Increasing of hot deformability of tool steels – preliminary results

Povečanje vroče preoblikovalnosti orodnih jekel – preliminarni rezultati

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Abstract: The influences on the hot deformability of ledeburitic tool steels are very complex since many processing parameters in process chain of steel are involved. For increasing the hot deformability of tool steels thus several research steeps should be carried out, i.e. determination of an appropriate soaking temperature, the ranges of safe hot deformation and optimal hot working conditions, optimisation of chemical composition of tool steels, appropriate dimensions of the ingot (cooling rate), etc. The results presented in the contribution demonstrate the importance of the suggested approach for increasing the hot deformability and were obtained on base of industrial practice and of experiments carried out on a Gleeble 1500D thermo-mechanical simulator.

Izvleček: V tem prispevku so prikazani nekateri koraki, ki jih moramo izvesti na ledeburitnih orodnih jeklih, da bi zvišali njihovo plastično sposobnost v vročem, t.j. določitev primerne temperature ogrevanja, določitev območij varnega vročega preoblikovanja ter najbolj optimalnih pogojev preoblikovanja, optimiranje kemične sestave, določitev primerne temperature litja, optimalne dimenzije ingota (hitrost ohlajanja), itd. Na posameznih primerih izbranih orodnih jekel so prikazani rezultati, ki ilustrirajo pomen predlaganega pristopa pri zvišanju plastičnih sposobnosti orodnih jekel. Rezultati, ki potrjujejo omenjeni pristop, so bili dobljeni tako v industrijski praksi kot tudi na simulatorju termomehanskih metalurških stanj Gleeble 1500D.

Keywords: tool steels, cooling rate, hot compression, soaking temperature, chemical composition, neural networks

Ključne besede: orodna jekla, ohlajevalna hitrost, vroče stiskanje, temperature ogrevanja, kemična sestava, nevronske mreže

Scientific paper

INTRODUCTION

The occurrence of surface cracking during hot forming (hot deformability) of ledeburitic tool steels is still an insufficiently investigated research area; it is influenced as much by processing and geometrical as by intrinsic (material) properties. Alloying elements (V, Cr, Mo, etc) in tool steels form carbides that improve hardenability, control grain growth, increase strength, hardness, wear resistance, etc. and decrease hot deformability and make hot working temperature range very narrow in comparison to conventional steels. Additionally the majority of tool steels are nowadays produced from scrap material and thus besides carbide-forming elements other elements such as copper and tin have a strong influence on hot deformability of tool steels when their concentration is not in the acceptable range. Their presence can form eutectic phases with low melting points or phases that are brittle and are predominantly precipitated on grain boundaries. Thus, determination of the acceptable chemical composition of any tool steel is in important step at increasing hot deformability. The relatively low hot deformability of tool steels is characterized by the production of external (surface) as well as of internal cracks during hot forming. This reduces the profitability of the production process, as well as the useful mechanical properties of the tool steel since the defects in the tool material originate in general from inadequate low hot deformability as well as from inappropriate hot working conditions[1-9].

Publications in the literature with regards to hot deformability of low alloyed steels as well as those regarding tool steels, are predominately of a partial nature. Namely, they study only the influence of particular factors on hot deformability i.e., determination of the upper and lower temperatures of hot working, determination of the limit of hot plasticity, influence of deformation parameters on hot deformability, precipitation of carbides, etc. Moreover, hot tension, hot compression, hot torsion and laboratory hot rolling tests were applied and the materials were predominately in the wrought (deformed) state; the influence of thermo-mechanical parameters (cooling rate, casting temperature, variable chemical composition, soaking temperature) in previous processing chains usually were not considered. Any contribution in this research area in which the occurrence of cracking during hot forming is studied by more integral approach and in which the basic points which characterize the relevant processes that take place in the materials in the whole processing chain of steel production, will be defined, is important and valuable. It is important to mention that the values of the chosen processing parameters in previous processing chains should have a positive influence on hot deformability; any eventual negative influence can be partly compensated by appropriately chosen hot deformation parameters. Modern practice proves that the above mentioned thermo-mechanical processing parameters significantly influence the chosen deformation parameters and thus they cannot be constant.

The investigation of the presented paper is dealing with processing of tool steels BRM2, OCR12VM, CRV3 and BRCMO2. Some steps that should be applied in order

