# Hot forming of Zn and ZnCuTi, ZnPb alloys

# Toplo preoblikovanje Zn in zlitin ZnCuTi ter ZnPb

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**Received:** September 19, 2007 **Accepted:** October 25, 2007

**Abstract:** Hot compression tests of pure zinc and zinc alloyed with copper, titanium and lead have been carried out on Instron 1255. Since the testing machine was not equipped with the proper heating system, a new heating device was developed. Specimens and compression tools were heated using oil bath. Specimens were in as-cast and pre-deformed state. Tests were performed at two constant tools speeds: 0.2 and 0.01 m/s and three temperatures: 80, 150 in 210 °C. Constants for flow stress description of Hajduk-Hensel equation were detrermined. The comparison between measured and predicted flow stresses are in good accordance.

**Izvleček:** Za določitev krivulj tečenja so bili z uporabo preizkuševalne naprave Instron 1255 narejeni topli tlačni preizkusi za čist Zn in zlitini: ZnCuTi ter ZnPb. Ker preizkuševalni stroj ni bil opremljen s sistemom za ogrevanje vzorcev, smo izdelali napravo, s katero smo vzorce in tudi orodje ogrevali v oljni kopeli. Vzorci so bili tako v litem kot tudi predhodno deformiranem stanju. Preizkuse smo vodili pri dveh konstantnih hitrostih pomika orodja: 0,2 in 0,01 m/s ter treh temperaturah: 80, 150 in 210 °C. Določene so bile konstante za izračun krivulj tečenja po Hajduk-Hensel. Izračunane vrednosti so v dokaj dobrem ujemanju z izmerjenimi vrednostmi.

**Key words:** Zn, Zn alloys, compression test, flow curves
**Ključne besede:** Zn, Zn zlitine, tlačni preizkusi, krivulje tečenja

## INTRODUCTION

Zinc is the fourth most common metal in use. Over 7 million tons of zinc is produced annually worldwide. Only annual production of iron, aluminium and copper are major. Zinc and zinc alloys are used in the form of coatings, casting and wrought zinc products. Wrought zinc and zinc alloys may be obtained as rolled strip, sheet and foil; extruded rod and shapes; and drawn rod and wire. These metals exhibit good resistance to corrosion in many types of service. Nearly half of annual production is used for galvanizing to protect steel from corrosion. Approximately 19 % are used to produce brass and 16 % go into the production of zinc base alloys to supply e.g. the die casting industry. Significant amounts are also utilized for compounds such as zinc oxide and zinc sulphate and semi-manufactures including roofing, gutters and down-pipes. Main application areas are construction, transport, consumer goods and electrical appliances and general engineering. Wrought zinc is easily machined using standard methods and tools. However, if it is necessary to machine zinc containing exceedingly coarse grains, the metal should be heated to a temperature between 70 and 100 °C in order to avoid cleavage of crystals.

Zinc strips are usually produced from 25 to 100 mm thick slabs. Finish rolling in the temperature range 120 to 150 °C is required to obtain a bright surface and high ductility. Rolled zinc is produced as pure zinc and in seven basic alloys. Pure zinc is brittle at room temperature and at temperatures above 150 °C, being workable only in the range between 100 °C and 150 °C. When alloyed with copper and titanium, zinc sheet is very creep resistant. This alloy is manly used in building industry for roofing, flashing and weathering applications. In common with many other metals and alloys, wrought zinc creeps under constant loads that are substantially less than its ultimate strength; that is, wrought zinc does not have clearly defined elastic module, and hence creep data from service tests must be used in designing for strength and rigidity under conditions of continuous stress. Rolled zinc alloyed with lead is mostly used for drawn or formed articles requiring some rigidity. It must be deformed under light continuous load at elevated temperatures[1], [2].

The aim of presented work is to intensify productivity on reversing hot rolling mill with slab lengthening. Industrial measurements of loads on the mechanical side (torque on the mean shaft) and on the energetic side (current, voltage, revolutions of electromotor, etc.), and laboratory test of rolled material were carried out. Due to increasing length of the slab, the rolling time is extended. This causes the change of the slab temperature evolution and consecutive the change of rolling mill load. Because of all these changes new pass schedule must be optimized. Flow curves are very important input data for numerical modelling of rolling pass schedules. Accurate knowledge of the mechanisms acting during hot rolling is important for the manufacture of high quality products, as well as for design of optimum pass schedules.

