Hot forming of AISI D2 tool steel

Vroče preoblikovanje AISI D2 orodnega jekla

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Abstract: Surface cracking during hot forming of AISI D2 tool steel is a serious problem since very frequently charges occur that exhibit decreased hot deformability in comparison to other charges. By means of laboratory hot compression tests the approximate framework of mean technological parameters of hot forming was obtained. The tests for as-cast and for deformed initial state in temperature range 850-1150 ºC, strain rate range 0.001-10 ºC and strain range 0-9 were carried out. On the base of obtained flow curves the processing maps for both states have been developed. The results obtained indicate that hot forming of as-cast state in initial phase of deformation process is not stable whereas the deformed state did not exhibit any un-stable area. Further improvement of hot deformability was obtained by optimisation of chemical composition based on data of surface cracking from industrial hot forming process. The analysis carried out by CAE neural network revealed the influences of carbide-forming element on occurrence of surface cracking. The results of analyse were additionally supported by THERMOCALC calculations. It was shown that variable nature of chemical composition of tool steel results also in variability of precipitation temperature of eutectic carbides.

Izvleček: Nastanek razpok med vročim preoblikovanjem AISI D2 orodnega jekla je zelo resen problem, saj se zelo pogosto pojavijo šarže, ki izkazujejo nižjo sposobnost plastičnega preoblikovanja v primerjavi z ostalimi šaržami. Z laboratorijskimi testi smo najprej določili okvirne vrednosti parametrov za vroče preoblikovanje. Omenjene teste smo opravili tako za lito, kot tudi za predelano izhodno stanje. Dobljene krivulje tečenja so nam služile za izdelavo procesnih map; ti rezultati kažejo na nestabilnost v začetni fazi preoblikovanja za lite mikrostrukture, medtem ko predelano stanje ne izkazuje nobenih nestabilnih področij. Nadaljnje izboljšanje vročega

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preoblikovanja smo dosegli z optimiranjem kemične sestave, s pomočjo CAE nevronskih mrež in na osnovi baze podatkov pridobljene v industrijski praksi, saj je bila predhodno opravljena analiza vplivov kemičnih elementov na izplen vročega valjanja. Nekateri rezultati omenjene analize so bili dodatno podkrepljeni tudi z izračuni s pomočjo THERMOCALC-a, ki kažejo na to, da variabilna kemična sestava (karbidotvorni elementi) vpliva na temperaturo izločanja evtektičnih karbidov.

Key words: D2 tool steel, hot deformability, as-cast state, deformed state, hot compression, processing map, chemical composition, CAE neural networks
Ključne besede: D2 orodno jeklo, vroča preoblikovalnost, lito stanje, predelano stanje, vroče stiskanje, procesne mape, kemična sestava, CAE nevronske mreže

INTRODUCTION

Very frequently and unexpected high density of surface cracking (Figure 1a-b) occurring in hot rolling of AISI D2 tool steel, despite the rolling process took place in prescribed technological parameters, is still today insufficient researched area. In order to achieve the desired mechanical properties the steels are alloyed with Cr, V, Mo etc (carbide-forming elements, M_7C_3, MC, M_6C, $M_{23}C_6$, etc) that results in higher yield strength, better tempering resistance, higher wear and fatigue resistance, and considerably lower hot ductility. Thus the windows of technological parameters for safe hot forming with regards to temperature, strains, strain rates, etc are very narrow. Additionally hot deformability is influenced by previous thermo-mechanical processing parameters, i.e. (casting temperature, cooling rate, soaking temperature, etc) and chemical composition. The mentioned carbides besides other brittle phases precipitated (segregation) on grain boundary accelerate cracking at lower and medium area of temperature range. The effect of carbides on hot ductility depends on their number and size, type, morphology and distribution. As deformation proceeds voids tend to form around the carbides by decohesion and/or fracture of the particles which, in addition to the usual wedge type cracks at triple points, lead to drastic lowering of the ductility of tool steel. Upper limit of temperature range is determined by begin of incipient melting (eutectic carbides and phases with low melting point) and consequently by extensive grain boundary decohesion[1-15].

Despite the hot forming of tool steels is of great interest from both fundamental and industrial viewpoints, there has been little research reported in the scientific literature about hot forming of tool steels. The researches are namely predominately focused on deformed state that usually exhibit considerably higher hot deformability in comparison to as-cast state; consequently the results do not approach enough to conditions occurring at initial and very critical phase of hot forming of as-cast microstructure.