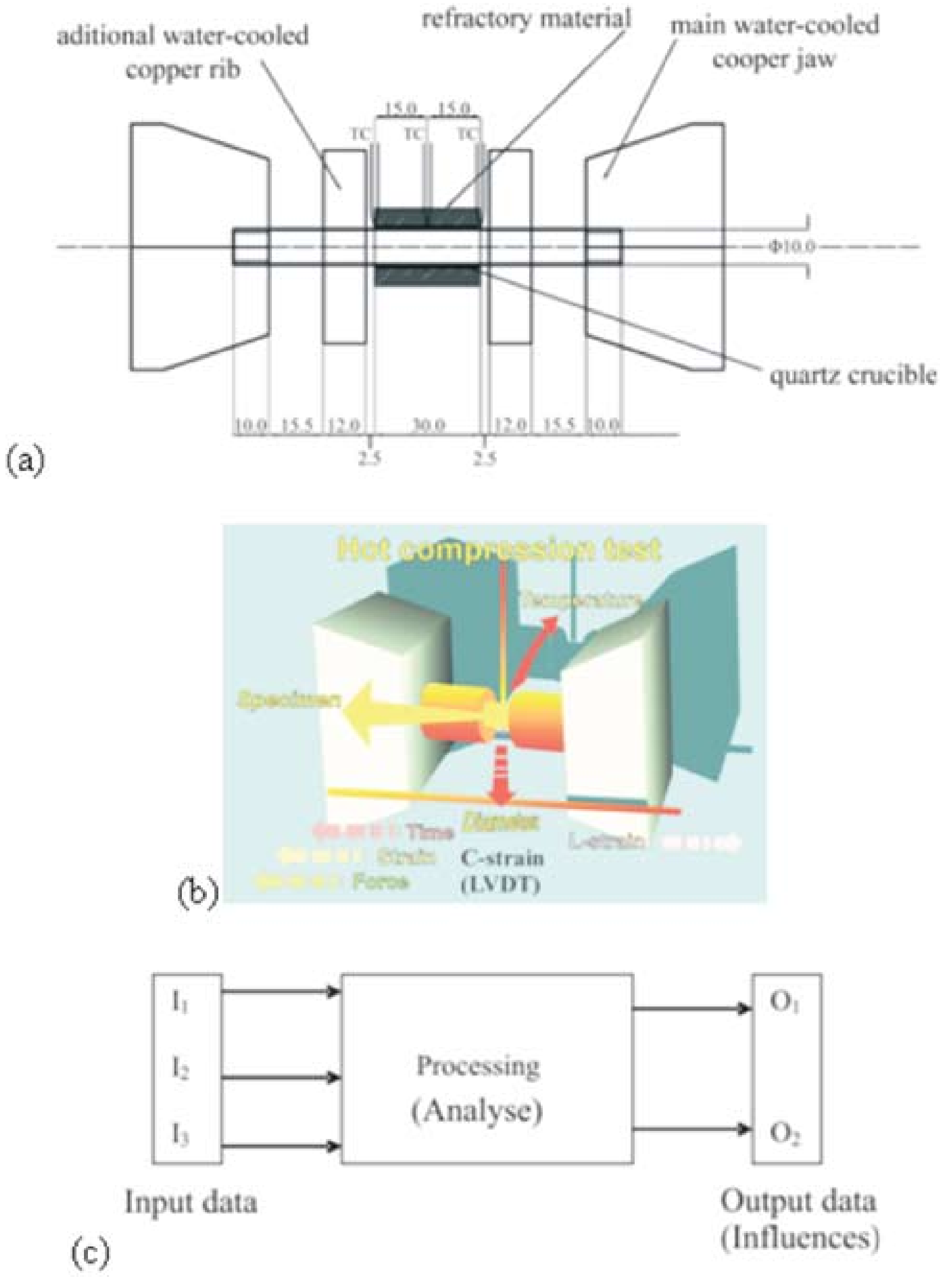

Figure 1. Applied method and tests: solidification test (a)[12], hot compression test (b), schematic presentation of analyse of influences on hot deformability by CAE neural networks (c)

Slika 1. Uporabljene metode in testi: test strjevanja (a)[12], tlačni preizkusi v vročem (b), shematski prikaz analize vplivov parametrov na vročo preoblikovalnost s CAE nevronskimi mrežami (c) to increase their hot deformability, i.e. determination of optimal casting temperature, cooling rate, soaking temperature, working range or safe hot deformation and determination of acceptable chemical composition are suggested. Thus, an extension of hot deformability and consequently improvement in the applied mechanical properties of tool steels can be achieved.

Experimental

Applied methods and equipment

Gleeble 1500D was applied so for simulation of solidification process at various rates as well as for hot compression. Specially developed test, presented in Figure 1a [12], was used for simulation of solidification process; the test is computer guided thus various process paths and resulting microstructures can be obtained with varying of solidification and cooling rates. Upper and lower temperature range of safe hot deformation was obtained by hot compression tests (Figure 1b). The applied criterion was occurrence or non-occurrence of cracks on deformed specimens at compression strain of 0.9. The data on hot deformability was colected in industrial conditions as well as in laboratory. Analyse of influences on hot deformability was carried out by CAE neural networks (see Figure 1c). The data base consists of industrial as well as of laboratory results. Optical mycroscopy (Olympus BX61) was used for observation of microstructure.

Description of applied tool steels

The proposed new approach will be illustrated with particular results obtained in thermo-mechanical processing of ledeburitic tool steels, i.e. BRM2 (HSS), OCR12VM (cold working tool steel), CRV3 (cold working tool steel) and BRCMO2 (super HSS). All these steels contain C and carbide-forming elements (Cr, W, Mo and V, chemical composition is given in Table 1). The microstructure of these steels consists of a martensitic matrix in which the ledeburitic and secondary carbides are present. These tool steels have specifically useful mechanical properties such as high hardness, wear resistance and high tempering resistance on one hand and higher flow stress and lower hot deformability on the other. The morphology, size, distribution and type of carbides influence on the behaviour of the material during hot forming were studied. During heating, soaking and hot deformation various processes take place: decay (decomposition) of carbide phases and formation of new carbide phases (secondary phases) and dissolution of carbides and of alloying elements. All these processes and properties of particular phases, their volume fraction (proportion) and chemical composition result in hardening during hot deformation that decreases hot deformability[2-7]. In Figure 2a-b typical microstructures of ledeburitic tool steels for as-cast and wrought (deformed) states are presented, respectively. Figure 2c shows the approximate values of microhardness of the relevant carbides.