## Experimental

### Initial state of specimens

In the present study pure zinc and two zinc alloys ZnPb (0.8 %Pb) and ZnCuTi (0.11 % Cu, 0.1 % Ti) in as-cast and deformed state were investigated. For hot compression tests cylindrical specimens with initial heights of 20 mm and initial diameters of 15.5 mm were used. For the as-cast state specimens were machined from the centre of gravity cast block of dimensions 40×80×1500 mm. The bottom of the gravity die was cooled down by water that caused appearance of fine grains. In the centre part of the block the crystallization was oriented similar to macrostructure founded in plates produced in real technological process. For this reason the specimens were taken from the upper two thirds of the block. Macrostructure of the transverse section in the centre of the block is presented in Figure 1. Specimens for predeformed state were taken from the centre of the strip which was 30 % deformed. Macrostructure of the transverse section in the centre of deformed plate shows that direction of recrystallized grains and direction of dendrite in as-cast are nearly the same (Figure 2). This effect is not presented in the specimens (Figures 3, 5 and 7) what confirmed the accurate procedure of taking specimens from plates. In deformed specimens (Figure 3b, 5b and 7b) the recrystallization of crystal grains is noticed. To clarify initial state of specimens microstructures are presented as well (Figures 4, 6 and 8) where uniformity is obvious.

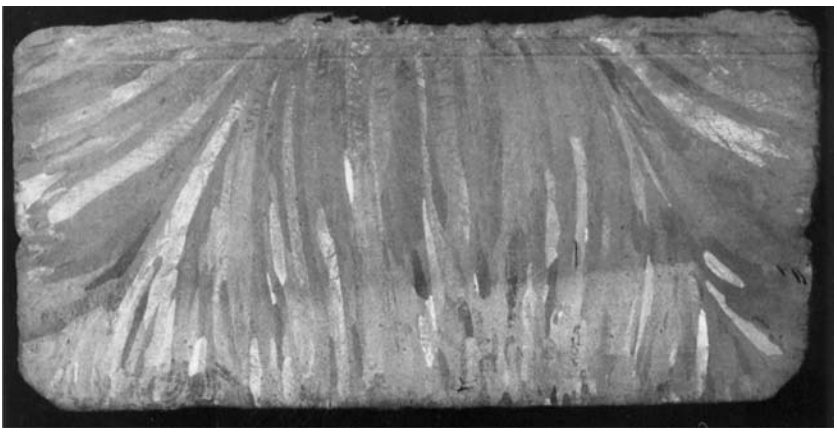


**Figure 1.** Transverse section of Zn cast block
**Slika 1.** Prečni presek ulitka iz Zn

**Figure 2.** Transverse section of 30 % deformed Zn plate
**Slika 2.** Prečni presek 30 % toplo deformiranega ulitka iz Zn

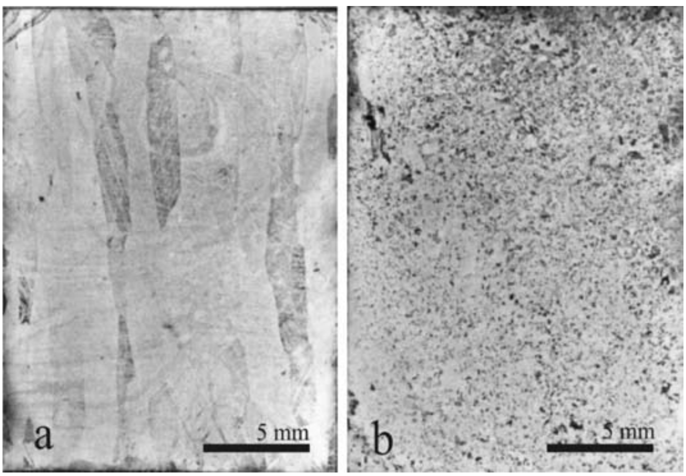



**Figure 3.** Macrostructure of Zn specimen: as-cast (a), deformed (b)
**Slika 3.** Makrostruktura Zn vzorca: ulit (a), deformiran (b)

