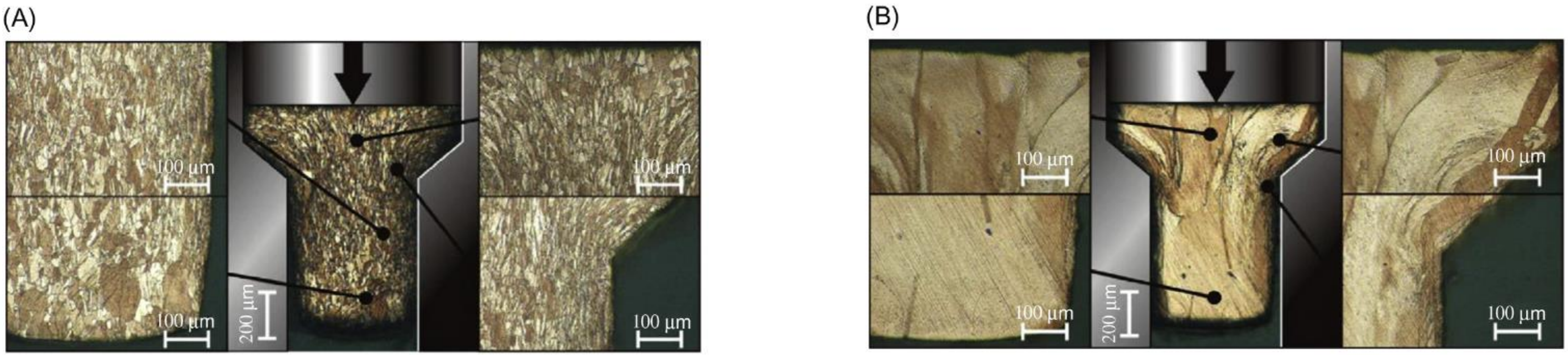
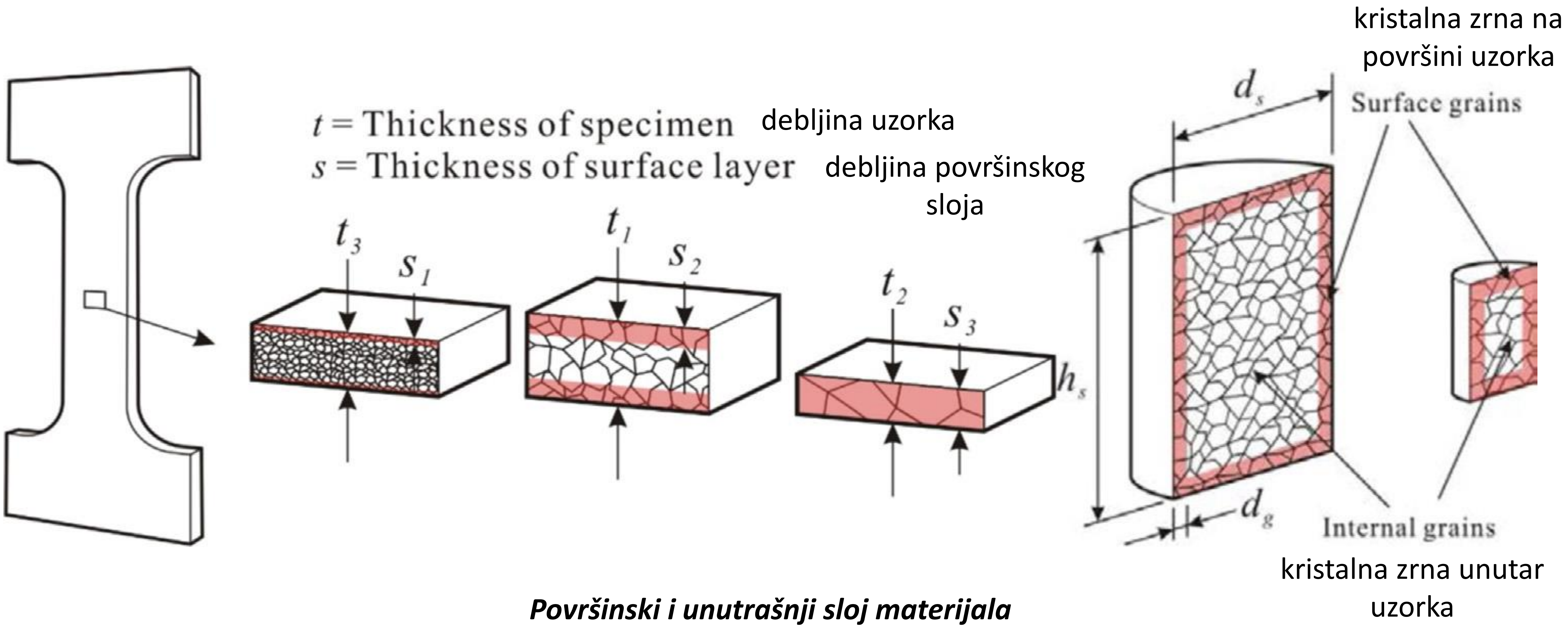


FIGURE 2.20 Microstructures of the micro-formed parts in micro forward extrusion [41]. (A) Original grain size of 20 μm and (B) original grain size of 150 μm.



Površinski i unutrašnji sloj materijala

Drugi problem jeste razvoj odgovarajuće merne tehnologije koja je u stanju izmeri najmanje dimenzije alata i proizvedenih delova. Konačno, proizvodnja delova malih dimenzija zahteva primenu “čistih soba” (eng. clean room) što dodatno povećava troškove.

Čista soba za sklapanje pumpi

Kako bi se umanjile dimenzije proizvoda (mikro komponenti) razvijene su nove tehnologije.

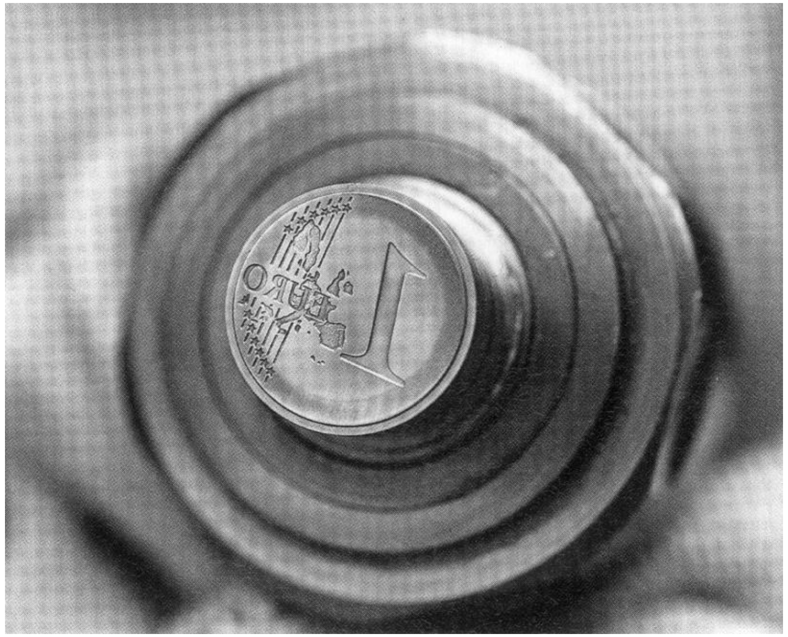
Jedna od proizvodnih metoda za mikro komponente jesu **umanjene konvencionalne tehnologije** (eng. scaled down) **plastičnog deformisanja**. Međutim, nije dovoljno samo smanjiti dimenzije alata.

Mikro deformisanje počinje da se razvija sa pojavom **mikro-žigova**, **mikro-matrica** i sa zahtevima za proizvodnjom u **velikim serijama**... Razvoj mikro rezanja započinje ranije – tj. sa pojavom mikro-glodala, lasera tj. alata koji mogu da se fokusiraju na malu oblast materijala.