Table 1. Chemical composition of applied tool steels (wt.%)
Tabela 1. Kemična sestava preiskovanih orodnih jekel (mas.%)

	C	**Si**	**Mn**	**Cr**	**Mo**	**V**	**W**	**Co**
BRM2	0.90	0.30	0.30	4.05	5.10	1.95	6.35	-
BRCMO2	1.09	0.26	0.25	3,81	9.32	1.09	1.40	8.20
OCR12VM	1.52	0.25	0.32	11.65	0.80	0.89	-	-
CRV3	1.17	0.24	0.26	11.3	1.35	1.48	2.24	-

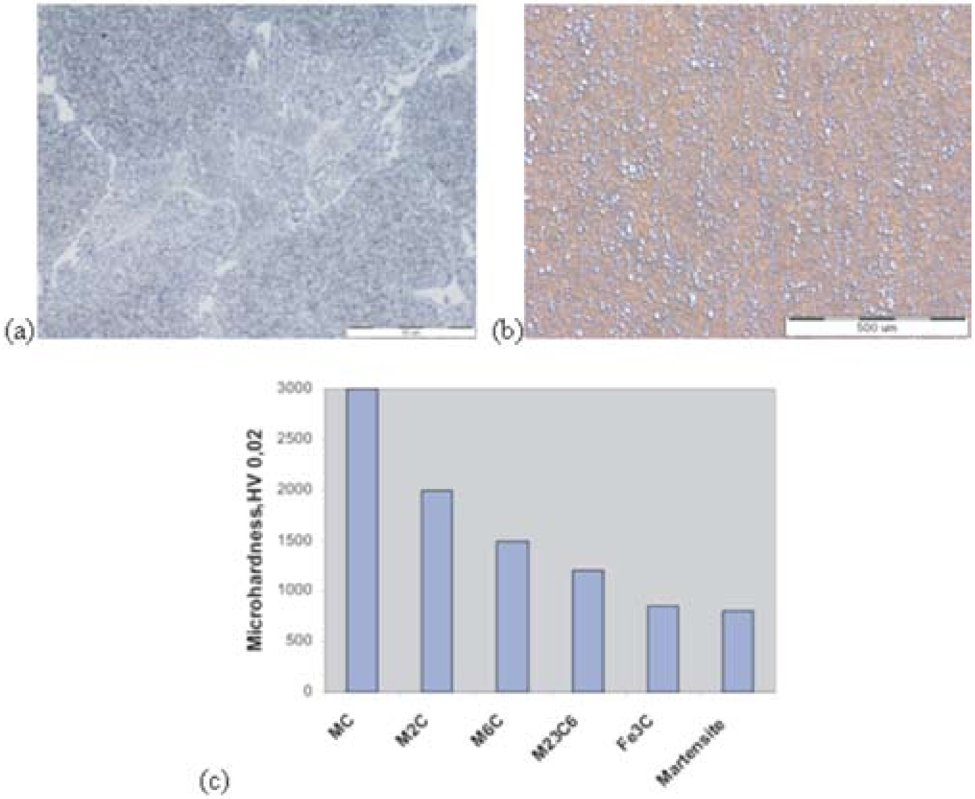

Figure 2. Typical microstructures of tool steels: BRCMO2 as-cast state (a), BRCMO2 in wrought (deformed) state (b), and microhardness values of carbides[4] (c)
Slika 2. Tipična mikrostruktura orodnih jekel: BRCMO2, lito stanje (a), BRCMO2 predelano stanje (b) in mikrotrdote posameznih karbidov[4] (c)

RESULTS ON EXPERIMENTAL AND COMPUTATIONAL STEPS NEEDED FOR INCREASING OF HOT DEFORMABILITY

Determination of an appropriate casting temperature and cooling rate

The casting temperature and cooling rate during solidification influence the diffusion processes. Depending on the cooling rate, precipitation of different types of carbides with different chemical composition, morphology and distribution may occur during solidification. This results in different microstructures with different proportion of particular phases with various properties and different hot deformability. In the ingot due to different cooling rates in the cross section, different microstructures are formed. The measured cooling rate[11] of the ingot core was approximately 0.36 K/s. Figure 3 presents the microstructure obtained at various cooling rates on solidification of super high speed steel (BRCMO2). In the vicinity of the ingot surface, where the cooling rate was the highest (>0.36 K/s), in the soft annealed microstructure of spheroidal perlite, M_2C type of eutectic carbides with fine lamellar morphology can be hardly visible (Figure 3a). In Figure 3b the microstructure ob-