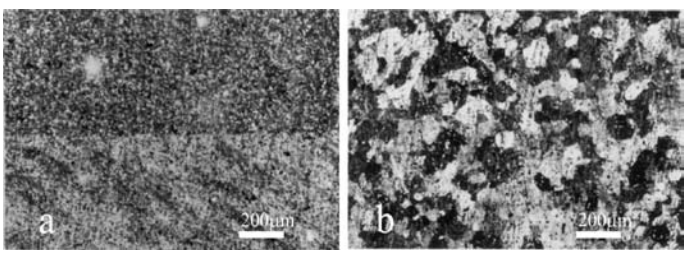



**Figure 4.** Microstructure of Zn specimen of as-cast (a), deformed (b)
**Slika 4.** Mikrostruktura Zn vzorca: ulit (a), deformiran (b)

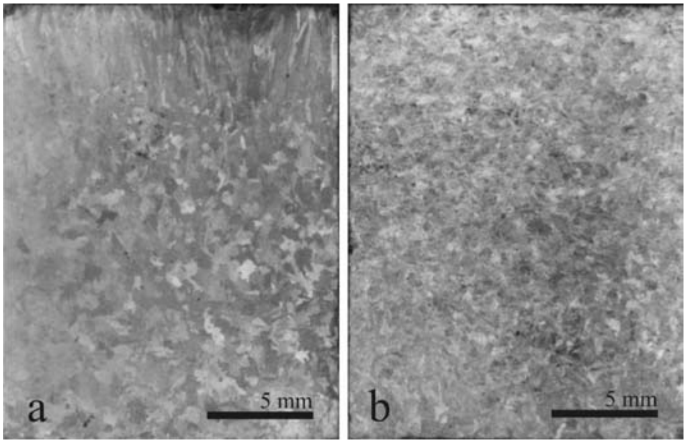



**Figure 5.** Macrostructure of ZnCuTi specimen: as-cast (a), deformed (b)
**Slika 5.** Makrostruktura ZnCuTi vzorca: ulit (a), deformiran (b)

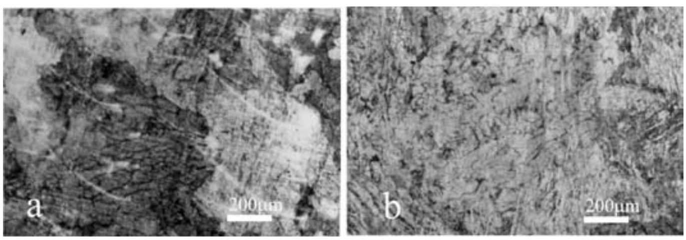



**Figure 6.** Microstructure of ZnCuTi specimen: as-cast (a), deformed (b)
**Slika 6.** Mikrostruktura ZnCuTi vzorca: ulit (a), deformiran (b)

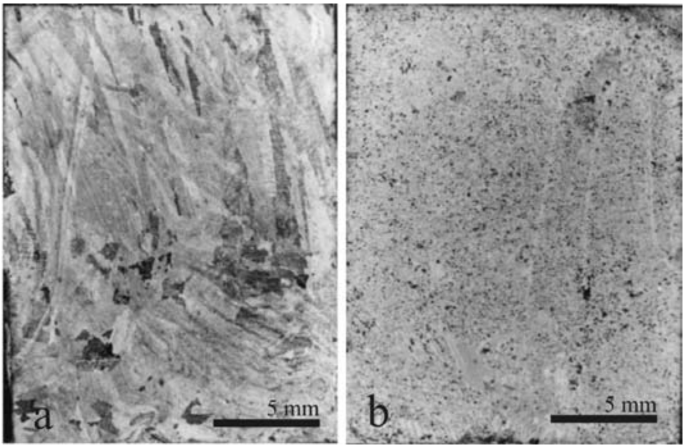



**Figure 7.** Macrostructure of ZnPb specimen: as-cast (a), deformed (b)
**Slika 7.** Makrostruktura ZnPb vzorca: ulit (a), deformiran (b)