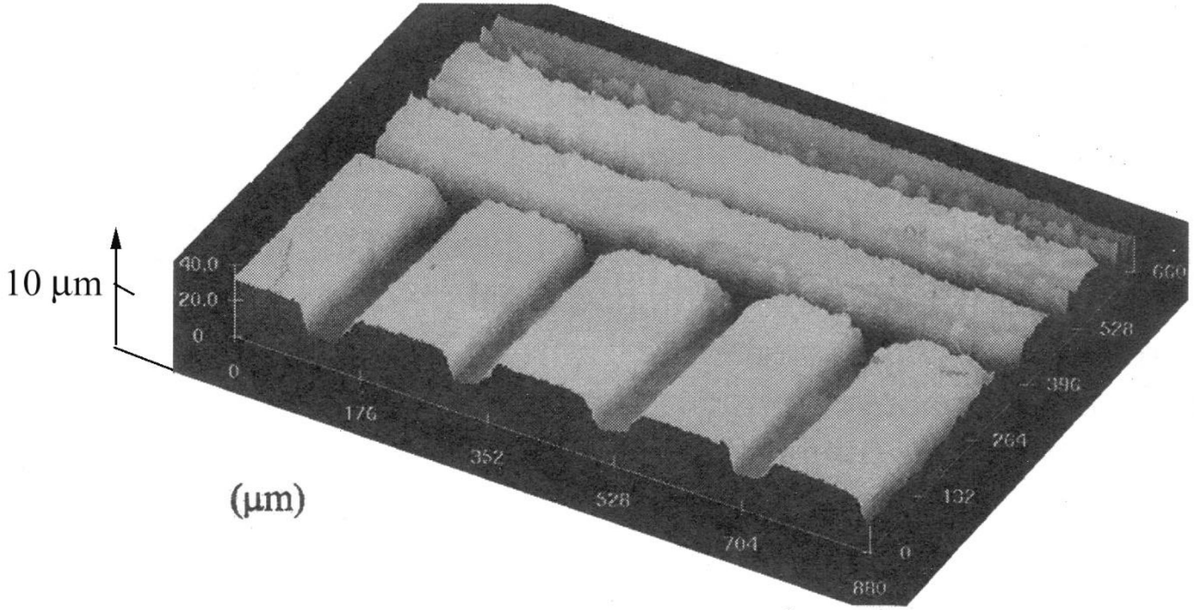
Posebna oblast mikro deformisanja jeste **reljefno zapreminsko mikro deformisanje** u cilju dobijanja isprofilisanih površina. Taj postupak poznat je, pre svega, po tome što se njime **izrađuju metalni novac**, medalje i slični proizvodi.

Ova obrada poznata je veoma dugo, ali se **u savremenim uslovima**, primenom novih znanja, metoda i savremene opreme postižu znatno veće tačnosti i kvalitet profila nego ranije. Time ova obrada dobija sasvim nov značaj i mesto u okviru TPD.

Reljef savremenog metalnog novca veoma je precizan kako po obliku tako i po dimenzijama. Postoje **strogi** nacionalni i internacionalni **standardi** u toj oblasti. Na slici prikazan je alat za izradu novčića od **1 €** i **mikro reljef japanske novčanice od 100 jena**, snimljen laserskim optičkim mikroskopom. Visina reljefa je 10 μm. U oba slučaja za izradu je primenjeno mikro deformisanje.