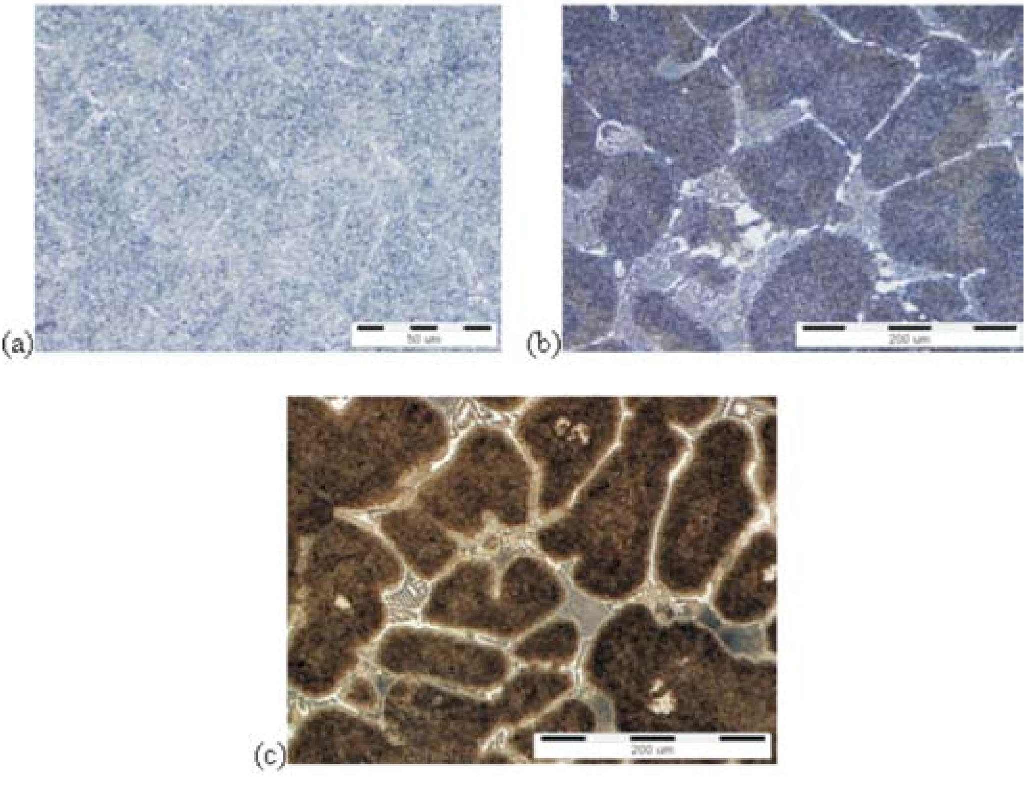

Figure 3. Microstructures obtained at various cooling rates of BRCMO2 tool steel, >0.36 K/s (a), 0.36 K/s (b) and 0.16 K/s (c)

Slika 3. Mikrostrukture dobljene pri različnih ohlajevalnih hitrostih za jeklo BRCMO2, >0,36 K/s (a), 0,36 K/s (b) in 0,16 K/s (c) tained 50 mm from the ingot centre where the cooling rate was approximately 0.36 K/s is presented. In the soft annealed basic microstructure coarse eutectic cells of coarser lamellar eutectic type M_2C and primary carbides is visible (compared to Figure 3a). The microstructure in Figure 3c was obtained by simulation of the solidification process at a cooling rate of 0.166 K/s; the solidification process was carried out on the Gleeble 1500D thermomechanical simulator as reported in[12]. In the microstructure beside M_2C eutectic carbides, the eutectic carbide M_6C with fish bone morphology can also be observed. It is obvious that the morphology, proportion of various types of carbides and their chemical composition are different at different cooling rates. Thus the weight and dimensions of ingots influences the obtained microstructures and consequently also the hot deformability.

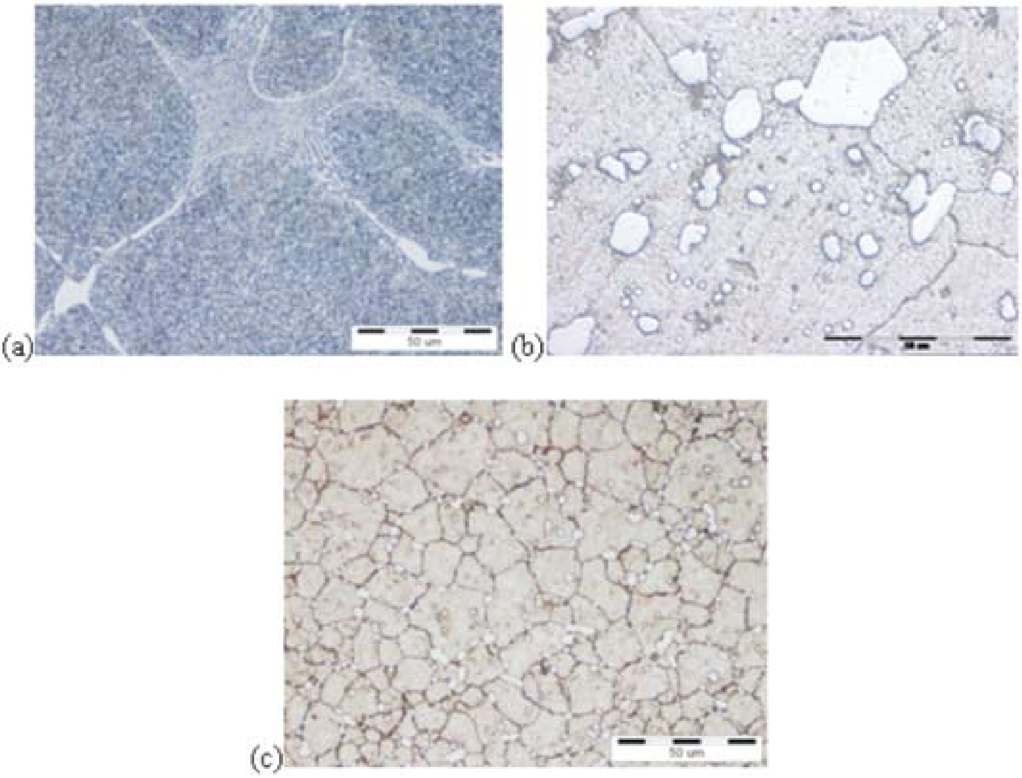

Figure 4. Initial as-cast microstructure of ingot (a); microstructure obtained in rolled piece at inappropriate soaking temperature (b); microstructure obtained in rolled piece at appropriate soaking temperature (c); BRCMO2 tool steel

Slika 4. Začetna mikrostruktura vlitega ingota (a); mikrostruktura dobljena iz končnega, valjanega dela, ogrevanega pri neprimerni temperaturi (b); mikrostruktura dobljena iz končnega, valjanega dela, ogrevanega pri primerni temperaturi (c); orodno jeklo BRCMO2

Assessment of an appropriate soaking temperature

Before conducting the hot compression tests, the appropriate soaking temperatures for as-cast and for the deformed initial state were assessed. This step is presented for the case of hot forming of BRCMO2 tool steel. The criterion for its assessment was the appearance of cracks on the compressed specimen surface at a strain of 0.9. The soaking temperature influences the processes of dissolution of fine carbides, coagulation and growth of coarse carbides, proportion of equilibrium phases, and growth of austenitic grains. The fine lamellar as-cast microstructure of an ingot (BRCMO2, Figure 4a) in the case of inappropriate (too high) soaking temperature deformed by hot rolling (in end rolled piece) with a microstructure consisting of coarse grains and coarse eutectic carbides (Figure 4b). In the case of an appropriate soaking temperature the initial microstructure can be deformed into an end piece with fine grained microstructure with fine and homogenously distributed eutectic carbides (Figure 4c). Thus the soaking temperature does not influence only the hot deformability but also the mechanical properties of the product. Further, hot compression testing (using the proposed criterion) revealed that the appropriate soaking temperature for a deformed microstructure (same chemical composition, same charge) differs from that for the as-cast state.