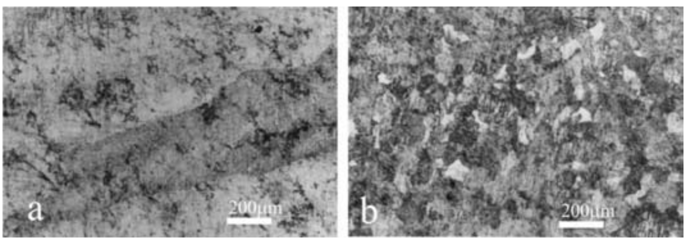
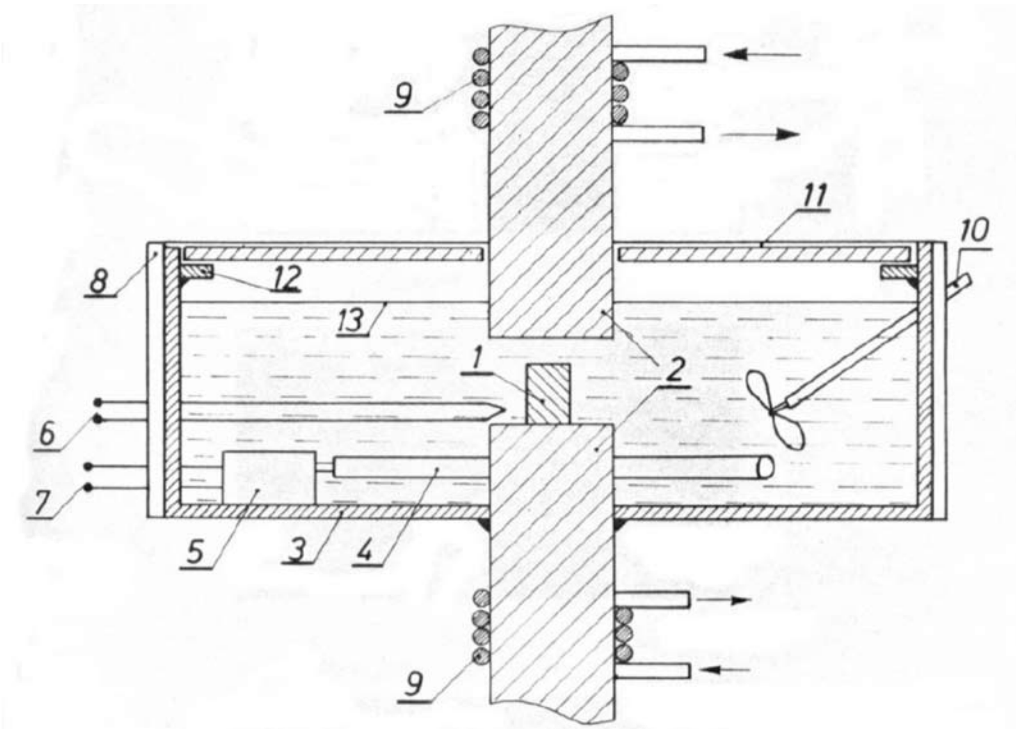



**Figure 8.** Microstructure of ZnPb specimen: as-cast (a), deformed (b)
**Slika 8.** Mikrostruktura ZnPb vzorca: ulit (a), deformiran (b)

**Compression tests**

A material testing machine Instron 1255 was used for compression testing. Testing was performed at two constant punch velocities: 0.01 and 0.2 m/s and three temperatures: 80, 150 in 210 °C what correspond technological condition of hot forming. Specimens were heated with use of special heating device (Figure 9). This device enables heating of specimens in the oil bath. Oil is used as a lubricant at the contact tool-specimen as well. In this way cooling of specimen when transported from furnace to tools was hindered. Power of a heater was 1 kW. Temperature field was homogeneous due the mechanical mixing of the oil bath. Control thermocouple was placed in the tool area. Temperature oscillation was in range of ±2.5 °C. Jaws of the testing machine were protected against overheating with water cooling.




1. specimen
2. tool
3. oil container
4. heater 100 W
5. holder of the heater
6. control thermocouple
7. power supply for the heater
8. asbestos isolation
9. cold winding
10. mixer
11. cover
12. holder of the cover
13. cylinder oil level

**Figure 9.** Hot compression test device
**Slika 9.** Shema naprave za tlačne preizkuse v vročem

**Determination of flow curves**

When performing compression tests, friction between specimen and tool can result in tangential stresses at the contact surfaces, which increase the forming force. Friction has negligible influence on elastic deformation but it causes barrel-shaped specimen on plastic deformation. In extreme cases, this can lead to sticking the specimen to the tool's surface. This is why we have to determine the coefficient of friction, considering the roughness of the tool's and specimen's surface, lubrication, temperature and the strain rate. The coefficient of friction was determined using the Burgdorf's methods. This value was lower than 0,02 and was taken into account while defining hot flow curves.

