Influence of casting temperature on the microstructure of AISI M42 high speed steel

Kerstin Baumgartner*[1], Christian Bernhard[1], Andreas Pfeiffer[1], Gerhard Wieser[1], Martin Hafok[2]
[1]Chair of Ferrous Metallurgy, Montanuniversität Leoben, Leoben, Austria
[2]Research and development, voestalpine Böhler Edelstahl GmbH & Co KG, Kapfenberg, Austria

Introduction/Background: Carbide size and distribution are of major importance for the operation properties of high speed steels. In general the sort and amount of carbide controls hardness and abrasion resistance and the size and distribution is important for susceptibility to cracking and machinability. The formation of these carbides is a direct result of ingot solidification. They are formed in the interdendritic region during a eutectic reaction. Therefore besides the subsequent heat treatment and forging steps, the conditions of solidification can be decisive for the material properties.

Objective(s)/Method(s): Experiments were carried out using a 20 kg induction furnace and AISI M42 high speed steel. To determine the influence of overheating on the solidification structure of the steel, four experiments with varying casting temperatures (1500, 1550, 1600 and 1650 °C) were performed. The changes in the solidification structure were documented through light microscopy and scanning electron microscope. The former was used to measure the secondary dendrite arm spacing λ_2 and the location of the columnar to equiaxed transition (CET) and the latter to investigate, if there have been changes in carbide structure.

Result(s): Simulations of the ingot solidification pointed to a noticeable influence of the casting temperature on local solidification time. The investigations of the solidification structure revealed the CET shifting towards the ingot center with higher casting temperatures, but the changes of λ_2 were not significant. The appearance of coarser carbide structures is increasing.

Conclusion(s): This work shows that controlling the casting temperature should be considered when trying to optimize the morphological structure of M42 high speed steel and the overheating of the melt should be adjusted carefully.

Keywords: High speed steel, carbide, casting temperature, columnar to equiaxed transition

Introduction

Among the class of tool steels high speed steels (HSS) are mostly used in cutting and drilling applications. Their most outstanding properties are high-temperature strength, tempering resistance up to 600 °C and compared with hot working tool steels, also a high hardness at high cutting speeds. Achieving these properties is an interaction between chemical composition, solidification structure, heat treatment and hot deformation. Figure 1 shows a typical phase diagram for HSS and that the chemical composition leads to a high amount of carbides formed in a~~n~~ eutectic reaction. Depending on the steel grade, eutectic carbides can exist in the form of MC, M_6C and M_2C, where M represents a mixture of carbide forming metals. The most important elements to control the formation of carbides are carbon (typically contained from 0.8 to 1.2 wt.-%), tungsten, molybdenum and vanadium. Figure 2 shows how the ratio of tungsten to molybdenum affects the type of carbide. Low ratios lead to the formation of the metastable M_2C and high amounts of tungsten promote the formation of M_6C. The carbides are responsible for the hardness and abrasion resistance of HSS, a small size and even distribution improve the susceptibility to cracking and the machinability of the material. On the one hand the final carbide size is determined by the forging and heat treatment steps following the casting process, but nevertheless without adapting the casting process to promote the precipitation of a fine eutectic, a small carbide size can only be reached with a considerate amount of additional work and expense. [1–4]

This paper will discuss a molybdenum-type HSS, namely the AISI M42 with 1 wt.-% C, 4 wt.-% Cr, 1.5 wt.-% W, 9 wt.-% Mo, 1 wt.-% V and 8 wt.-% Co. Austenite dendrites are the first phase to precipitate from the melt, they grow until the eutectic composition is reached, then the remaining liquid steel is solidifying through a~~n~~ eutectic reaction in the interdendritic spaces and between the primary grains. For this steel grade the typical carbide formed in this reaction is M_2C. As M_2C is a metastable carbide, it will decompose into MC and M_6C during heat treatments and hot deformation. [5–7]