The soaking temperature also influences the lower limit of the temperature range for safe hot forming. This example is presented for the case of hot forming of OCR12VM tool steel in Figure 5. In the case of an appropriate soaking temperature it was possible to deform at 850 ºC without the occurrence of micro-cracks in the deformed piece (Figure 5a-b). In the case of an inappropriate soaking temperature and hot forming at the same temperature (850 ºC), micro- (on triple points and along grain boundaries) and macro-cracks occurred (Figure 5c-e). Thus the working temperature range is narrowed due to the shift of lower temperature of safe hot forming to higher values. This could be explained by intensive precipitation of secondary carbides along the grain boundaries (Figure 5e) during the deformation phase; coarser eutectic carbides are formed as a consequence of the inappropriate soaking temperature that decreases hot deformability. It is general known that too coarse carbides precipitated on grain boundaries decrease the hot deformability especially on lower limit of working range.

Determination of safe hot working range

This step is illustrated on CRV3 tool steel for wrought (deformed) initial state. After the determination of the optimal soaking temperature, hot compression tests were carried out in order to determine the flow stresses and range of safe hot deformation. Physical simulation of the hot working process was carried out on the Gleeble 1500D thermo-mechanical simulator. Cylindrical specimen dimensions of ϕ=10 mm × 15 mm were applied. The following testing conditions were chosen: temperature range 850-1180 °C, strain rates 0.001-6 s^{-1} and true strains 0-0.9 (Table 2). On the basis of the obtained flow curves, the range of safe hot deformation was estimated by Prasad’s processing map. This was developed on the basis of a dynamic

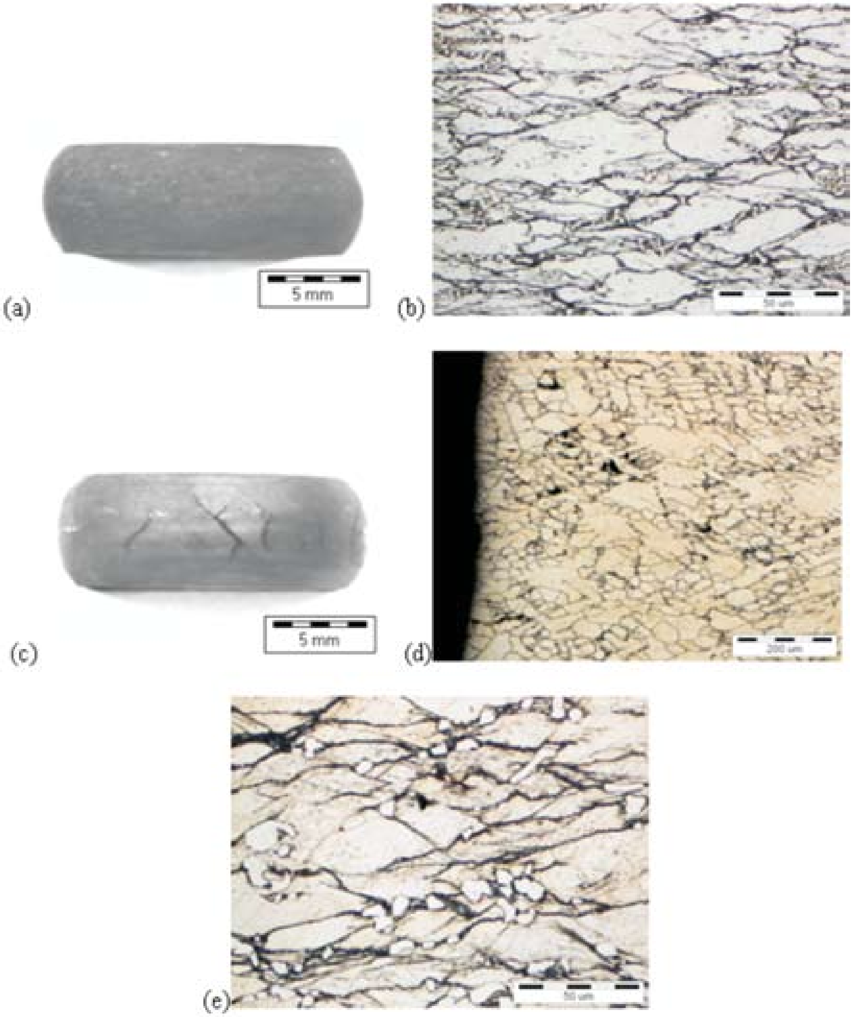

Figure 5. Influence of soaking temperature on hot deformability at 850 °C for OCR12VM, macro view of deformed specimen (soaked at an appropriate temperature) (a), microstructure of deformed specimen (soaked at an appropriate temperature) (b), macro-cracks on deformed specimen soaked at an inappropriate temperature (c), formation of micro-cracks on grain boundaries (soaked at an inappropriate temperature) (d), precipitated carbides on grain boundaries and coarser eutectic carbides (soaked at an inappropriate temperature) (e)