AISI D2 tool steel has found his application mainly for cold forming, i.e., rolling threads, trimming tools, cutting tools, broaches, etc. Due to its relatively low hot deformability it reduces the profitability of the production process as well as the useful mechanical properties of the tool steel because of the defects in the material that can originate from its hot deformation.

For elucidation of occurrence of cracking in initial phase of hot rolling of AISI D2 tool steel the hot compression tests for as-cast and for deformed state, and analyse (CAE NN) of influences of chemical composition on surface cracking were carried out. Obtained results were additionally supported by THERMOCALC calculations of influences of chemical composition on precipitation temperature of eutectic carbides. Processing maps have been developed in order to reveal area of safer hot forming.

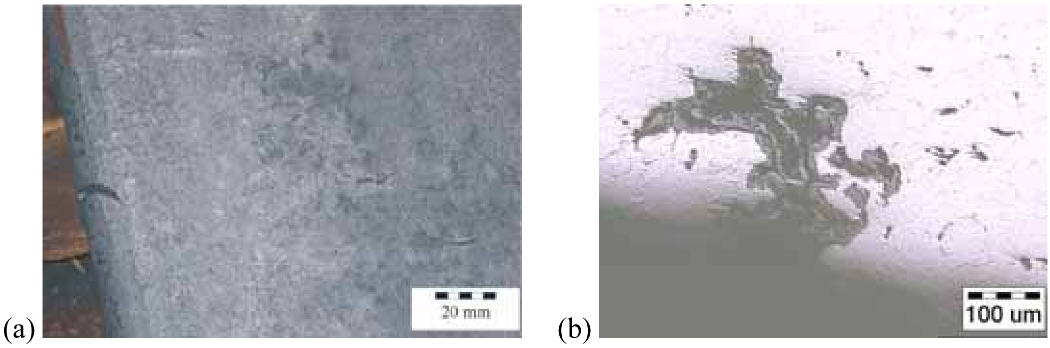


Figure 1. Occurrence of the surface cracks on rolling (AISI D2), macro-view (a), and detailed presentation of crack (b)
Slika 1. Pojav površinskih razpok med vročim valjanjem AISI D2 orodnega jekla, makro posnetek (a), in detajlnejši prikaz razpoke (b)

EXPERIMENTAL – LABORATORY TESTING AND MATERIALS

Applied materials and hot compression

Computer controlled servo-hydraulic machine Gleeble 1500 was applied for hot compression testing to study hot forming of as-cast and of deformed initial state of AISI D2 tool steel. The allowable range of chemical composition of AISI D2 tool steel is given in Table 1. Cylindrical hot compression specimens of Rastegew type with dimensions ϕ=10 mm x 15 mm were cut from ingot (as-cast state) of cross-sectional 400x400 mm and from rod (deformed state) of cross-sectional ϕ=20 mm. For reduction of friction between the cylindrical specimen and the tool, and to avoid their mutual welding, graphite lubricant and tantalum follies were used. After deformation the specimens were rapidly quenched with water.

The hot compression tests was performed in the temperature range from 850 °C to 1180 °C, at five different strain rates (0.001, 0.01, 0.1, 1 and 10 s^{-1}) and in strain range 0 - 0.9 (Figure 3). The heating rate was 3 °C/s, soaking time of 5 min at 1160 °C, followed by cooling at a rate of 2 °C/s down to the deformation temperature and with a soaking time of 5 min again. The initial microstructure of as-cast state and the deformed state are given in Figure 2a and Figure 2b, respectively.

Table 1. The ranges of permissible variation of chemical composition according to EN ISO 4957 (wt%), D2 tool steel

Tabela 1. Področje dovoljenega variiranja kemične sestave glede na EN ISO 4957 (wt%), D2 orodno jeklo

	C	**Si**	**Mn**	**Cr**	**Mo**	**V**	**P**	**S**
Range of variation	1.45 1.60	0.10 0.60	0.20 0.60	11.0 12.0	0.70 1.00	0.70 1.00	max 0.030	max 0.030

