The effect of cooling rates on microstructures and hot workability of BRCMO2 tool steel

Vpliv ohlajevalnih hitrosti na mikrostrukturo in vročo preoblikovalnost orodnega jekla BRCMO2

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Abstract: The influence of solidification and cooling rate on obtained microstructure is especially emphasized in BRCMO2 tool steel. Various cooling rates during solidification process result in considerably different size of grains as well as in different type, size, shape and distribution of carbides. Cast ingot is solidified with different cooling rates across its section leading to different hot workability. Consequently dimensions of ingot are very important since they determine the lowest acceptable cooling rate of the tool steel. Time course of temperature field during the solidification of ingot made from BRCMO2 tool steel has been simulated and obtained microstructures have been analyzed. Finite element analysis was used for estimation of cooling rates and calculation of fractions of solid/liquid at various locations of selected cross-sections of ingot during its cooling. The hot workability of BRCMO2 tool steel was studied using hot compression tests at different deformation conditions on Gleeble 1500D testing equipment.

Izvleček: Vpliv hitrosti strjevanja in ohlajanja na mikrostrukturo je posebej poudarjen pri hitroreznem orodnem jeklu BRCMO2. Tako različne hitrosti ohlajanja med procesom strjevanja kritično vplivajo na različno velikost in razporeditev zrn, prav tako pa tudi na tip, velikost, obliko ter razporeditev karbidov. To se pogosto zgodi pri vlitju jekla v ingot, kjer so hitrosti strjevanja in ohlajanja različne v različnih delih ingota. To ima za posledico tudi različno preobliko-

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valnost v vročem. Tako so dimenzije ingota zelo pomemben parameter, saj določajo najpočasnejšo ohlajevalno hitrost v njem. V tem delu je bil analiziran potek temperature v različnih delih ingota med strjevanjem in ohlajanjem. Z metodo končnih elementov je bila ocenjena ohlajevalna hitrost ter razmerje med talino in trdnim stanjem. Z uporabo naprave Gleeble 1500D je bila preiskana vroča preoblikovalnost na podlagi tlačnih preizkusov.

Keywords: BRCMO2 tool steels, hot workability, cast microstructure, carbide distribution, effect of cooling rates
Ključne besede: orodno jeklo BRCMO2, vroča preoblikovalnost, lita mikrostruktura, razporeditev karbidov, vpliv ohlajevalnih hitrosti

INTRODUCTION

The dissolution of alloying elements and precipitation of carbides in ledeburitic tool steels result in a high strength and hardness, small deformation during the heat treatment, a very good wear resistance, and poor hot plasticity. Thus, tool steels usually exhibit a decreased but sufficient hot deformability only in a relatively narrow hot-working range, and as such belong to the group of low-deformable steels.[1–4]

During hot working of ledeburitic tool steels a large number of mutually dependent process parameters influence the intrinsic material properties that make an investigation in this area very specific. Solidification rate can essentially influence the obtained microstructure. During solidification, heating, soaking and hot deformation, various processes take place in the tool material: the formation of carbides, their decomposition, dissolution, growth, etc. Consequently the size, distribution, type and fraction of carbides, the thermo-mechanical history, the temperature range, etc., have a major influence on the hot workability of ledeburitic tool steels. As a result, hot workability cannot be considered as a constant, but rather as a variable property.[4–8]

BRCMO2 tool steel has excellent hot hardness and wear resistance and is commonly employed to machine hard materials in high speed cutting applications as well as for cold-working dies. But on other hand the tool steel exhibits very poor hot deformability in industrial practice thus improvement in its production is desired. In this contribution time course of temperature in various cross-sections of ingot during solidification of BRCMO2 ledeburitic tool steel have been calculated by FEA. Additionally, microstructures at various cooling rates were determined and their influence on hot workability has been investigated.

MATERIALS AND METHODS

Materials

BRCMO2 is a molybdenum type tool steel. The chemical composition is given in Table 1. The samples for metallographic analysis were cut from various spots on three various cross section of ingot, i.e. ingot head, ingot bottom, ingot half height, and on various distances from ingot surface, i.e. ingot surface, 10 mm, 50 mm, 90 mm from the surface, and in ingot center.

Optical microscopy (OM, Carl Zeiss AXIO Imager.A1m) was applied for the observation of the microstructure and measurements of the size of eutectic cells where intercept method was applied. The specimens for the optical microscopy were grinded with a sequence of sand papers from 180 to 1200 meshes of granulation, followed by polishing with diamond paste of 1 μm and 0.25 μm granulation and then etched with Nital.