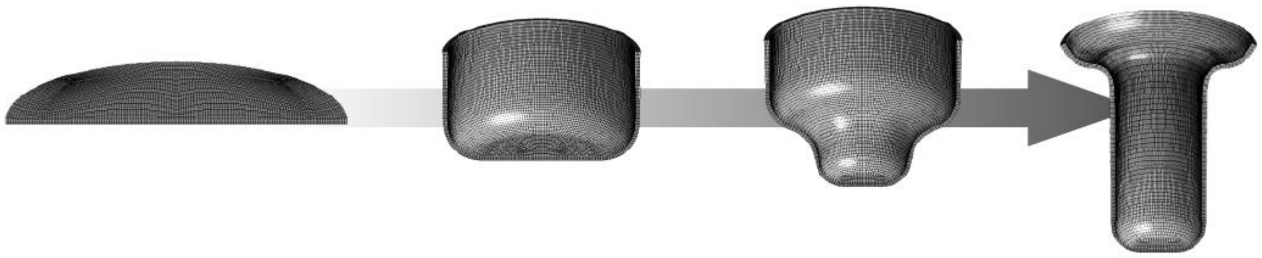


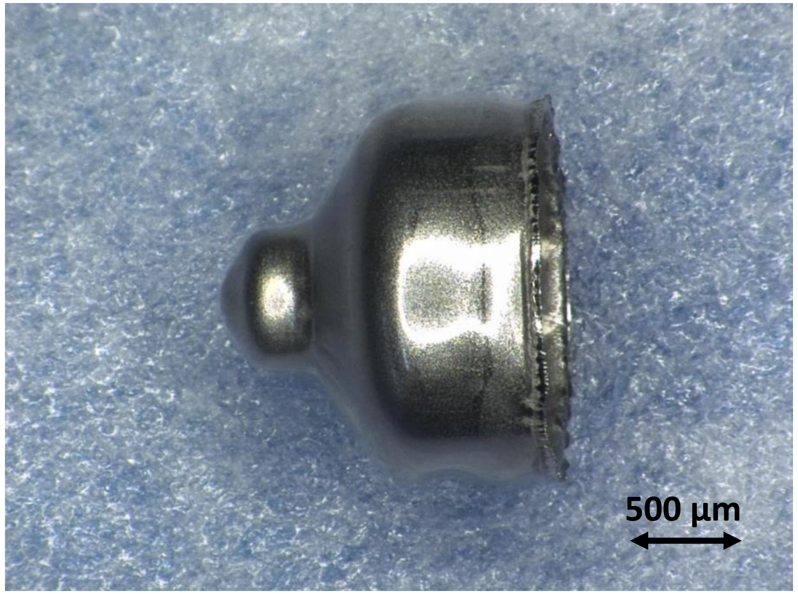
Alat za izradu novčića od 1 €



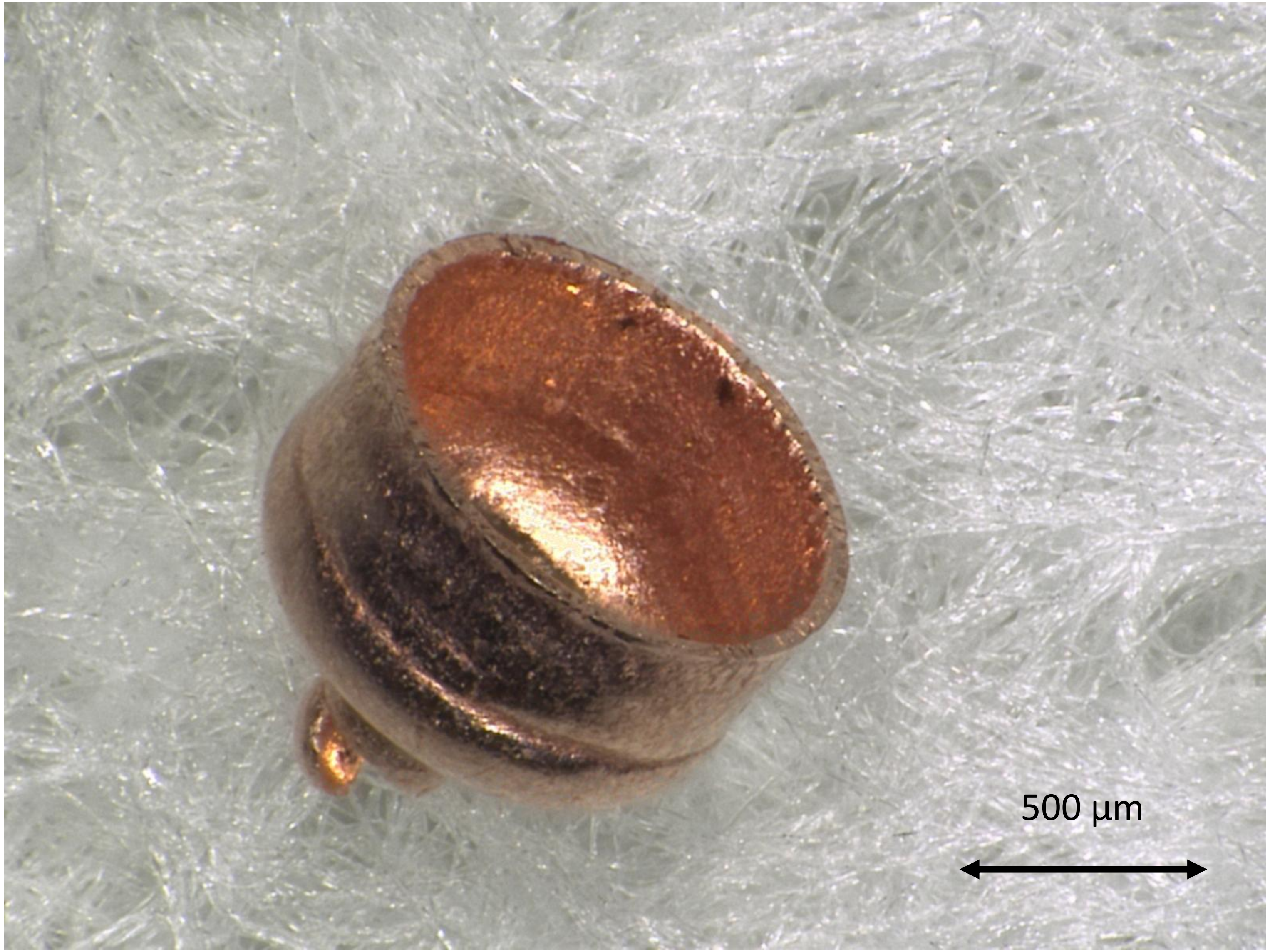
Mikro reljef japanske novčanice od 100 jena