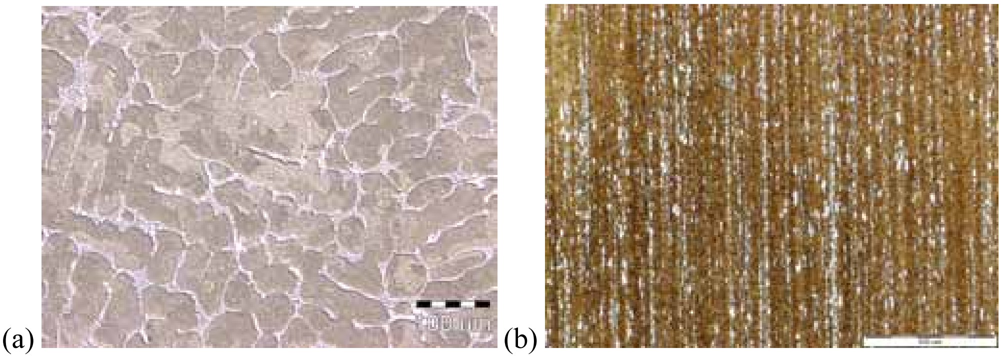


Figure 2. Initial microstructures of applied tool steel (AISI D2), as-cast state (network of eutectic carbides) (a), deformed state (b)

Slika 2. Začetna mikrostruktura uporabljenega orodnega jekla (AISI D2), lito stanje (mreža evtektičnih karbidov) (a), deformirano stanje (b)

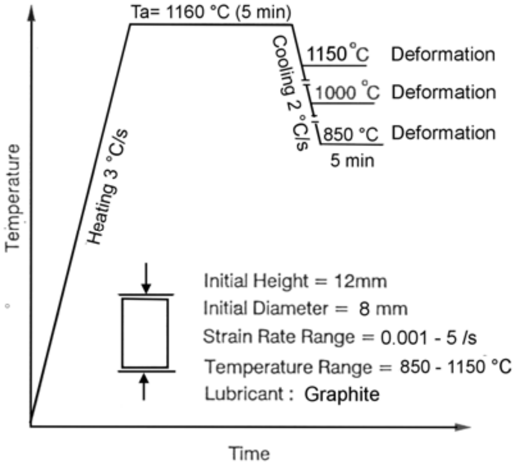


Figure 3. Schematic representation of the time-temperature course for the tested cylindrical specimens

Slika 3. Shematski prikaz poteka temperature vzorcev med vročimi stiskalnimi preizkusi

Flow curves

In such way obtained flow stresses for as-cast and for deformed state at strain rates of 1 s^{-1} and 0.1 s^{-1} are presented on Figure 4a and Figure 4b, respectively.

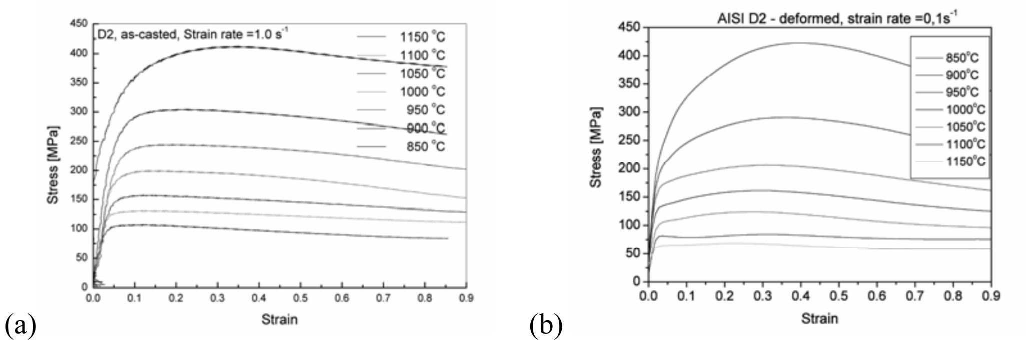


Figure 4. Flow stresses in temperature range 850-1150 °C for as-cast initial state (strain rate of 1 s^{-1}) (a), for deformed initial state (strain rate of 0.1 s^{-1}) (b)

Slika 4. Vroče krivulje tečenja v temperaturnem območju 850-1150 °C, za lito stanje (hitrost deformacije 1 s^{-1}) (a), za predelano stanje (hitrost deformacije 0,1 s^{-1}) (b)

PROCESSING MAPS

Efficiency of power dissipation processing maps

Processing maps are developed on the basis of a dynamic material model (DMM) which has been suggested and widely used by the group of Prasad[16-17]. The processing map of the material can be described as an explicit representation of its response to the imposed process parameters. It is a superimposition of the efficiency of power dissipation and an instability map.