Considering the coefficient of friction we calculated flow stresses for all materials at different thermo mechanical conditions and initial states from measured load and displacement of compression tool[3].

$$\sigma_f = \frac{4 \cdot F \cdot h}{\left(1 + \frac{\mu \cdot d_o}{3 \cdot h_o}\sqrt{\frac{h_o}{h}}\right) \cdot d_o^2 \cdot h_o \cdot \pi} \qquad (1)$$

$F$ - force
$h$ - instantaneous specimen height
$h_o$ - initial specimen height
$d_o$ - initial specimen diameter
$\mu$ - coefficient of friction

Because flow stress curves are defined at constant temperature and strain rate, thermo mechanical constants for the selected mathematical equation for flow curves were defined using experimentally acquired values with linear regression. These values are written in Table 1. Matching the measured (dashed line) and the calculated values (solid line) is shown on Figures 7, 8 and 9.

Flow curves can be written in the following form[4]:

$$\sigma_f = \sigma_{f0} A_1 e^{-m_1 \vartheta} A_2 \varepsilon^{m_2} e^{-m_3 \varepsilon} A_3 \dot{\varepsilon}^{m_4} \qquad (2)$$

$$\varepsilon = \ln \frac{h_o}{h} \qquad (3)$$

$$\dot{\varepsilon} = \frac{v}{h} \qquad (4)$$

where $\varepsilon$ is the strain, $\dot{\varepsilon}$ is the strain rate, $\vartheta$ is the temperature, $\sigma_{fo}$, $A_1$, $A_2$, $A_3$, $m_1$, $m_2$, $m_3$ are constants, $h_o$ is the initial slab height, $h$ is the instantaneous slab height, and $v$ is the tool velocity.

A new constant B (Table 1) replaces product of the constants $\sigma_{fo}$, $A_1$, $A_2$, and $A_3$.

## Results and discussions

All three materials were deformed in the temperature range between 80 and 210 °C. In this temperature range flow stresses increase with strain trough work hardening up to a critical strain beyond which softening is initiated. Softening includes dynamics recovery and dynamic recrystallization where substructure rearrangements and dislocation reduction lead to decrease in flow stress. With decreasing strain rate or increasing temperature, the strain hardening effect becomes weaken, while the degree of strain softening becomes notable. This phenomena is more evident is as-cast materials. Under a constant strain rate, the peak stress and the peak strain increased with decreasing temperature (Figure 13). Under the same temperature, the peak stress and the peak strain increased with increasing strain rate.

ZnPb alloy indicated minimum values of flow stress in as-cast state at both punch velocities. At the velocity of 0.2 m/s and at the temperature of 210 °C are the values of flow stresses for pure zinc essential greater than for ZnCuTi and ZnPb alloys, at 80 °C they are all nearly the same. Flow stresses for ZnCuTi and ZnPb are similar at higher velocity while flow stresses for Zn in ZnCuTi are similar at lower velocity.

In deformed state and at punch velocity 0.2 m/s values of flow stresses for ZnTiCu and ZnPb are similar to pure Zn with the exception of those at 210 °C where they are all very similar. At lower velocity is the value of flow stress for pure Zn lower as is case for ZnCuTi and ZnPb. At the temperature 210 °C flow stresses for Zn and ZnPb are similar, while for ZnCuTi is higher.

**Table 1.** The values of thermo mechanical constants
**Tabela 1.** Vrednosti termomehanskih konstant

| Material | Initial state | B [MPa] | $m_1$ | $m_2$ | $m_3$ | $m_4$ |
|---|---|---|---|---|---|---|
| Zn | as-cast | 545 | 0.00472 | 0.104 | 1.578 | 0.116 |
| | deformed | 694 | 0.00582 | 0.257 | 1.629 | 0.116 |
| ZnPb | as-cast | 888 | 0.00547 | 0.347 | 1.682 | 0.089 |
| | deformed | 803 | 0.00599 | 0.299 | 1.441 | 0.100 |
| ZnCuTi | as-cast | 1027 | 0.00460 | 0.407 | 1.890 | 0.061 |
| | deformed | 619 | 0.00531 | 0.210 | 1.085 | 0.085 |

Figures 10, 11 and 12 show the stress-strain curves of pure zinc and two alloys ZnCuTi and ZnPb under different deformation conditions. Dynamic recrystallization (DRX) is evident in all cases, even at increasing strain rates. Although calculated flow stress curves have similar shapes as the measured ones, they cannot follow the processes of dynamic softening, present at higher temperatures.