- mikro duboko izvlačenje

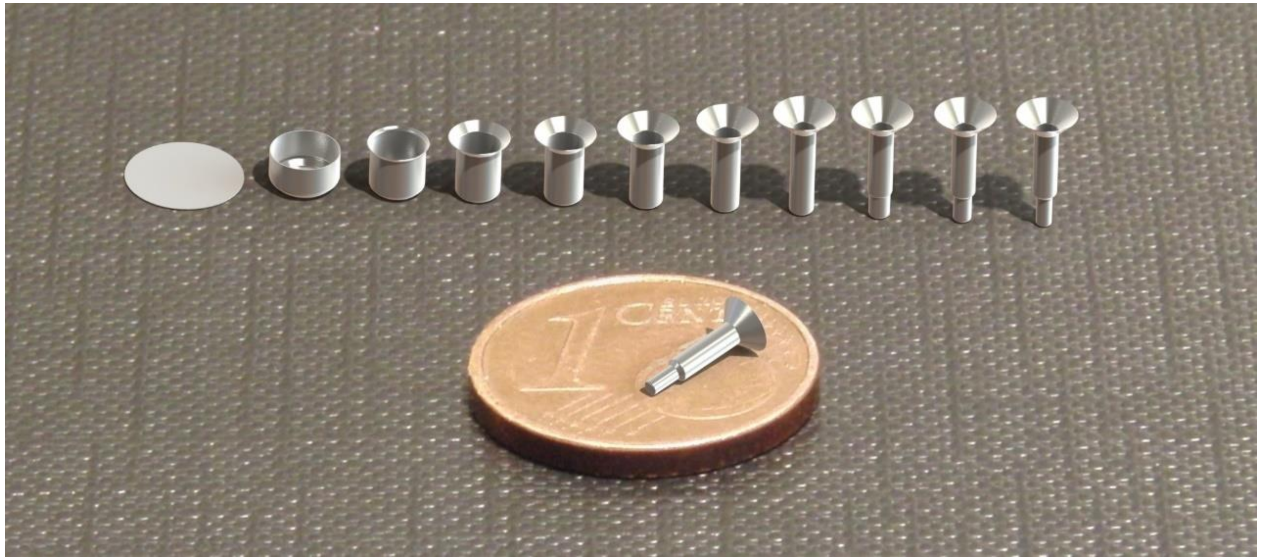


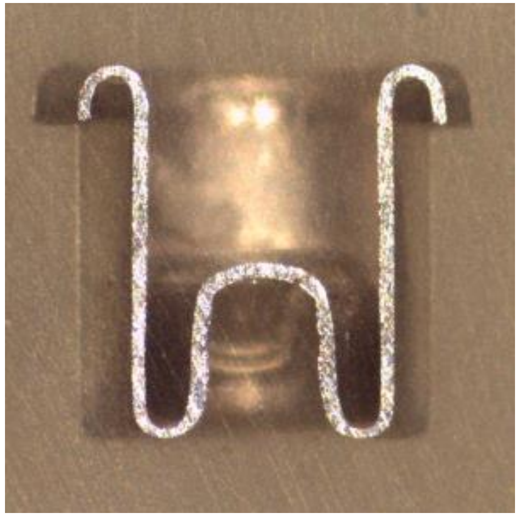


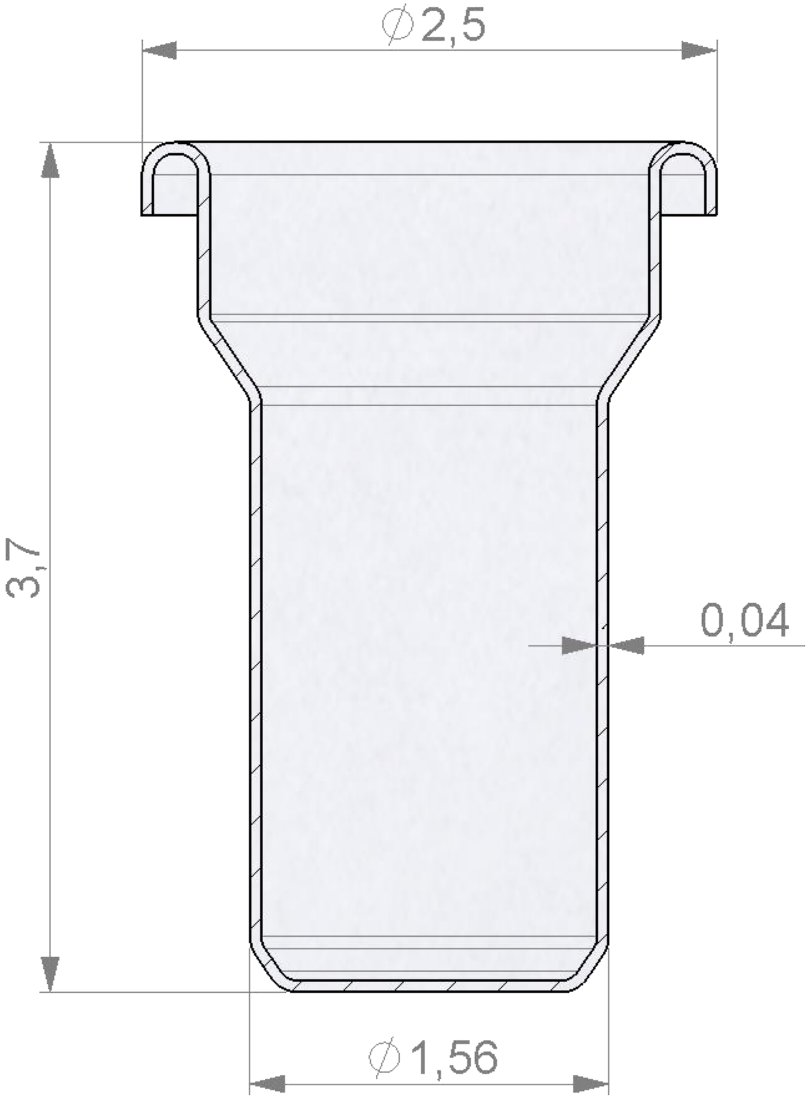
Mašina za mikro duboko izvlačenje



Posuda prečnika 1,4 i 0,44 mm dobijena mikro dubokim izvlačenjem



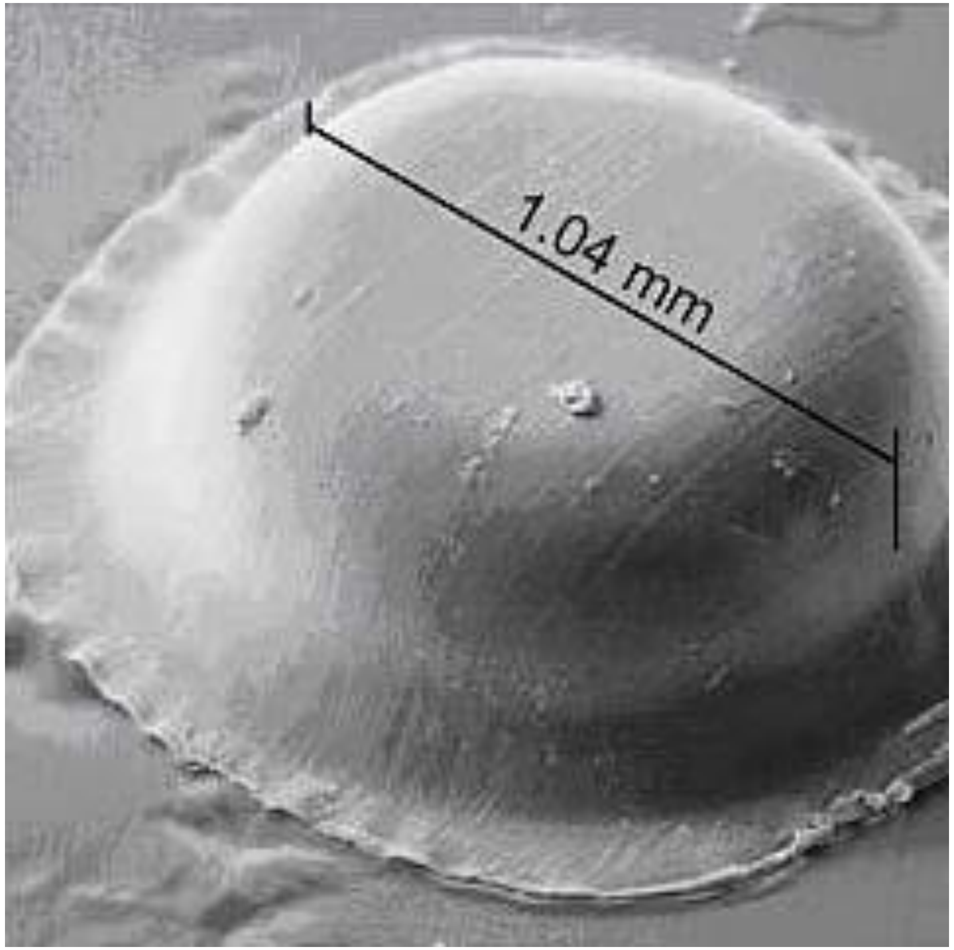


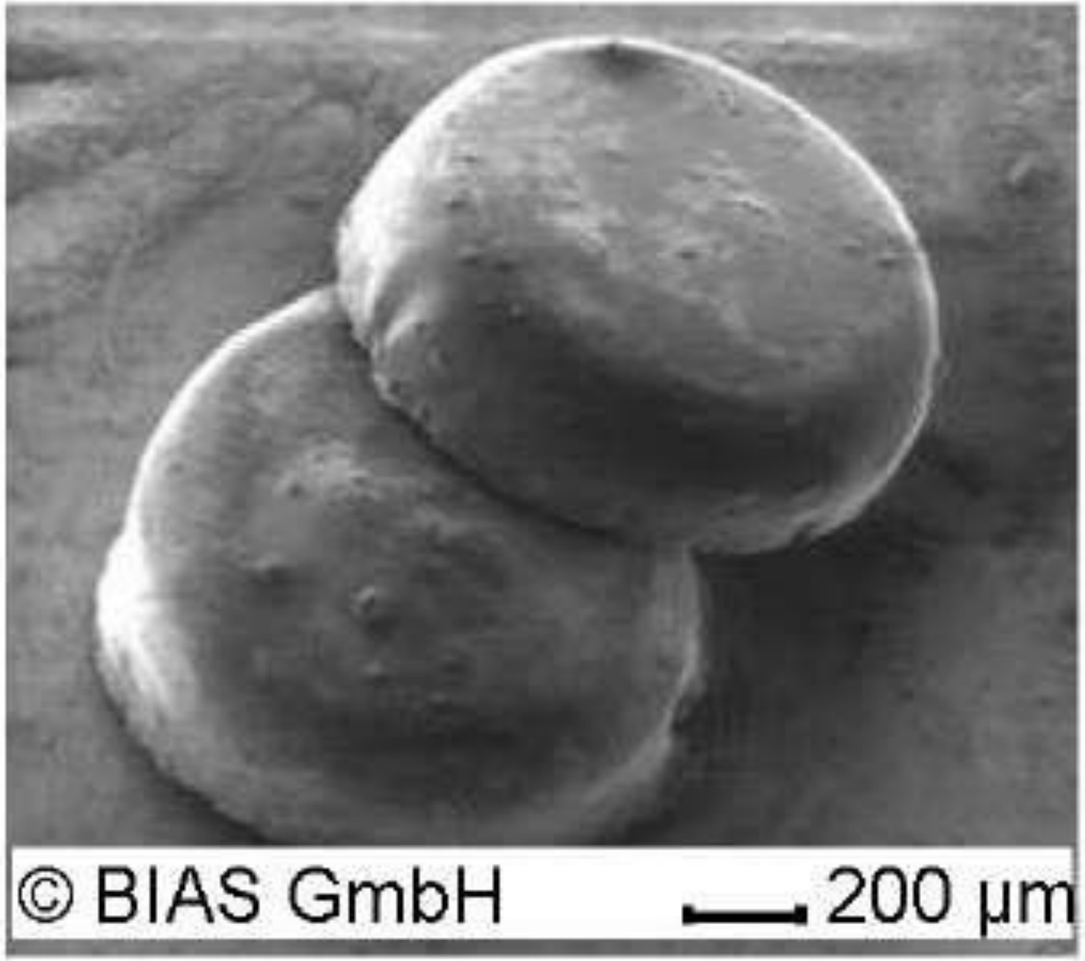


∅2,5
3,7
0,04
∅1,56

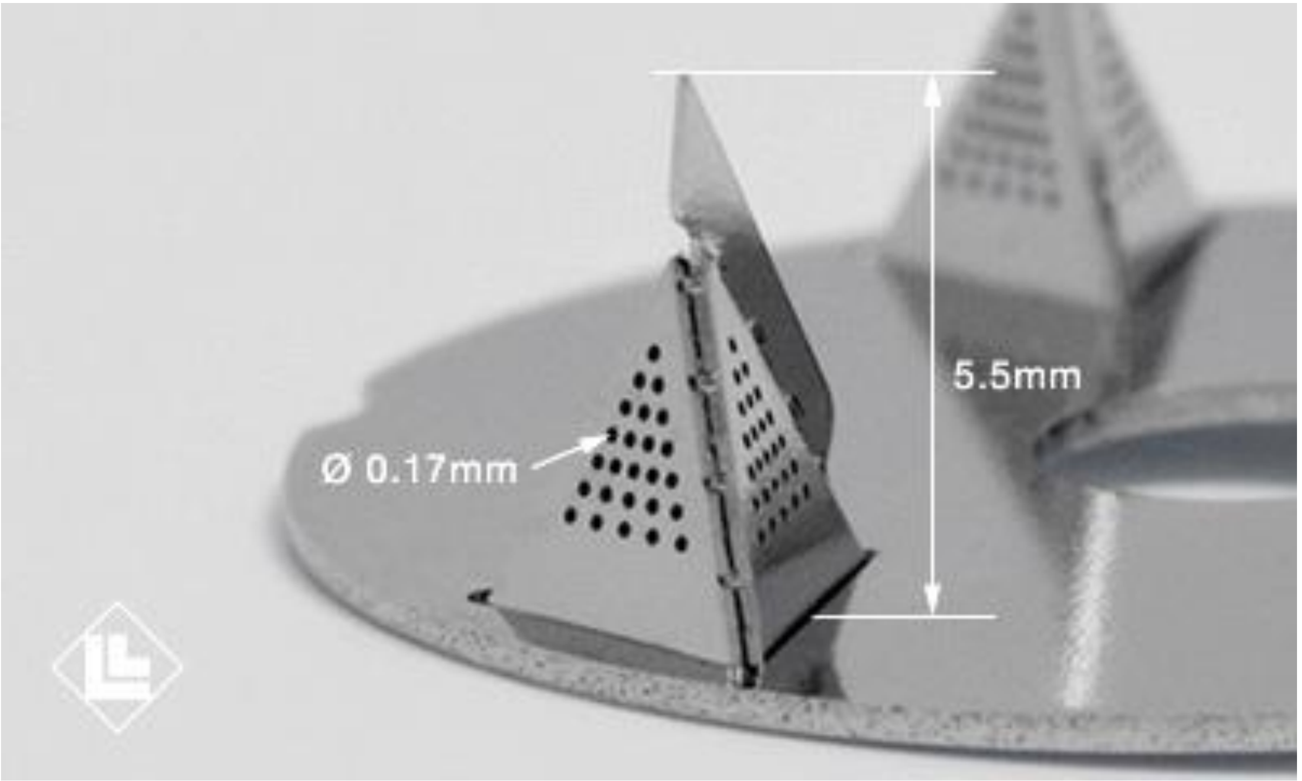
Na slici ispod je prikazan širok dijapazon proizvoda koji prikazuje naše mogućnosti. Naši proizvodi dobijeni dubokim izvlačenjem se koriste u različitim granama industrije. Kompanija Mubion se fokusira na proizvodnju mikro komponenti veličine od 400 do 20 µm, prečnika od 5 do 0,2 mm.