The work-piece under hot deformation conditions of this model works as an essential energy dissipater. The constituent equation describes the manner in which energy *P* is converted at any instant into two forms, thermal energy *G* making temperature increase and microstructural change caused by transform of metallurgical dynamics *J*, which are not recoverable. In general, most of the dissipation is due to a temperature rise and only a small amount of energy dissipates through microstructural changes. The power partitioning between *G* and *J* is controlled by the constitutive flow behaviour of the material and is decided by the strain rate sensitivity *m* of flow stress as shown in the equation

$$\frac{dJ}{dG}=\frac{\dot{\bar{\varepsilon}}\,d\bar{\sigma}}{\bar{\sigma}\;d\dot{\bar{\varepsilon}}}=\frac{\dot{\bar{\varepsilon}}\,\bar{\sigma}\,d\ln\bar{\sigma}}{\bar{\sigma}\,\dot{\bar{\varepsilon}}\,d\ln\dot{\bar{\varepsilon}}}\approx\frac{\Delta\log\bar{\sigma}}{\Delta\log\dot{\bar{\varepsilon}}}=m \qquad (1)$$

For an ideal dissipater it can be shown that both quantities *J* and *G* are equal in their amount, which means that *m* = 1 and *J* = J_{max} whereas the efficiency of power dissipation η is given by:

$$\eta=\frac{J}{J_{\max}}=\frac{2m}{m+1} \qquad (2)$$

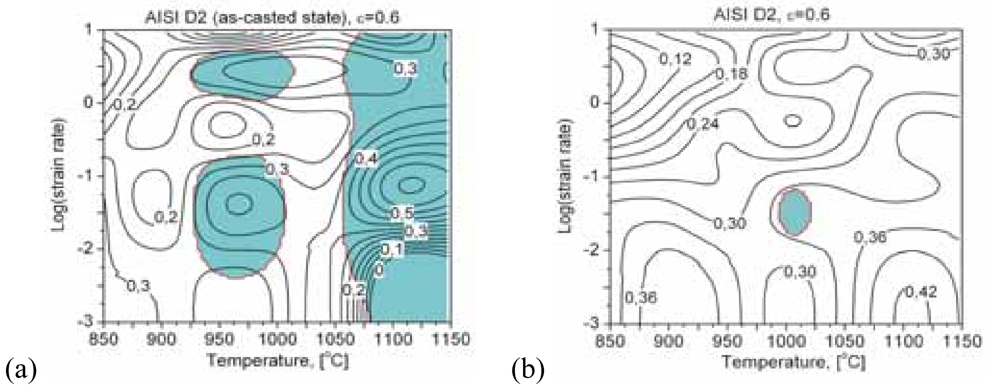
The variation of η with temperature and ε represents the relative value of energy dissipation occurring through microstructural changes. Microstructural changes, which includes a dynamic recovery and dynamic recrystallization, are predominately stable, and instable, which includes wedge cracking, void formation at hard particles, dynamic strain ageing and macro-structural cracking. As new surfaces are formed during instable changes, more energy is required, while stable changes always take place by grain boundary migration.

Flow instability

The instability map is defined by a stability criterion for a dynamic material, where the differential quotient of its dissipative function has to satisfy an inequality condition, given by Equation 3, to allow a stable flow.

$$\xi\left(\dot{\bar{\varepsilon}}\right)=\frac{\partial\ln(m/(m+1))}{\partial\ln\dot{\bar{\varepsilon}}}+m>0 \qquad (3)$$

Figures 5a-b represents processing maps for temperature range from 850 °C to 1150 °C and strain rates 0.001 s^{-1} to 10 s^{-1} at strain 0.6 for as-cast and deformed initial state. The maps are similar at various strains. For as-cast initial state (Figure 5a) the instable zone with $\xi<0$ appears in the temperature range approx. 1060 °C to 1150 °C at all strain rates and at temperatures around 900 °C for higher strain rates. On the contrary for deformed initial state (Figure 5b) instable zone appears in very limited range at strain rates of approx. 0.1 s^{-1} and around temperature 1000 °C.