Simulation of cooling rates in ingot using ProCast software

The measured temperature of the melt in the ladle was 1490 °C. It was considered that this temperature was also temperature of the melt in the filled ingot. The simulation of filling and solidification of ingots was calculated using finite element casting simulation program, ProCast. Fluid flow was calculated according to Navier-Stokes equations and solidification properties were based on heat flow according to Fourier's equation.[9] Whole geometry of molds and other parts needed during ingot solidification were modeled in 3D geometry and meshed in ProCast by tetrahedral elements.

Thermodynamic properties of die material, fireclay, exothermic and insulation materials were taken from the ProCast database. Properties of pouring material were calculated using CompuTherm software on the basis of chemical composition. For better results of solidification and cooling the stress module was activated in the software to account for the effect of gap formation on metal/die interface on cooling of ingot.[9] Initial heat transfer coefficient (HTC) *h* between solidified ingot and mold was considered to

Table 1. Chemical composition of applied BRCMO2 in mass fractions, $w_t/\%$

C	Si	Mn	Cr	Mo	V	W	Co
1.09	0.26	0.25	3.81	9.32	1.09	1.40	8.20

be around 2000 W/(K m^2). In general HTC is decreasing with gap formation during solidification and contraction. When the metal is liquid, HTC between the metal and die is a function of ferrostatic pressure given by the equation:

$$h = h_0 \cdot \left(1 + \frac{P}{A}\right)$$

where h_0 is initial heat transfer coefficient, P is pressure and A is empirical constant to account for contact pressure.[8]

Cooling rates were calculated on the basis of the difference between time and temperature from the start of casting to complete solidification.

Hot compression tests

Hot compression tests were applied for assessment of hot deformability as well as for determination of flow curves. For assessment of hot deformability the procedure described in [1] was used. For determination of flow curves samples were taken so from the surface part as well as form centre of ingot's head. The following testing conditions were selected: temperature range 850–1130 °C, strain rates between 0.001 s^{-1} and 5 s^{-1} and a true strain of 0.9. The specimens were heated to 1130 °C with a heating rate of 3 °C/s which was followed by holding them for 10 min at this temperature, and cooling with a rate of 2 °C/s to the deformation temperature, holding for 10 min, followed by hot compression and water quenching afterwards. Tantalum foil with a thickness of 0.1 mm was inserted between the cylindrical specimen and the compression anvil, and a Ni-based lubricant was used. For the higher strain rates the obtained flow curves were temperature compensated according to the procedure described in [7].

Results and discussion

FEM calculated results on ingot cooling and obtained microstructures

The simulated distribution (Figure 1) of solid fraction (left) and of temperature (right) during solidification of ingot at various times after begin of filling; i.e. 570 s (a), 950 s (b), and 1470 s (c) after casting start. It can be noticed that solidification starts on the bottom of ingot already during its filling. The solidification front is then moving from ingot surface towards the center and up to the head of ingot where solidification ends.

On Figure 2 calculated time courses of temperature on spots with various distances from ingot surface are presented. It is clearly seen that due to rapid fall of temperature spots closer to ingot surface undergo considerably higher cooling rates. Furthermore, it is also clear that that fall of temperature is considerably higher on ingot bottom in comparison to ingot head. Calculated values of cooling rates in ingot head cross-section are given in Table 2. Calculated cooling rates on ingot surface are higher than 10 ºC/s while in the ingot center these values are higher than 0.18 ºC/s.

Ledeburitic steels solidifie through the eutectic transformation is the last transformation of liquid to solid in the solidification process. Therefore, the nucleation and growth of eutectic (eutectic carbides + austenite) occurs in the remaining liquid area between primary dendrites. As-cast microstructure of ledeburitic tool steel consists of dendrites surrounded by an almost continuous inter-dendritic network of eutectic carbides and the size of eutectic cells is directly dependent on solidification rate. Consequently average size of eutectic cells on ingot surface was relative small and amount ca 21 µm while in ingot center these values are around 121 µm. From point of view of deformability obtained values for size of eutectic cells in ingot center indicates on approaching of upper limit of their size. Figure 3a shows microstructure obtained in the center of ingot's head which underwent slowest cooling rates. In the soft annealed condition the solidified microstructure of BRCMO2 steel consist colonies of eutectic carbides and blocky carbides inserted in the basic microstructure from ferrite and spheroidised carbides. In the vicinity of the ingot surface, where the solidification rate was the highest, eutectic cells are smallest and eutectic carbides are impossible to distinguish from the base microstructure detect using OM (see Figure 3b). With the increasing distance from the ingot surface, the eutectic colonies and eutectic carbides became incomparably coarser and also the size and the number of blocky carbides increase. Thus the size of the eutectic cells increase from few micrometers under the ingot surface up to about 86 µm at the 50 mm distance from the ingot surface (see Figure 3c) and in ingot center are around 121 µm where also some micro-porosity was observed. Through the whole cross-section of the ingot the eutectic carbides have lamellar morphology typical for M_2C type of eutectic.