Below is a wide range of products which lies in our capabilities. Our deep drawing parts are being used in different fields of industry. Mubion is focussed on supplying micro components from 400um till 20um, with a diameter from 5mm till 0.2mm.


1.04 mm

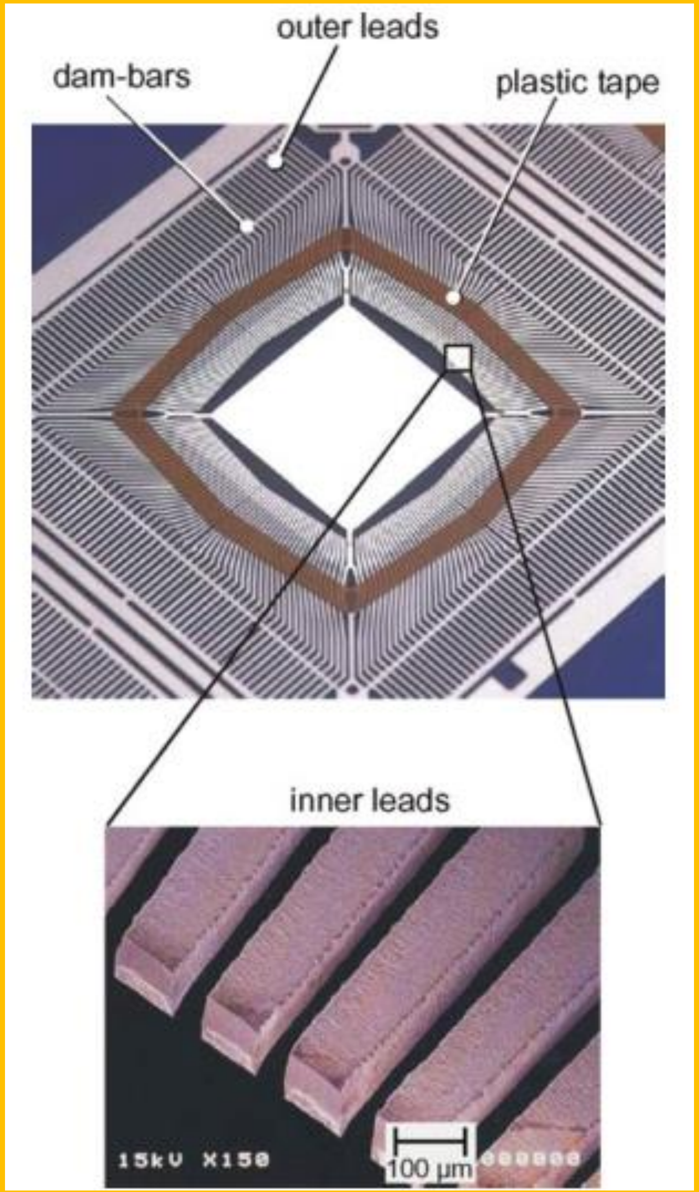

© BIAS GmbH
200 µm

- mikro savijanje



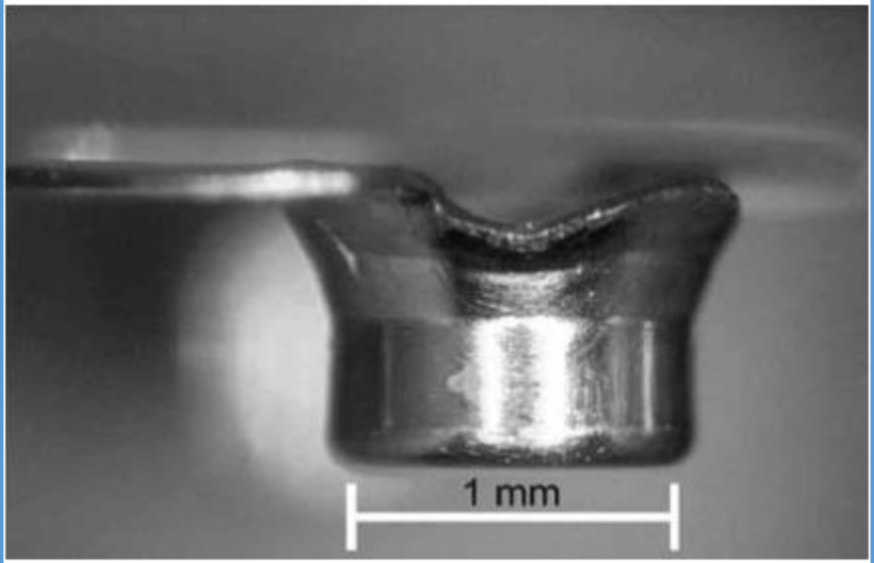
[video](https://www.youtube.com/watch?v=B76r-ustAIA)

https://www.youtube.com/watch?v=B76r-ustAIA



Konektor za elektroniku (212 nožica)

- debljina lima 150 µm
- rastojanje između nožica 168 µm
- materijal – legura bakra i legura nikla i železa
- brzina savijanja – od 160 (kompleksni delovi) do 2000 (jednostavni delovi) komada u minutu