(a) (b)

Figure 5. Processing maps for D2 tool steel, for as-cast initial state (a) and for deformed initial state (b), at strain $\varepsilon = 0.6$

Slika 5. Procesne mape za D2 orodno jeklo, za lito stanje (a) in za predelano začetno stanje (b), deformacija $\varepsilon = 0,6$

It is visible from Figure 6b that micro-cracks occurred on specimen edge (see Figure 6a) at average strain 0.8 where also tensile stresses occurred. On the contrary, in the specimen centre (see Figure 6a) micro-cracks free microstructure was obtained since predominately compression stresses prevail on this spot. Thus as-cast microstructure is very sensitive to micro-cracking at initial deformation on high temperatures (1150 °C) and higher strains (>0.5). No cracks were obtained at lower strains.

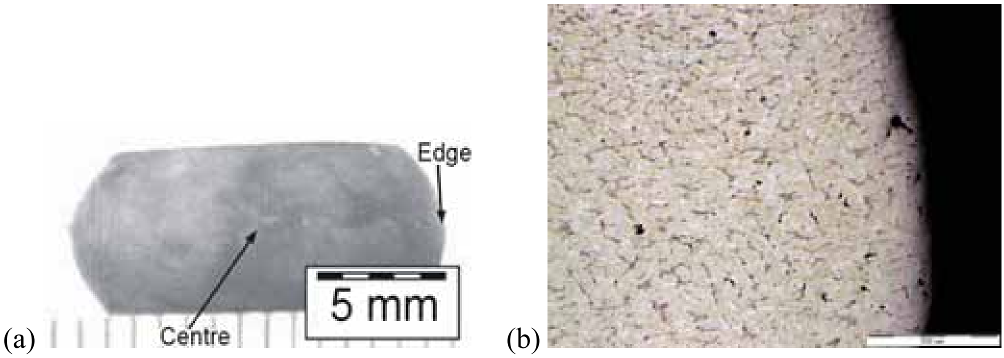


Figure 6. Macro-view of deformed specimen (a), occurrence of micro-cracks on network of eutectic carbides (specimen edge) (b), average strain ε = 0.8, deformation temperature 1150 °C

Slika 6. Makro pogled deformiranega vzorca (a), pojav mikrorazpok na mreži evtektičnih karbidov (rob deformiranega vzorca) (b), deformacija ε = 0,8, temperatura 1150 °C

ANALYSE OF INFLUENCES OF CHEMICAL COMPOSITION ON CRACKING DURING HOT ROLLING

Forming of data base

In the presented study the database contained 80 hot-rolled samples. In comparison, Szilvassy et al.[13] applied 128 samples with various chemical compositions for the statistical treatment of the influence of chemical composition on the hot deformability of AISI M2 tool steel. All the rolled pieces had the same nominal chemical composition, which varied from charge to charge within certain limits and thus varied also the phenomenon of surface cracking on the rolled stock. The contents of chemical elements (Si, Cr, V, Mn, Mo, W, etc.) was established by the spectrometric method have an error (depending on the element) between 0.01 % and 0.1 %.

The content of carbon is usually determined by specimen ignition in an induction furnace in combination with detection based on infrared spectre absorption. The typical error is around 1%. The random variation of chemical composition easily covered the whole problem space, though the majority of the information was concentrated somewhere in the middle of the permissible intervals of variation for a single element. Therefore, the diagrams of the relationships are shown only for the interval of greater concentration of infor-mation. The appearance of surface cracks was observed for rolled pieces with dimen-sions 200 mm x 200 mm that were rolled (in the temperature range 1170-900 °C) in 20 passes from an ingot with dimensions 400 mm x 400 mm x 1200mm, that were previously soaked for 2 hours at 1200 °C. Thus, the influence of chemical composition on the hot deformability was studied; in our case using information on the variation of industrial charge compositions and the formation of surface cracks on the rolled stock. The deformability criterion was thus the yield percentage during hot rolling that varied in the approximate interval 78-95 %. The interval of permissible variations for the most important elements was relatively narrow, and it is given in Table 1.