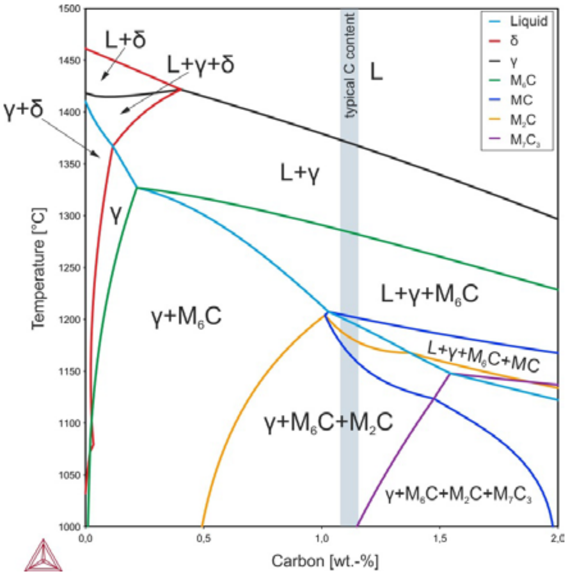
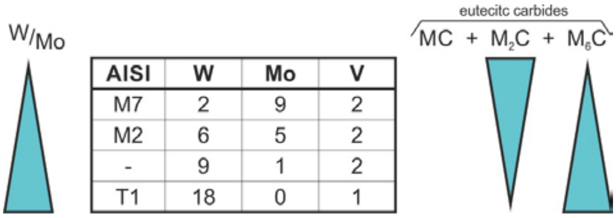


Figure 1: Equilibrium phase diagram of AISI M42 calculated with Thermocalc database TCFE8.1



AISI	W	Mo	V
M7	2	9	2
M2	6	5	2
-	9	1	2
T1	18	0	1

Figure 2: Effect of W/Mo ratio on the eutectic carbide formation, adapted from [2]

Comment [CB1]: Ganz klar wäre mir bei den beiden rechten Dreiecken nicht, welches wofür gilt (wenn ich das Bild nicht kennen würde).

It is well known that one of the main factors controlling the solidification structure is the cooling rate. According to equation (1) the critical radius r* for a stable nuclei is decreasing, if the undercooling of the melt ΔT is increasing.

$$r^* = \frac{2\,\sigma\, T_M V_S}{\Delta H\, \Delta T} \qquad (1)$$

σ is the surface energy, T_M the equilibrium melting point, V_S the molar volume and ΔH latent heat of solidification. This means a greater undercooling leads to smaller nuclei that are able to survive in the melt. The formula describing the nucleation rate I is given in equation (2). It is evident that with increasing undercooling, also the nucleation rate is rising fast.

$$I \cong B_1 e^{\left(-\frac{16\,\pi\,\sigma^3\, T_M^2\, V_S^2}{3\,\Delta H^2\, \Delta T^2\, k\, T}\right)} \qquad (2)$$

B_1 is a pre-exponential term, k is the Boltzman-constant and T is the temperature. Equation (3) shows that the dendrite arm spacing d is proportional to the temperature gradient G and the growth rate v. G is defined in equation (4), where x is the direction normal to the isothermal lines.

$$d \propto G^{-0.5} v^{-0.25} \tag{3}$$

$$G = \frac{dT}{dx} \tag{4}$$

~~So t~~The cooling rate stands in correlation with the temperature gradient G and subsequently the dendrite arm spacing and ~~it~~ has an effect on the undercooling ΔT and thus the nucleation rate.

In summary higher cooling rates should result in a smaller dendrite arm spacing and a smaller critical radius r* and a higher amount of stable nuclei, thus there is a potential for higher cooling rates to refine the cast structure. Figure 3 shows schematically the possible changes during solidification that can result of high and low cooling rates. [8–10]