Table 2: Calculated cooling rates and the size of eutectic cells on ingot head cross-section at various distances from ingot surface.

Distance /mm	Assessed cooling rates	The average size of eutectic cells /µm
Up to 1.7	>10 ºC/s	21
10	>0.8 ºC/s	36
50	>0.23 ºC/s	86
center	>0.18 ºC/s	121

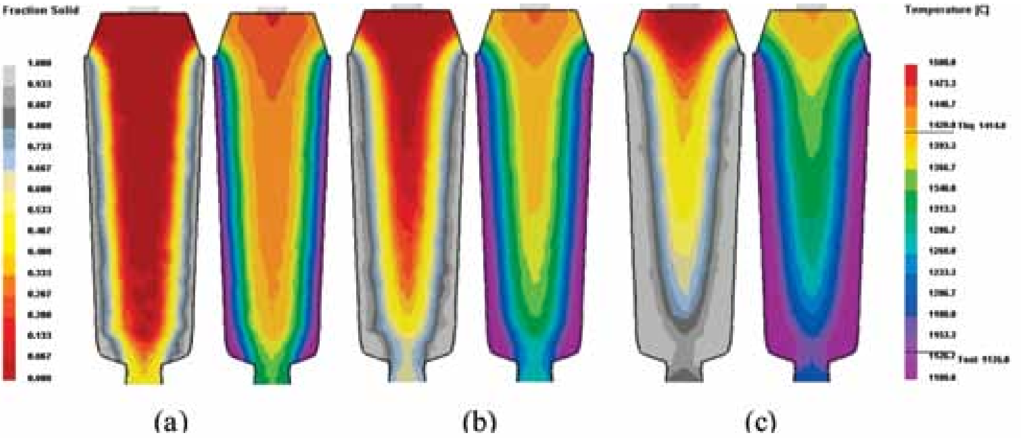

Figure 1. Simulated distribution of solid fraction (left) and of temperature (right) during solidification at: 570 s (a), 950 s (b) and 1470 s (c) after begin of filling.

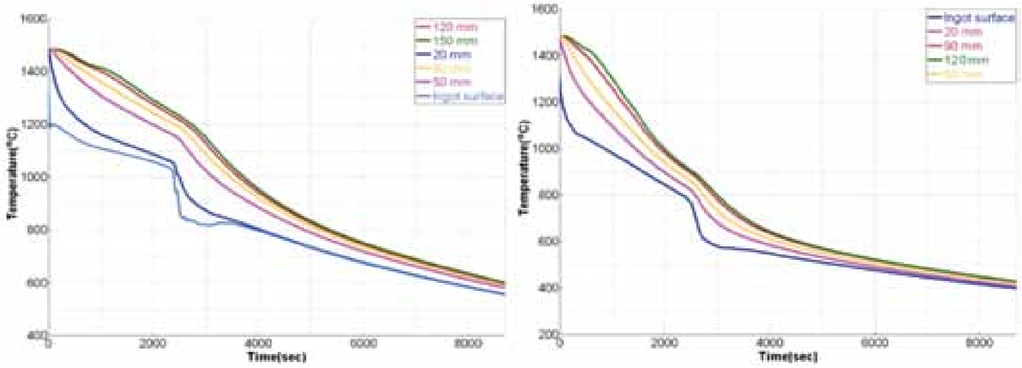

Figure 2. Simulated cooling curves on different depths from ingot surface: top of the ingot (ingot head) (a) and 20 cm from bottom (b).