Influence of the chemical composition on surface cracking

Influence of the carbon

The CAE NN was applied to analyze both the individual and group influences on the phenomenon of surface cracking. Figure 7a makes it evident that the yield is improved by reducing the carbon content (the distribution frequency is given in Figure 7b). This means that the carbon content must be on the lower limit of the permissible interval of variations. These results correspond to the experimental findings (M2 tool steel) given in reference[18] where a better hot deformability was obtained with lower carbon contents. Carbon forms carbides with the V, Cr, Mo, Ti, and W present in steel, which in general increases the yield strength and simultaneously reduces the hot deformability very significantly.

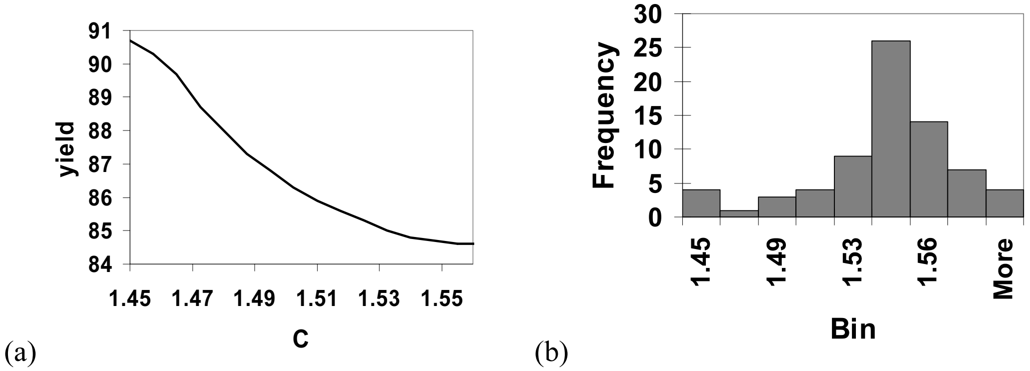


Figure 7. Yield depending on the carbon content (a), and histogram of the distribution frequency of the data (b)

Slika 7. Izplen v odvisnosti od vsebine ogljika (a), histogram frekvence porazdelitve podatkov (b)

Influence of V/C ratio

The yield as a function of the vanadium / carbon ratio (V/C) is presented in Figure 8a, and the distribution frequency of the data is presented in Figure 8b. It is evident that some of the vanadium data are somewhat outside the interval of permissible variations (up to approxi-mately 0.3 % V). Furthermore, Figure 8a makes it evident that there is no correlation between the yield and the carbon and vanadium contents for the interval of permissible variations (0.8-1.1 %).

If the data outside the interval of permissible variations are also enclosed in the database, then Figure 8a shows that the yield is increased with lower vanadium contents. In the interval of permissible variations of the carbon and vanadium contents there is nearly no correlation between the V/C ratios and the yields; the same finding is also given in reference[18]. If the data outside the permissible interval are also enclosed in the database then it is evident that reduced V/C ratios (V on the lower permissible limit) give better yields. This unclear relationship (i.e., nearly no correlation) in the permissible interval for vanadium (at V/C ratios of about 0.4 or higher) can be ascribed to the already-mentioned lower accuracy in determining yields and to the relatively narrow interval of the permissible variations of vanadium in the AISI D2 tool steel. Similar relationships, i.e., higher hot-deformability values at lower vanadium contents, were also found by Szilvassy et al.[13] for the BRM2 tool steel, which had a somewhat wider interval of permissible variations, and by Mohamed[19], for ordinary steel.

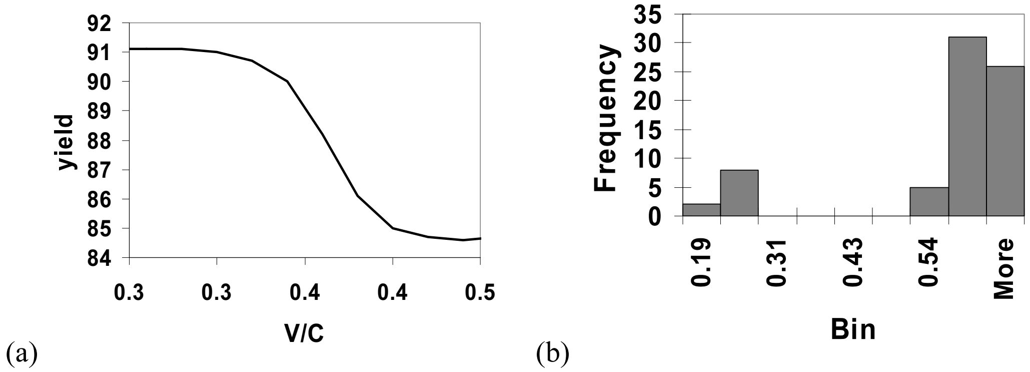


Figure 8. Yield as a function of the V/C ratio for $w_{min} = 0.07$ and $w_{max} = 0.15$ (a) with the frequency distribution (b)
Slika 8. Izplen v odvisnosti od razmerja V/C za $w_{min} = 0{,}07$ in $w_{max} = 0{,}15$ (a) s frekvenco porazdelitve podatkov (b)