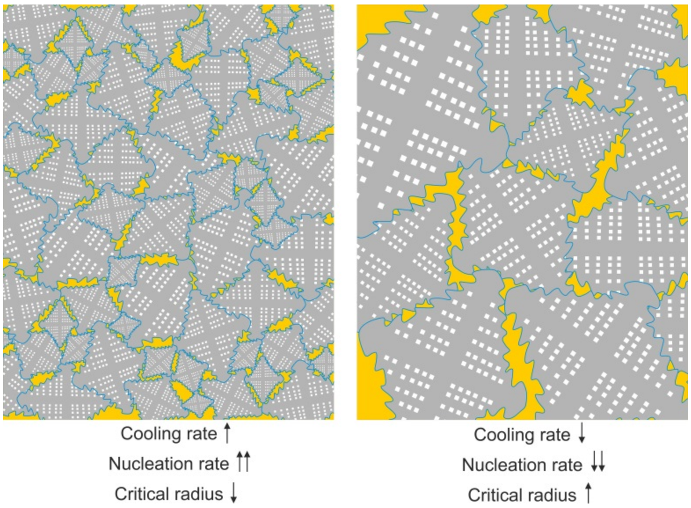


Figure 3: Effects of cooling rate on microstructure

Various publications showed that cooling rate as well as overheating of the melt have a significant influence on the solidification structure and the morphology of carbides [4,10–14]. Another beneficial effect is that a faster solidification leads to M_2C which decomposes easier during heat treatment.~~,~~ ~~this~~ This is favorable, because it leads to smaller carbides in the final product [4,15].

As the superheat~~overheating~~ of the melt before casting is a process parameter which is very easily adapted and calculations performed with calcosoft-2D showed a noticable influence of the casting temperature on the cooling rate, experiments were carried out casting the steel with 1500, 1550, 1600 and 1650 °C. Figure 4 shows the calculated cooling rate along the cross section A-A of the ingot. Towards the edges the cooling rates rise rapidly, but in the center they are constant and vary between 55 °C/min for a casting temperature of 1500 °C and 49 °C/min for 1650 °C.

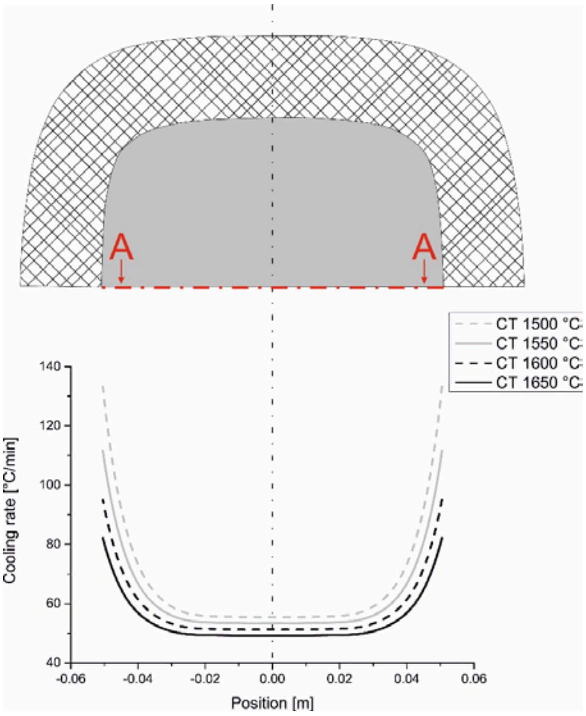


Figure 4: Simulation of cooling rate along the cross section A-A with calcosoft-2D

Experimental

To investigate the effect of different casting temperatures from 1500 to 1650 °C on AISI M42 steel, melting experiments took place and were followed by metallographic analysis.

Casting experiments

The trials were carried out in the melting shop at the Chair of Ferrous Metallurgy. A medium frequency induction furnace with a maximum capacity of 20 kg and MgO lining was used. The first step was to melt industrially produced AISI M42 tool steel, provided by voestalpine Böhler Edelstahl GmbH. Next the chemical composition was controlled and if necessary adjusted to the original contents. Table 1 contains the chemical compositions of the four castings. Last the temperature was adjusted to the requested casting temperature and the melt was cast in grey iron moulds into ingots of 12 kg with dimensions of ~ 80 x 80 x 300 mm.

Table 1: Chemical composition of the experimental castings

	Chemical composition in wt-%									
	C	Si	Mn	Cr	Mo	Ni	V	W	Co	Fe
CT1500	1.02	0.43	0.21	3.67	9.35	0.34	1.03	1.28	7.81	Bal.
CT1550	1.06	0.46	0.2	3.69	9.39	0.35	1.01	1.32	7.78	Bal.
CT1600	1.06	0.46	0.2	3.69	9.39	0.34	1.02	1.32	7.81	Bal.
CT1650	1.04	0.43	0.19	3.71	9.02	0.37	0.88	1.43	7.61	Bal.