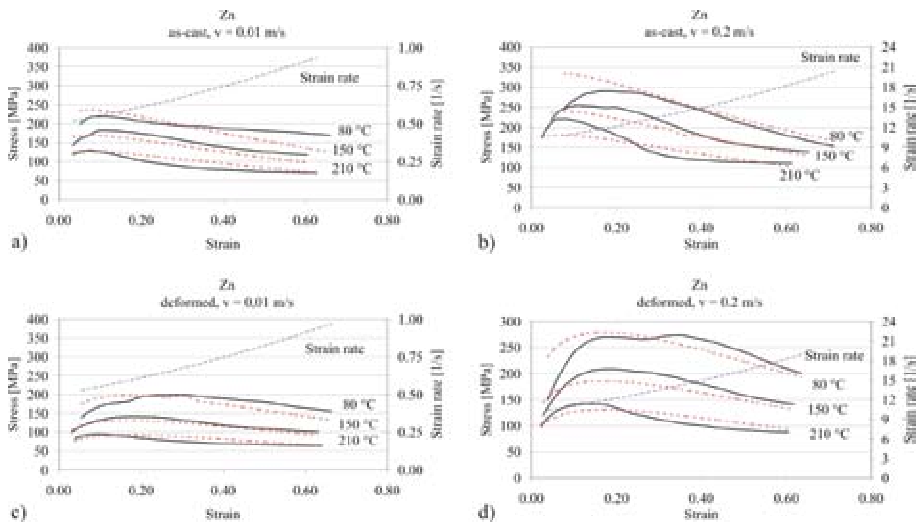



**Figure 10.** Flow stress curves for Zn in as-cast: $v = 0.01$ m/s (a), $v = 0.2$ m/s (b), and deformed state: $v = 0.01$ m/s (c), $v = 0.2$ m/s (d)

**Slika10.** Krivulje tečenja za Zn v ulitem: $v = 0{,}01$ m/s (a), $v = 0{,}2$ m/s (b) in deformiranem stanju: $v = 0{,}01$ m/s (c), $v = 0{,}2$ m/s (d)

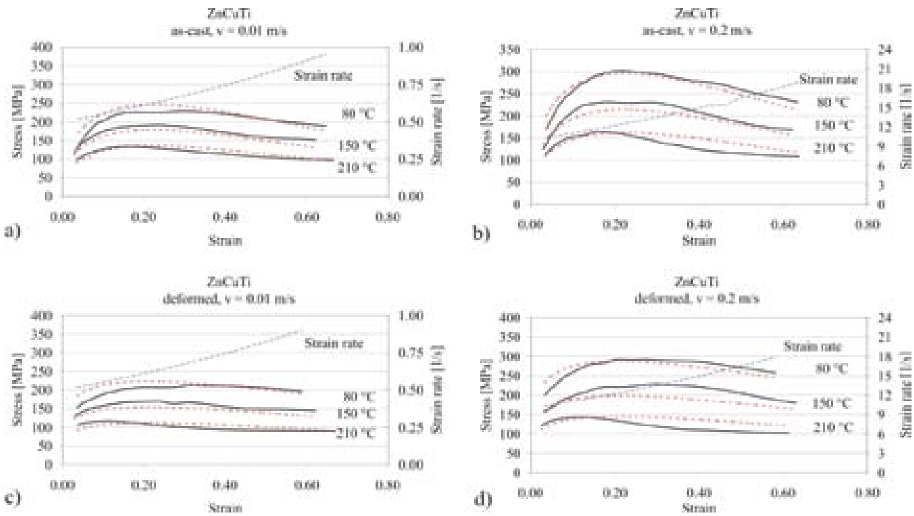



**Figure 11.** Flow stress curves for ZnCuTi in as-cast: $v$ = 0.01 m/s (a), $v$ = 0.2 m/s (b), and deformed state: $v$ = 0.01 m/s (c), $v$ = 0.2 m/s (d)
**Slika 11.** Krivulje tečenja za ZnCuTi v ulitem: $v$ = 0,01 m/s (a), $v$ = 0,2 m/s (b) in deformiranem stanju: $v$ = 0,01 m/s (c), $v$ = 0,2 m/s (d)