Influence of the Cr/C ratio

The results of the analysis of the chromium's/carbon ratio influence are given in Figure 9a (the chromium/carbon distribution is given in Figure 9b). The yield is improved with higher chromium contents in the tool steel. However, this could be explained by the following:

- Vanadium tends to form carbides of the MC type, which are extremely hard and thus they hinder the movements of dislocations; chromium, which has a similar affinity for carbon as vanadium (i.e., a similar Gibbs free energy) tends to form carbides of the $M_{23}C_6$ type, which are softer and thus they hinder movement of dislocations to a lesser extent, since they can be crushed during the working. Thus, chromium competes with vanadium to bind with carbon. The chromium content on the upper limit would thus increase the volume portion of softer $M_{23}C_6$ carbides and therefore reduce the portion of harder MC carbides. This results in a higher workability of the tool steel and thus a higher yield[4-5].

- Higher Cr content could increase the temperature (above 1150 °C) of precipitation of eutectic carbides (M_7C_3) on grain boundaries and thus could influence on deformability at the initial deformations of ingots.

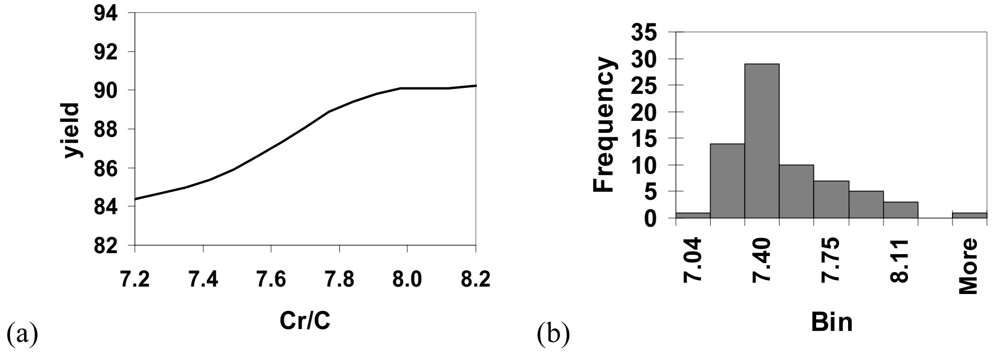


Figure 9. Yield as a function of the Cr/C ratio (a), and histogram of the corresponding frequency distribution of the Cr/C ratio (b)

Slika 9. Izplen v odvisnosti od razmerja Cr/C (a) s frekvenco porazdelitve podatkov (b)

Influence of the Mo/C ratio

There also exists a clear relationship between the molybdenum/carbon ratio and yield: the smaller molybdenum content increases the yield (Figure 10a), Figure 10b shows the frequency distribution. Molybdenum forms carbides of the M_6C type, which have a detrimental influence on the hot deformability.

As already mentioned, the analysis of the influence of vanadium content in the interval of its permissible variations within the V/C ratios did not show any clear relationship with the yield. Therefore, unclear relationships occur between the yield and the groups of elements enclosing vanadium. On the other hand, there is a very clear relationship between the Cr/Mo ratio and the yield. This indicates that chromium and molybdenum are competitors in reactions with carbon and thus in the formation of carbides. It can be concluded that carbides formed with chromium are less detrimental to the hot deformability.

Hwang et al.[20-21] obtained in high speed steels used for rolls a reduced quantity of MC carbides at higher chromium concentrations if vanadium was simultaneously present.