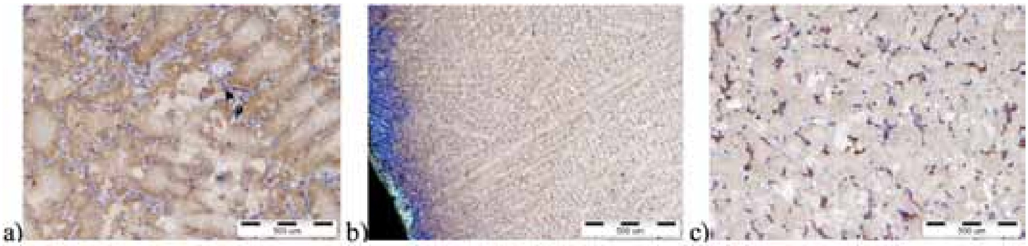

Figure 3. Obtained microstructure on ingot head cross-section: in center (a), on surface (b) and 50 mm from ingot surface.

Hot workability

Different microstructures obtained at different cooling rates result in different hot workability. This was investigated by hot-compression tests at max strain of 0.9, a strain rate of 5 s^{-1} and various deformation temperatures.[1] The as-cast microstructure (Figure 3b) taken from the region under the ingot surface when cooling at a rate >10 ºC/s does not crack during the upsetting at 1130 °C, whereas the cast microstructure from the ingot core, formed at a cooling rate of 0.18 ºC/s cracks under these deformation conditions. Eutectic cells are believed to be responsible for this behavior. On the other hand at values of strains around 0.6, that are also typical in practice, the cracks were not observed on compressed samples. These results indicate on upper limit of dimensions of ingot since these determine lowest acceptable cooling rate. In laboratory simulation of solidification at cooling rate of 0.167 ºC/s new type of eutectic carbide appeared in microstructure that additionally reduced hot deformability.

As mentioned, flow curves for various temperatures and strain rates were obtained. The comparison of the flow curves is presented in Figure 5. The data gathered from the specimens at the surface of the ingot exhibit higher flow stresses and shape of flow curves indicate on dynamic recrystallization. The samples taken from the center of the ingot reach about 100 MPa lower flow stresses. Samples from ingot center exhibited lower hot deformability since most of them exhibited surface cracking during hot compression at applied strain of 0.9.

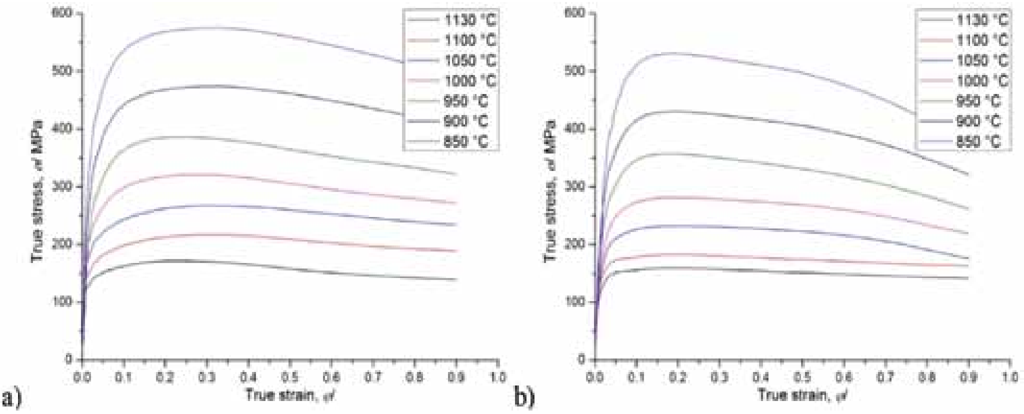

Figure 4. Flow curves measured at different temperatures at strain rate of 5 s^{-1}. Ingot surface (a), center of ingot's head (b).

Conclusions

Calculation of time course of temperatures by FEM on various spots of various cross-sections of ingot during solidification of BRCMO2 tool steel has been carried out. Hot workability of cylindrical samples has been studied by hot compression tests. The following conclusions can be drawn from the presented study:

- Maximal calculated cooling rate on surface area of ingot head amounts >10 ºC/s while the lowest value in centre of ingot head amounts around 0.18 ºC/s.
- BRCMO2 tool steel is very sensitive on cooling rate since this influence on solidified microstructure. Higher cooling rate (>10 ºC/s) results in considerable lower size of dendrites as well as eutectic cells in comparison to lowest calculated cooling rate in solidified ingot.
- From point of view of hot deformability microstructure obtained at cooling rate of about 0.18 ºC/s presents transition from acceptable to non-acceptable microstructure.
- Hot deformability of samples taken from ingot surface does not considerable differ from samples taken from ingot center.
- Applied dimensions of ingot for this tool steel present the upper limit since lower cooling rate would be obtained in ingot with larger dimensions.
- Obtained values for flow curves of compressed samples from ingot surface are higher in comparison to values of samples taken from ingot center.

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