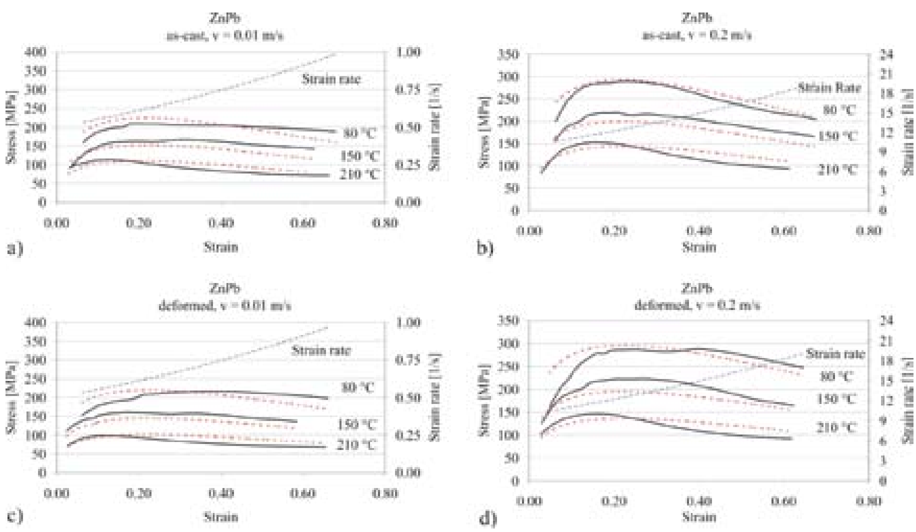



**Figure 12.** Flow stress curves for ZnPb in as-cast: $v$ = 0.01 m/s (a), $v$ = 0.2 m/s (b), and deformed state: $v$ = 0.01 m/s (c), $v$ = 0.2 m/s (d)
**Slika 12.** Krivulje tečenja za ZnPb v ulitem: $v$ = 0,01 m/s (a), $v$ = 0,2 m/s (b) in deformiranem stanju: $v$ = 0,01 m/s (c), $v$ = 0,2 m/s (d)

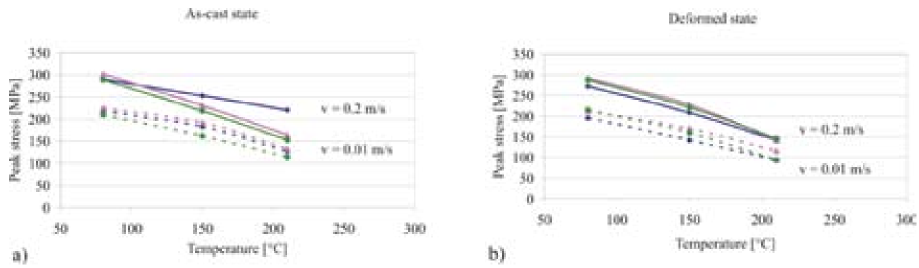



**Figure 13.** Peak stresses for as-cast (a) and deformed state (b)
**Slika 13.** Natezne trdnosti v ulitem (a) in deformiranem stanju (b)

## CONCLUSIONS

1. True stress-strain curves for Zn and its alloys were defined at known thermo mechanical parameters.
2. Multilevel linear regression method was used to define thermo mechanical constants in dependence of initial state of material, strain, strain rate and temperature. These constants were obtained for extensive area of the thermo mechanical parameters and therefore they render impossible to describe all fineness, which have influence to stress-strain dependences.
3. For more accurate estimation of flow stress, applied mathematical expression should be improved or the area of thermo mechanical parameters should be tightened.
4. In as-cast state softening process is more evident.