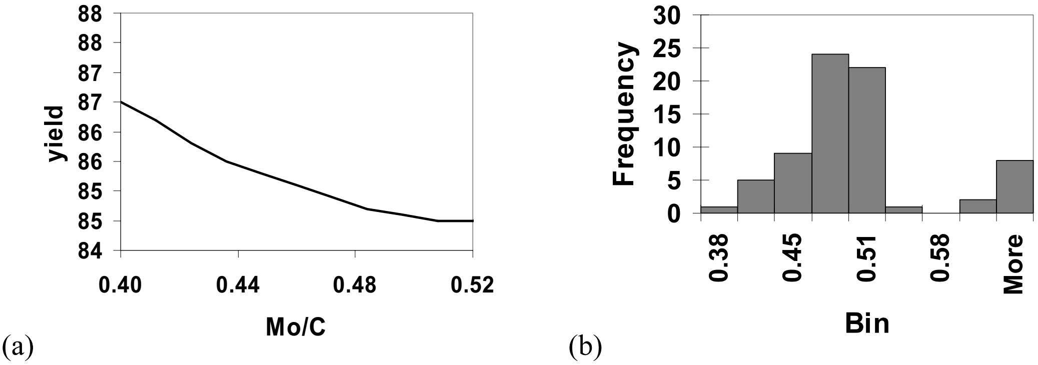


Figure 10. Yield as a function of the Mo/C ratio (a), and the corresponding frequency distribution (b)
Slika 10. Izplen v odvisnosti od razmerja Mo/C (a) s frekvenco porazdelitve podatkov (b)

Calculation of equilibrium phase diagram THERMOCALC for various V, Mo, Cr and C content (lower and upper allowable limit) confirmed the results of the CAE NN analysis. In the case that Cr content is on upper limit it results in increasing of temperature of precipitation of eutectic carbides.

CONCLUSIONS

In order to increase the hot deformability if AISI D2 tool steel hot compression tests for as-cast and for deformed state in temperature range 850-1150 °C, strain rate range 0.001 - 10 s^{-1} and strain range 0-0.9 were carried out. Hot deformation behaviours have been also studied by using Prasad's processing maps (efficiency of power dissipation and instability maps) developed on the basis of dynamic materials model. The result revealed that deformation of specimens in as-cast state in the temperature range approximately above cca 1060 °C is not stable due the occurrence of micro-cracks on network of eutectic carbides.

Additionally influence of chemical composition on appearance of surface cracking during hot rolling by means of CAE NN was obtained. It was found that carbon, vanadium and molybdenum should be on the lower limits of the intervals of permissible variations, whereas the chromium content should be on the upper limit in order to improve the yield. Calculations with THERMOCALC confirm that higher Cr content increase the temperature of precipitation of eutectic carbides and thus elucidate the one of the possible reason for occurrence of cracks in initial stage of deformation of ingots when as-cast microstructure prevails. We can conclude that to each chemical composition of AISI D2 tool steel also corresponds optimal temperature range of the initial deformations.

POVZETKI

Vroče preoblikovanje AISI D2 orodnega jekla

Da bi izboljšali vročo preoblikovalnost AISI D2 orodnega jekla smo izvedli vroče stiskalne preizkuse v temperaturnem območju 850-1150 °C, v območju hitrosti deformacij 0,001-5 s^{-1} ter deformacijskem območju 0-0,9. Obnašanje materiala med preoblikovanjem je bilo proučevano tudi s Prasadovimi procesnimi mapami (učinkovitost porazdelitve energije in mape nestabilnosti). Mape nestabilnosti nam kažejo na nestabilnost v začetni fazi preoblikovanja lite mikrostrukture (1150-1080 °C) saj pride v vzorcu na mestih s pretežno nateznim napetostnim stanjem do nastanka mikrorazpok. Posledično se moramo pri liti mikrostrukturi izogibati nateznim napetostnim stanjem v deformacijski coni in temu ustrezno izbrati tudi optimalni preoblikovalni postopek.

S pomočjo CAE nevronskih mrež in na osnovi podatkov o izplenu iz industrijske proizvodnje smo analizirali vpliv kemične sestave na zvišanje preoblikovalnosti. Rezultati analize kažejo na to, da morajo biti ogljik, V in Mo na spodnji meji, medtem ko pa Cr na zgornji meji območja dopustnega variiranja. Ti rezultati so bili potrjeni tudi z izračuni s pomočjo THERMOCALC-a, ki kažejo na variabilnost temperature izločanja evtektičnih karbidov v odvisnosti od kemične sestave. Vsaki kemični sestavi tako ustreza neko optimalno področje začetnih deformacij.

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