Slika 5. Vpliv ogrevne temperature na vročo deformacijo pri 850 °C za jeklo OCR12VM, makroposnetek deformiranega vzorca (ogrevanega na primerno temperaturo) (a), mikrostruktura deformiranega vzorca (ogrevanega na primerno temperaturo) (b), makro razpoke na površini deformiranega vzorca (ogrevanega na neprimerno temperaturo) (c), nastanek mikro razpok na mejah zrn deformiranega vzorca (ogrevanega na neprimerno temperaturo) (d), izločeni karbidi na mejah zrn in grobi evtektski karbidi (ogrevano na neprimerno temperaturo) (e) material model (DMM). The processing map of the material can be described as an explicit representation of its response to the imposed process parameters. This is a superimposition of the efficiency of power dissipation (equation 1) and an instability map (equation 2).

$$\eta = \frac{2m}{m+1} \tag{1}$$

$$\xi\left(\dot{\bar{\varepsilon}}\right) = \frac{\partial \ \ln(m/(m+1))}{\partial \ln \dot{\bar{\varepsilon}}} + m > 0 \tag{2}$$

In equations 1 and 2, η is efficiency of power dissipation, m is strain rate sensitivity, ξ is parameter expressing stability or instability of flow behaviour (ξ<0 indicates on instable flow behaviour) and $\dot{\bar{\varepsilon}}$ is average strain rate.

One can find details about processing maps in[10]. In Figure 6a-b the efficiency of power dissipation and the instability map at strains of 0.2 and 0.4 are presented, respectively. The relatively low values for the efficiency of power dissipation indicate smaller microstructural changes (dynamic recrystallization and recovery) and consequently also possible lower hot ductility. Instable areas of hot deformation occur at lower strain rates (approximately at 0.01 s^{-1}) and lower deformation temperatures (below 950 °C) as a consequence of precipitation of secondary carbides on grain boundaries (Figures 7a-b).

Laboratory assesment of the upper and lower limit of the working range

At the upper limit of the working range for CRV3 tool steel, due to the increase (up to 40 ºC) of specimen temperature during deformation, local melting and precipitation of thin films of eutectic carbides took place along the grain boundaries, resulting in a rapid decrease of hot deformability. In this case precipitated new eutectic has lamellar morphology (Figure 8). On

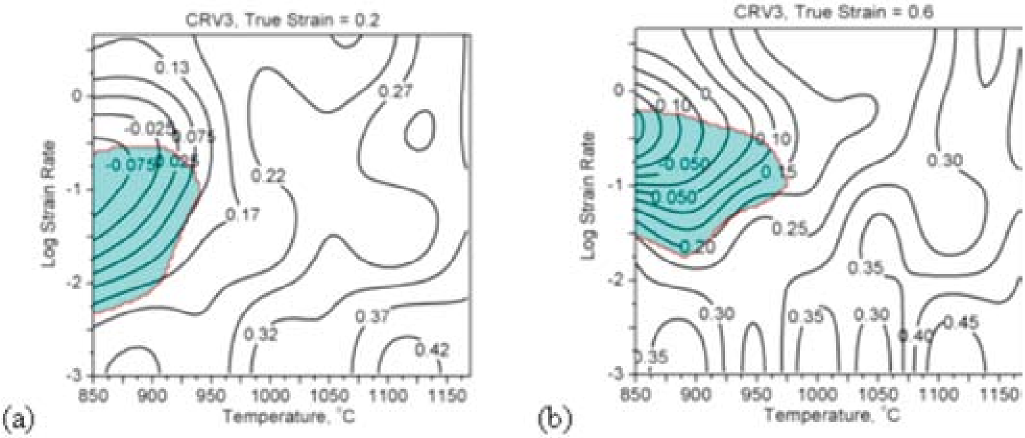

Figure 6. Superimposition of efficiency of power dissipation and instability map for CRV3 tool steel for deformed state at strain of 0.2 (a) and at strain of 0.6 (b)

Slika 6. Učinkovitost porabe moči in mape nestabilnosti za CRV3 orodno jeklo, pri deformaciji 0,2 (a) in 0,4 (b)

Table 2. Testing (hot compression) conditions for CRV3 tool steel
Tabela 2. Tesni pogoji za tlačne preizkuse v vročem za CRV3 orodno jeklo

Deform. temp./ ºC	**Strain rate / s^{-1}**
850, 900, 950, 1000, 1050, 1100, 1150, 1160, 1170, 1180	0.001, 0.01, 0.1, 1.0, 6.0

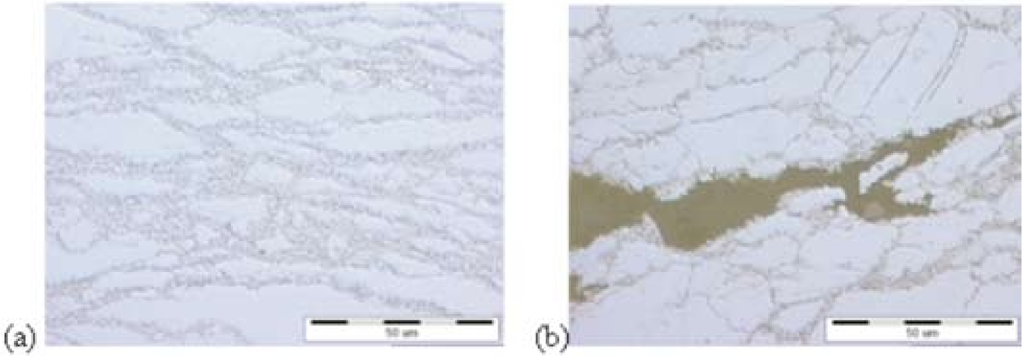

Figure 7. Microstructure of deformed specimen obtained at 850 °C, showing precipitation of carbides on grain boundaries (a), and occurrence of cracking on grain boundaries (b); strain rate 0.01 s^{-1}, CRV3 tool steel
Slika 7. Mikrostruktura vzorca deformiranega pri 850 °C z izločki na mejah zrn (a) in pojavom razpok na mejah zrn (b); hitrost deformacije 0,01 s^{-1}, orodno jeklo CRV3

the same figure cracking caused by grain boundary melting is also presented. At the lower limit of the working range the carbides that have precipitated during hot deformation along grain boundaries (Figure 7a) are responsible for the occurrence of cracking (Figure 7b). Carbides inhibit the movement of grain boundaries as well as processes of dynamic recrystallization, leading to occurrence of cracking at higher strains ($\varepsilon = 0.6$). Thus examination of the microstructure confirms the position of the instability area shown in Figure 6.