Posuda za izvor elektrona u TV-u savijanje + duboko izvlačenje

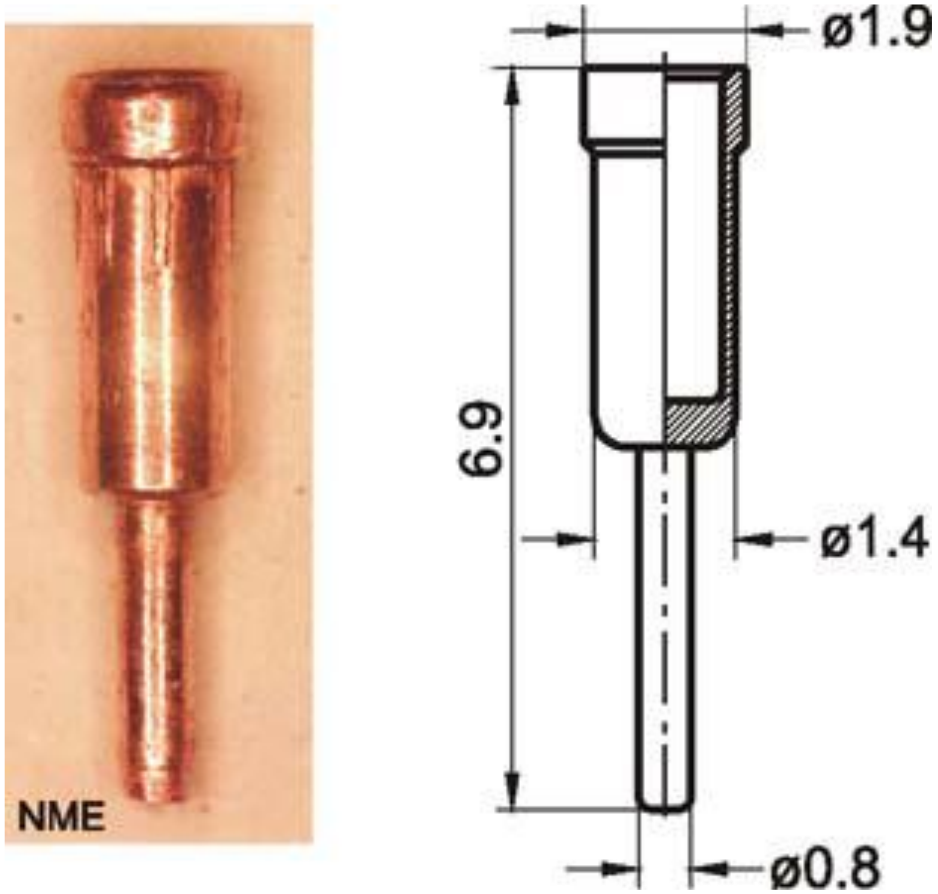
Mikro opruge i vlakna

(medicina i elektronska industrija)

- prečnik žice oko 100 µm (specijalno 60 µm kod spirala za endoskopiju)
- dalje umanjenje prečnika je ograničeno preciznim pomeranjem alata

Drugačiji problem se javlja kod hladnog istiskivanja. Dok kod procesa savijanja žice obradak ostaje pričvršćen za žicu, kod procesa istiskivanja se žica mora prvo iseći kako bi se napravio pripremak određenih dimenzija. To uslovljava i precizno prenošenje i pozicioniranje obratka.

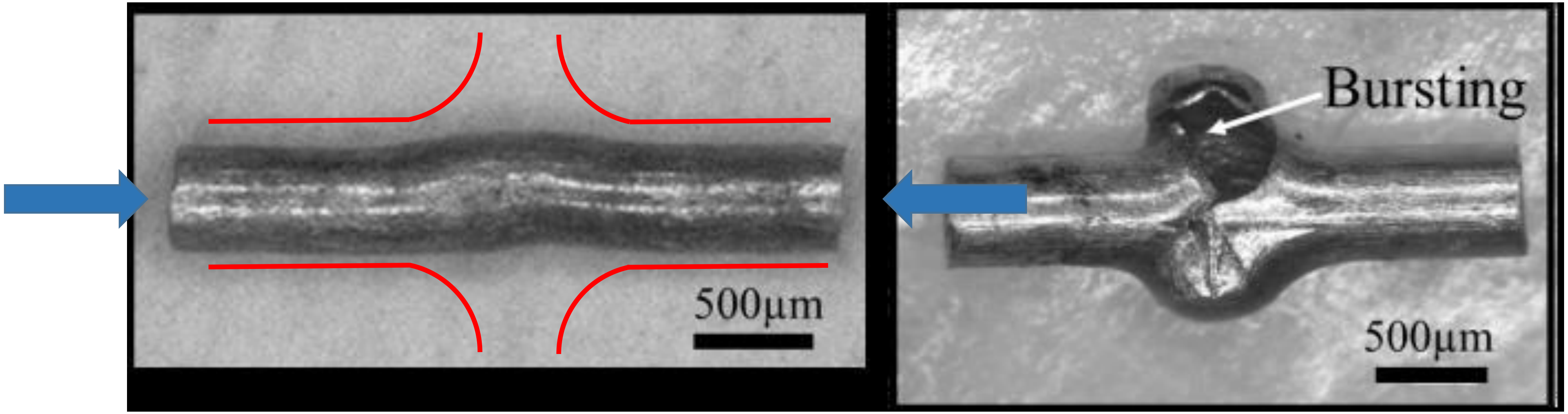
Određena zahtevana brzina i preciznost, u kombinaciji sa malom težinom pripremka (obično nekoliko miligrama, kao i problemi vezani za prihvatanje i pozicioniranje predstavljaju glavni ograničavajući faktor pri minijaturizaciji.