## POVZETEK

### Toplo preoblikovanje Zn in zlitin ZnCuTi ter ZnPb

Raziskali smo tople preoblikovalnosti čistega cinka, zlitine ZnPb (0,8 %Pb) in zlitine ZnCuTi (0,11 % Cu, 0,1 % Ti) v litem in predhodno deformiranem stanju (30 %). Za določitev preoblikovalnih lastnosti smo uporabili tlačni preizkus. Preizkušanci so bili valjčki premera 15,5 mm in višine 20 mm. Za lito stanje so bili valjčki odvzeti iz sredine ulitih trakov dimenzije 40×80×1500 mm. Ker je bilo dno kokile vodno hlajeno, se je v tem področju tvorilo območje drobne kristalizacije. Srednji del traka je imel značilno območje usmerjene kristalizacije, ki je bilo primerljivo z dejansko makrostrukturo plošč izdelanih v realnih pogojih tehnološkega procesa. Tudi v deformiranih ploščah je še vedno razvidna določena usmerjenost rekristaliziranih zrn v smeri ulitih dendritskih zrn. Ta usmerjenost pa ni razvidna v makrostrukturi vzdolžnih presekov valjčkov, kar je dokaz o pravilnem odvzemu vzorcev iz plošč.

Ker preiskuševalni stroj za tlačne preizkuse ni bil opremljen s sistemom za ogrevanje vzorcev, smo izdelali napravo, s katero smo vzorce in tudi orodje ogrevali v oljni kopeli. Preizkuse smo izvajali pri dveh hitrostih pomika orodja: 0,2 in 0,01 m/s ter treh temperaturah: 80, 150 in 210 °C. Iz izmerjenih vrednosti sil in deformacij in z upoštevanjem koeficenta trenja (<0,2) smo določili preoblikovalne trdnosti.

Ker so krivulje tečenja definirane za konstantne temperature in hitrosti deformacij, smo na osnovi eksperimentalno dobljenih vrednosti z linearno regresijo določili termomehanske konstante za izbran matematičen zapis krivulj tečenja. Analitično izračunane vrednosti iz funkcijskega izraza se z regresijsko dobljenimi konstantami za eksperimente celotnega variiranja termomehanskih parametrov bolj ali manj prilagajajo izmerjenim rezultatom. Izračunane krivulje imajo sicer podobno obliko t.j. najprej naraščajoč potem pa padajoč značaj, ne morejo pa povsem slediti procesom dinamičnega mehčanja.

Vsi preiskovani materiali so v temperaturnem območju med 80 in 210 °C nahajajo v toplem stanju, to pomeni, da začetnemu utrjevanju sledi po dosegu kritične deformacije mehčanje dinamičnega značaja. Maksimumi napetosti tečenja teh krivulj se z naraščajočo temperaturo pomikajo k nižjim deformacijam, z naraščajočo hitrostjo deformacije pa proti višjim vrednostim deformacij. Ta zakonitost je podobna za vse preiskovane materiale. Nastopajo bistvene razlike v poteku preoblikovalnih trdnosti, če imamo za izhodišče enkrat lito drugič pa deformirano stanje. V litem stanju je intenziteta mehčanja večja, kritična napetost tečenja pa je dosežena že pri nekoliko nižjih deformacijah kot v deformiranem stanju.

V litem stanju so vrednosti preoblikovalnih trdnosti pri obeh hitrostih stiskanja najnižje za zlitino ZnPb. Pri hitrosti stiskanja 0,2 m/s in temperaturi 210 °C so vrednosti za čisti Zn bistveno večje od ostalih dveh, medtem ko so si vrednosti pri 80 °C približno enake. Pri višji hitrosti sta si preoblikovalni trdnosti za ZnCuTi in ZnPb podobni, pri nižji hitrosti pa sta si podobni preoblikovalni trdnosti za Zn in ZnCuTi.

V deformiranem stanju se pri hitrosti stiskanja 0,2 m/s vrednosti preoblikovalnih trdnosti za ZnTiCu in ZnPb bistveno ne razlikujeta in sta višji od čistega Zn razen pri temperaturi 210 °C, ko so si vrednosti enake. Tudi pri hitrosti stiskanja 0,01 m/s je preoblikovalna trdnost za Zn nižja kot pri ostalih dveh kvalitetah. Pri temperaturi 210 °C pa sta si vrednosti za Zn in ZnPb enaki, medtem, ko je preoblikovalna trdnost za ZnCuTi višja.

Zlitine se med seboj glede na legirne elemente ločijo po zahtevani napetosti tečenja in v splošnem velja brez izjem, da je proces mehčanja, ki ga pripišemo rekristalizaciji deloma pa tudi popravi, intenzivnejši pri litem stanju.

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