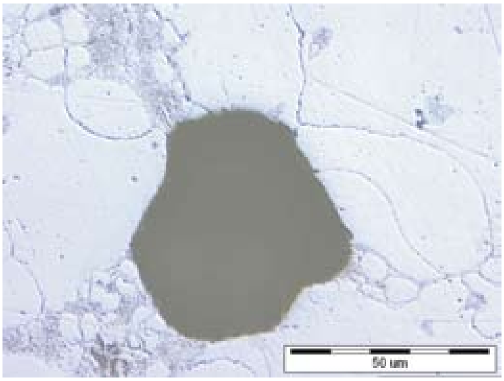

Figure 8. Formation of eutectic with lamellar morphology and grain boundary cracking
Slika 8. Tvorba evtektika z lamelarno morfologijo in pokanje na mejah zrn

Precipitation of carbides along grain boundaries is also expressed by the increasing of maximum flow curve values at lower strain rates. Namely, at lower strain rates the processes of carbides precipitation during hot deformation is more emphasised in comparison to higher strain rates, leading to higher values of the flow curves (peak values, Figure 9). The processes of hardening are so intense during the deformation at 850-950 °C that the values of peak stresses at lower strain rates intersect the values of peak stresses obtained at higher strain rates. Chemical composition of tool steel effects on upper limit of working range, since the temperature of precipitated eutectic carbides can vary up to 20 °C.

Determination of optimal chemical composition

Neural networks enable analysis of each individual parameter, as well analysis of the simultaneous influence of several parameters on hot deformability. The last step which contributes to increase of hot deformability is optimisation of chemical composition in the framework of its allowable variations. But at least two ranges should be considered separately, i.e. upper limit of working range and medium of working range. For analysis of the influence of chemical composition on hot deformability, the application of artificial neural networks is more appropriate than classical statistical methods. Beside the presence of carbides in the microstructure, other elements (oligo elements, trace elements) also influence the hot deformability.

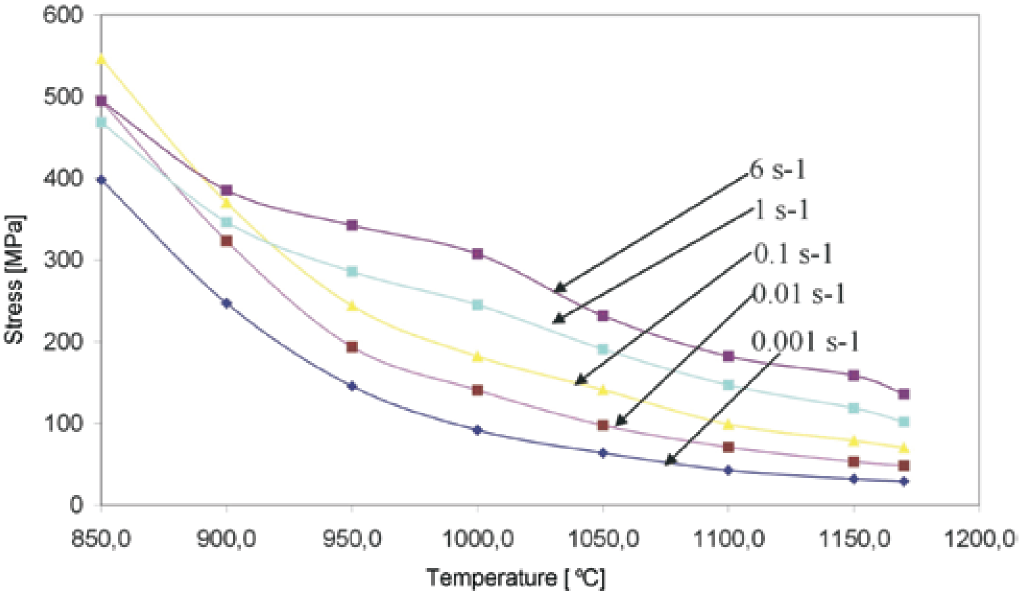

Figure 9. Influence of strain rates and temperatures on peak values of flow curves, CRV3 tool steel

Slika 9. Vpliv hitrosti deformacije in temperature na maksimalne napetosti tečenja za orodno jeklo CRV3

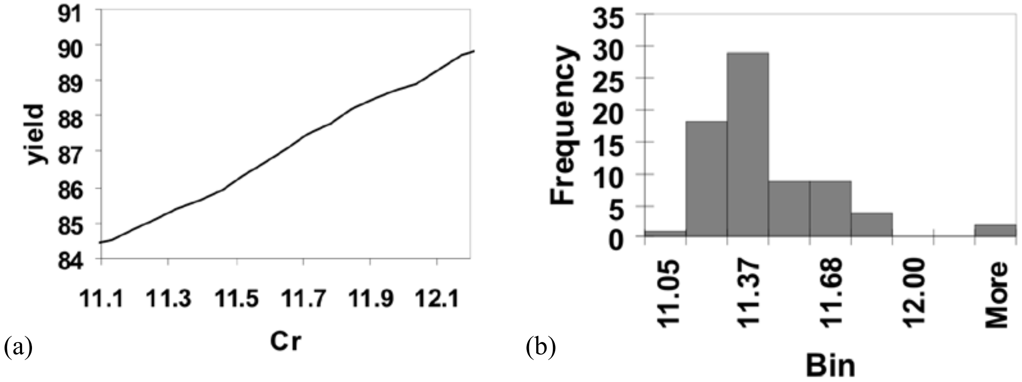

Figure 10. Influence of Cr on yield of hot rolling (influence on upper working range) (a) and frequency of distribution of Cr (b), OCR12VM tool steel
Slika 10. Vpliv Cr na izplen vročega valjanja (a), frekvenca razporeditve Cr (b) za orodno jeklo OVR12VM