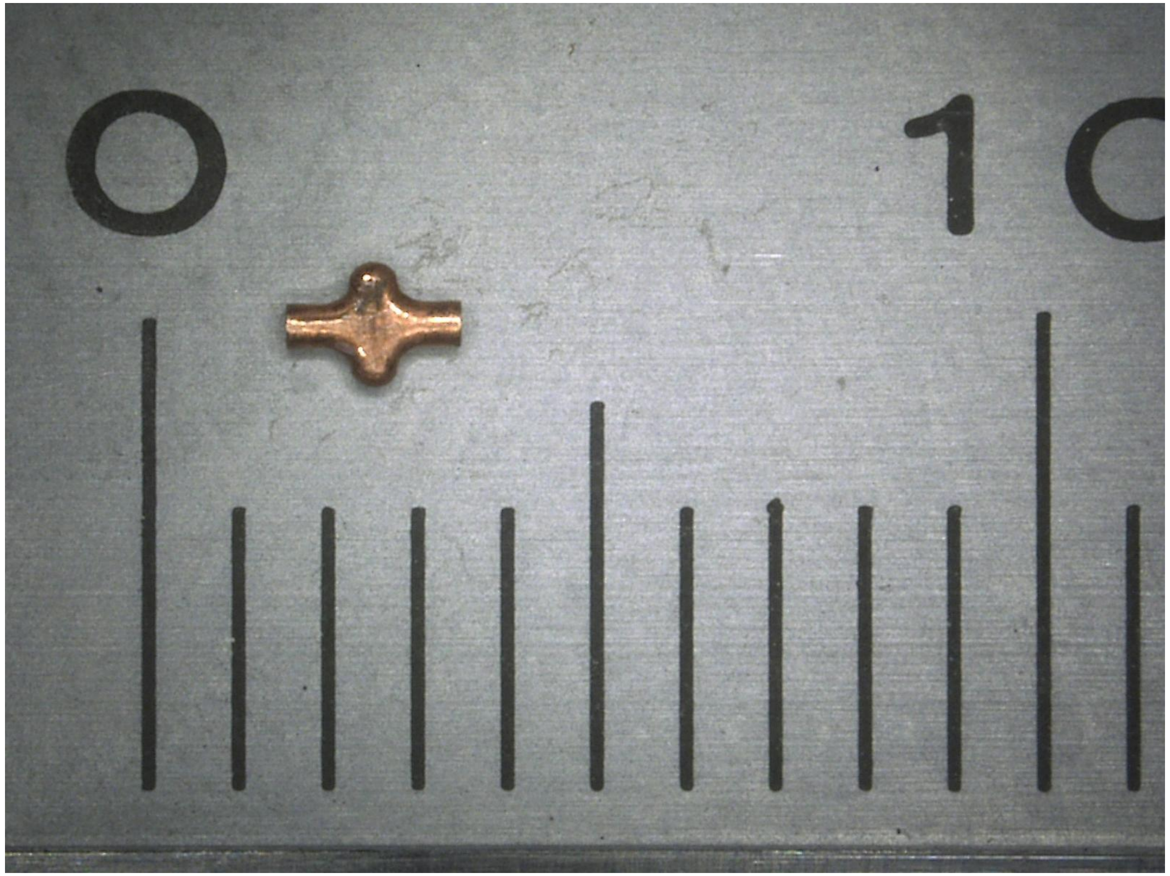
Vučena bakarna igla

- mikro hidrodeformisanje

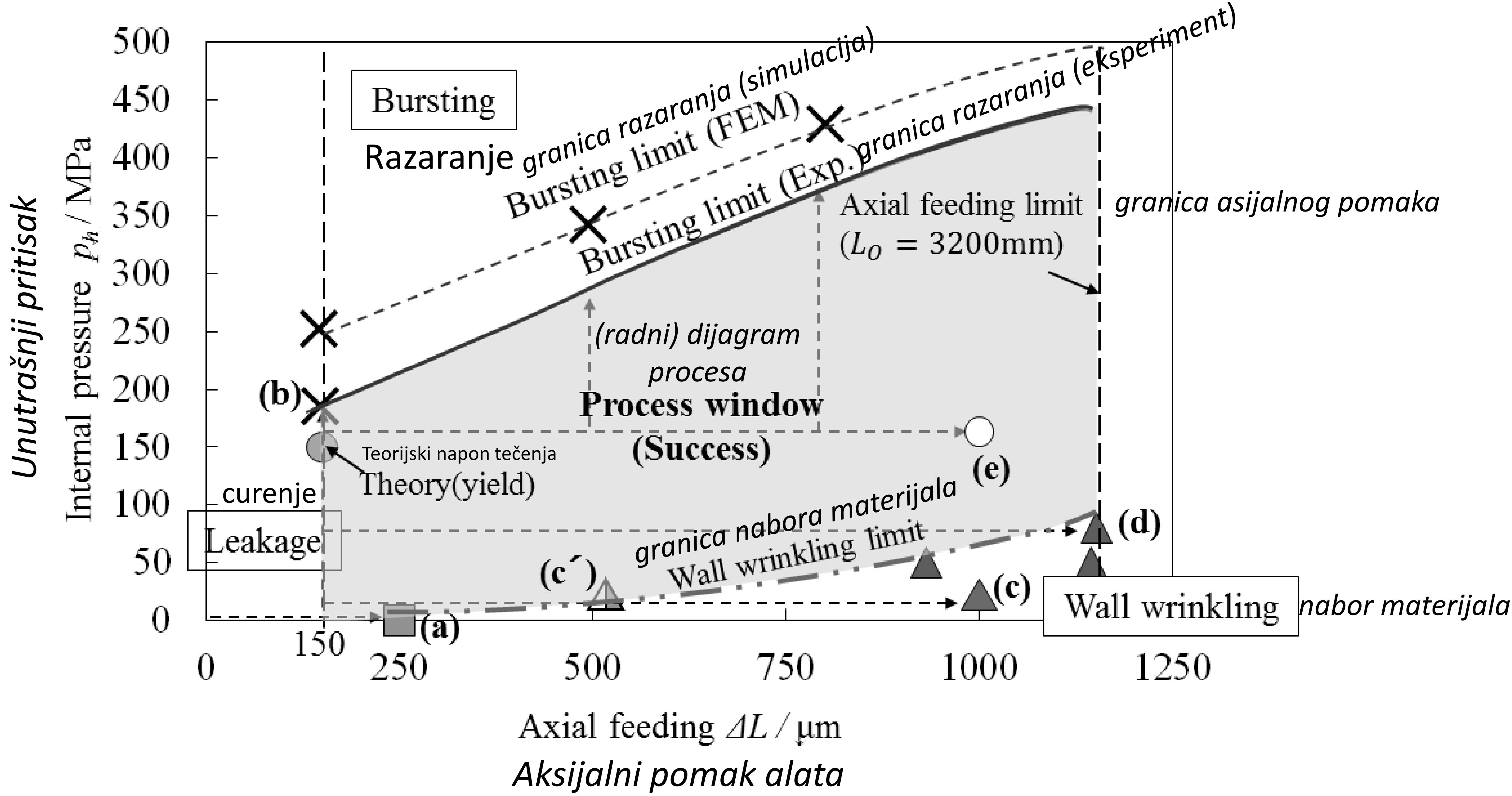
pucanje/razaranje materijala



Princip mikro hidrodeformisanja



Mikro hidrodeformisanje cevi (0,5 x 0,3 mm)
od čistog bakra

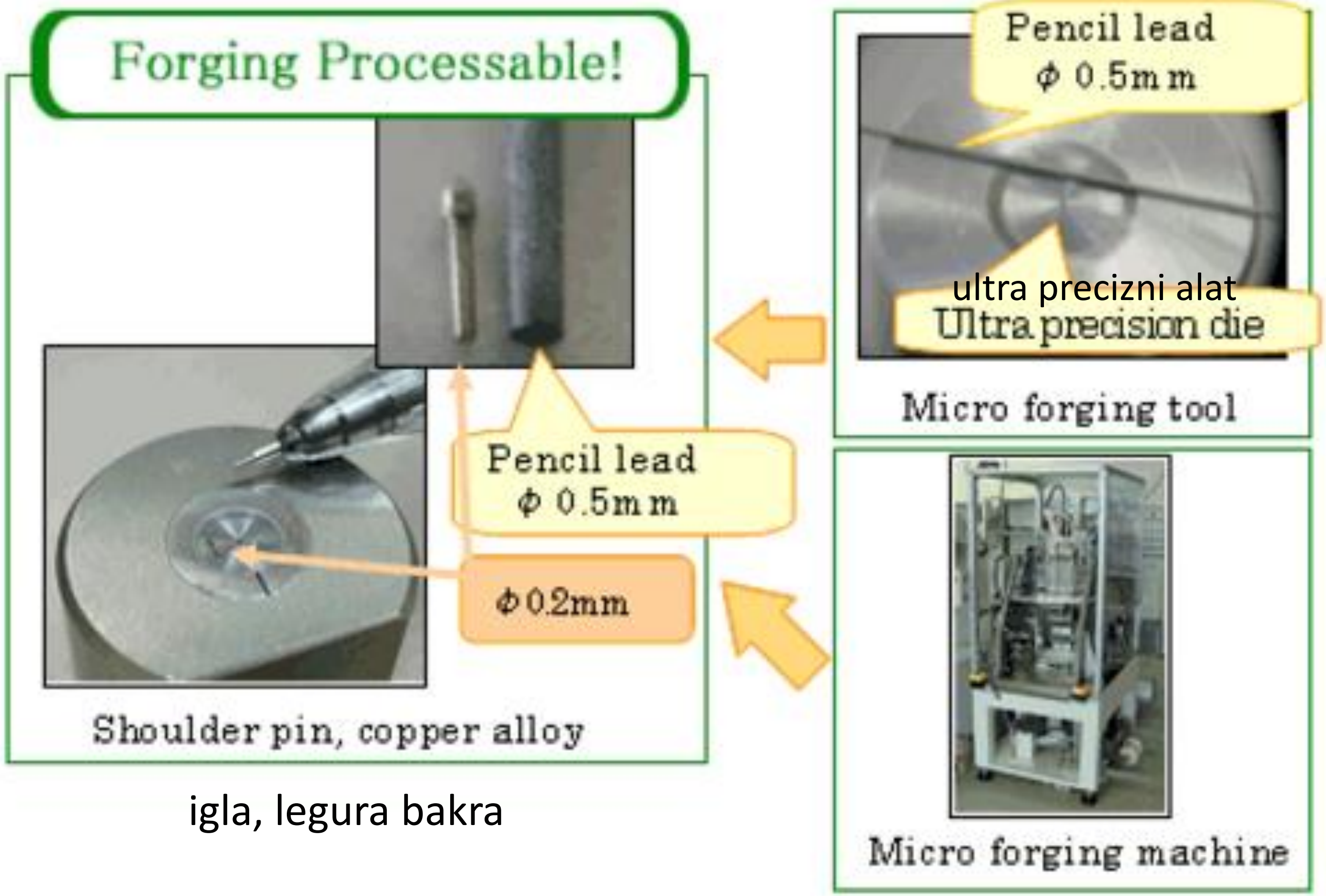


Dijagram procesa mikro hidrodeformisanja

- mikro kovanje

Ultra precizno mikro kovanje tvrdih metala (nerđajući čelik, titanium itd)