Optimisation of chemical condition considering upper limit working range

Upper limit of working range is determined by occurence of incipient melting, i.e. usually presence of eutectic carbides and phases with low melting point are decisive factors. On base of industrial data (yield and chemical composition) for OCR12VM tool steel where the ingots were soaked on upper limit of the temperature range and after this also hot rolled, and by means of CAE NN the results of influence of Cr on hot deformability (yield) is given in Figure 10a. On Figure 10b the frequency of Cr distribution is given. From the Figure 10a it is visible that increased content of Cr results in increased yield. The result was proven also by thermocalc calculation; increased content of Cr also increases temperature of precipitation of eutectic carbides. Also other chemical elements (especially carbide-forming) influence the temperature of precipitation of eutectic carbides. The results indicate that upper limit of working range can vary in range of about 25 °C thus chemical composition should be considered as a determining factor in processing parameters.

Optimisation of chemical condition considering medium working range

For BRM2 tool steel hot torsion tests (medium working range, temperature of deformation 1060 °C, strain rate $1s^{-1}$) were carried out in order determine hot deformability (number of spins up to breakdown of the tested specimen[9]). In this analysis 128 various test specimens (deformed state) with different chemical composition were included. On Figure 11a-b the influence of carbon and vanadium on hot deformability are presented. Allowable variation of carbon is in range 0.86-0.94 wt.% and of vanadium 1.7-2.1 wt.%. From Figure 11 it apparent that the optimal value for carbon is 0.88 wt.%, while the values of vanadium should be at the lower limit of the allowable variation.

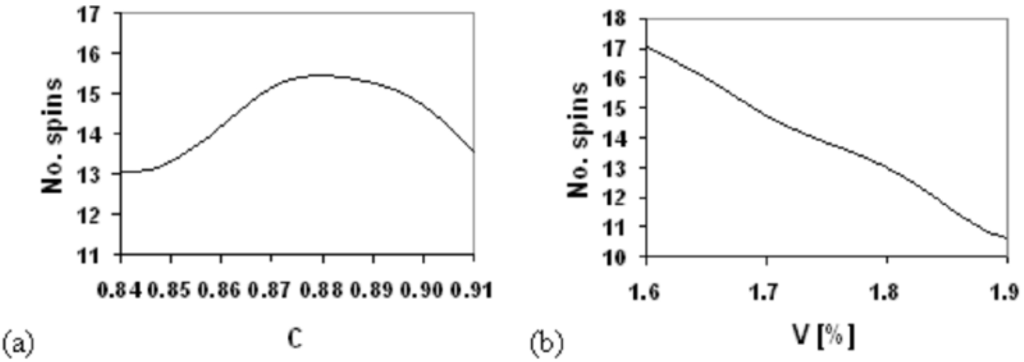

Figure 11. Hot deformability (plasticity) as function of content of chemical elements for medium working range: (a) carbon (C), (b) vanadium (V), BRM2 tool steel
Slika 11. Vroča plastičnost kot funkcija vsebnosti kemijskih elementov za orodno jeklo BRM2: ogljik (a) in vanadij (b)

CONCLUSIONS

The influences of processing parameters (factors), chemical composition, etc on the hot deformability of ledeburitic tool steels are very complex. Many processing parameters (in all process chains) of steel production (including soaking and hot forming) are involved thus integral research approach should be applied in order to increase hot deformability. In this contribution some recomended steps that should be carried out for increasing hot deformability are presented. The following should be emphasised:

1. The cooling rate influences the formation of various phases and the types of carbides of differing morphology, size, chemical composition and properties.
2. Soaking temperature influences the dissolution, the growth and coagulation of carbides, growth of austenitic grains and the precipitation of carbides at lower temperatures in the working range.
3. Chemical composition, despite its variation within the allowable range, influences the hot deformability of tool steels but in different way on upper working range in comparison to medium working range.
4. The highest temperature of the working range is determined by the beginning of incipient melting, while the lowest temperature is defined by the occurrence of micro-cracking as a consequence of precipitation of carbides on grain boundaries.
5. The deformations (strains) can be higher in the range of optimal hot working condition.

POVZETEK

Povečanje vroče preoblikovalnosti orodnih jekel – preliminarni rezultati

Vplivi procesnih parametrov izdelave, kemične sestave itd. na vročo plastičnost ledeburitnih jekel so zelo kompleksni, zato je potreben bolj integralni pristop, če želimo dvigniti vročo preoblikovalnost. Rezultati raziskave so strnjeni v naslednjem:

1. Hitrost ohlajanja vpliva na formiranje različnih faz ter karbidov z različnimi morfologijami, obliko, tipom in velikostjo.
2. Temperatura ogrevanja vpliva na raztopitev, rast in koagulacijo karbidov, rast avstenitnih zrn in izločanje karbidov na spodnji meji temperaturnega območja preoblikovanja.
3. Kemična sestava, kljub variranju v dopustnih mejah različno vpliva na preoblikovalnost na zgornji meji oz. v sredini področja preoblikovanja.
4. Zgornja temperatura preoblikovanja je določena s pričetkom taljenja na kristalnih mejah, spodnja meja pa s pojavom mikrorazpok kot posledica izločanja karbidov.
5. Deformacije so lahko večje v srednjem temperaturnem območju preoblikovanja.

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