olovno srce olovke Ø 0,5 mm

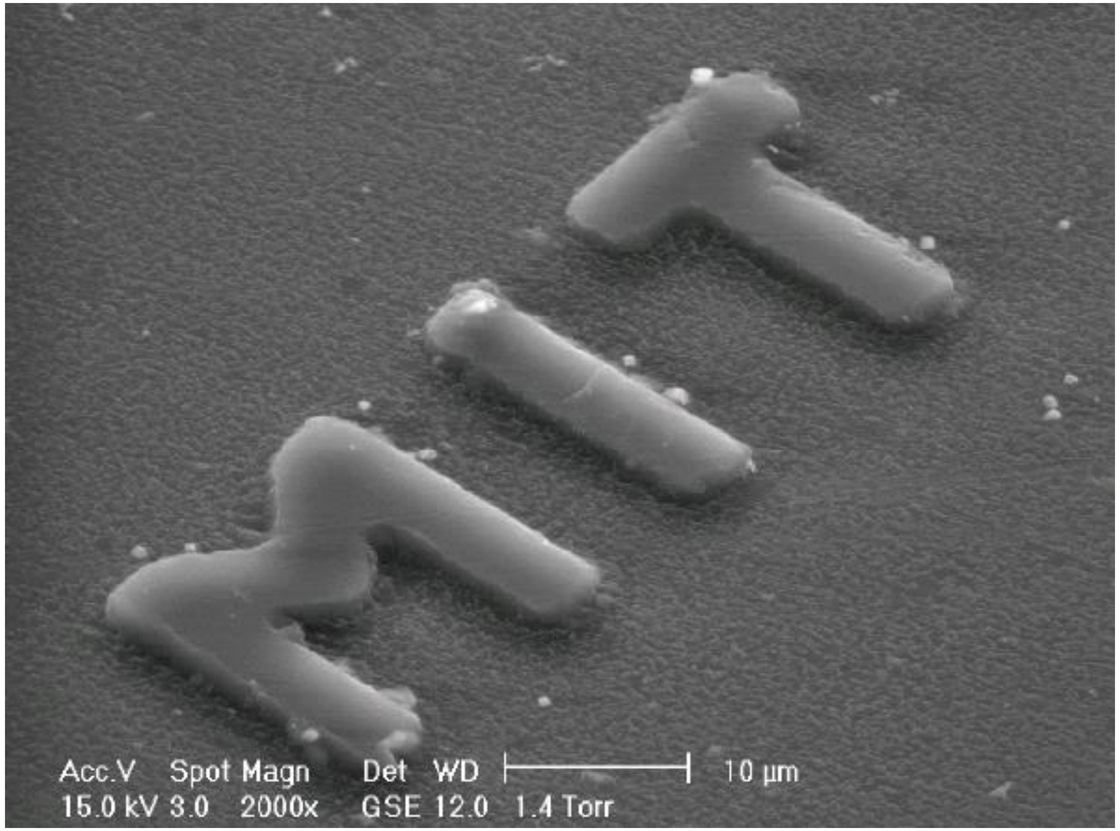


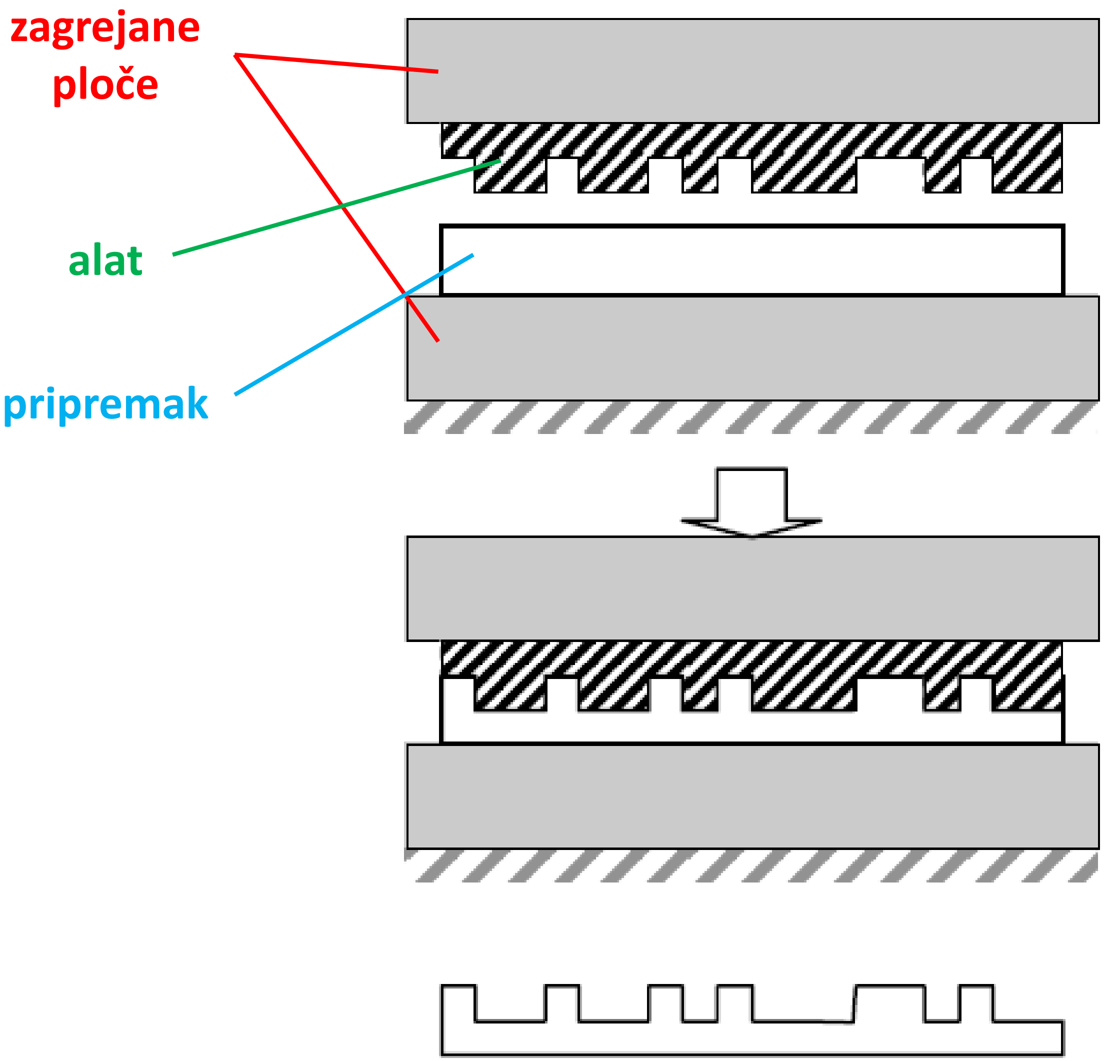
alat za mikro kovanje

igla, legura bakra

mašina za mikro kovanje

- mikro utiskivanje





Šema procesa mikro utiskivanja