Metallographic analysis

Specimens were taken at a height of 115 mm from the ingot bottom and cut into symmetrical pieces for metallographic processing. Metallographic methods implemented in this paper were light microscopy as well as secondary electron microscopy (SEM). A JEOL 7200F SEM was used to determine the carbide content and carbide morphology. To investigate the columnar to equiaxed transition (CET) and the secondary dendrite spacing λ_2 a Nikon MM40 and a Polyvar Pol light microscope were used. Image analysis was conducted with the help of the Clemex Vision 7 software.

Results & Discussion

For the investigation of the changes in micro- and macrostructure of the as-cast ingots different methods were implemented. The results shall be presented in next passages. If not stated differently all measurements took place in the ingot center.

Effect of casting temperature on solidification structure

The columnar-to-equiaxed transition (CET) is a typical value to evaluate the macrostructure of a cast ingot. Normally a slower solidification results in a longer columnar zone, because it takes longer for the melt in the center to reach the right temperature and heat removal conditions to start the equiaxed solidification and to stop the columnar growth. The CET was measured via light-microscopy. Therefore images taken with the light microscope were assembled to large mosaic pictures, in which the dendrite directions were clearly visible, and the CET could be marked as exactly as possible. Figure 5 shows how the CET changes with the casting temperature and it is marked in white in the macroscopic etchings. ~~There seems to be no~~The area fraction of ~~continuous growth of the~~ columnar ~~zone~~growth~~, but a jump~~ does not increase continuously with temperature but rises suddenly between 1550 and 1600 °C from 30 to 60 %. Limitations in the proper control of the experiment might (e.g. asymmetrical filling of the mold) might influence this result.~~Several factors led to this result, measuring the CET highly depends on the human operator and it is not symmetrical around the whole ingot, this could be due to the experimental setup, where the pouring of the melt into the mold takes place from above and it cannot be assured that the melt fills the mold completely the same in every experiment.~~

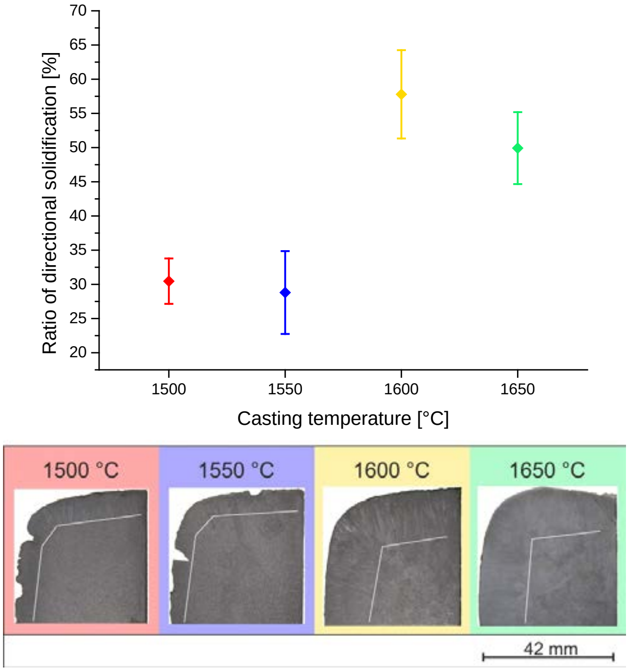


Figure 5: Influence of casting temperature on the ratio of direcional soldification and the corresponding macro etchements of the specimens

As mentioned above the secondary dendrite spacing λ_2 also stands in direct correlation with the cooling rate. As can be seen in Figure 6 there is a tendency towards larger λ_2 with higher casting temperatures. This corresponds well with the calculated effect of the casting temperature on the cooling rate in Figure 4. λ_2 is only changing slightly, this can be attributed to the also not very large changes of the cooling rate.

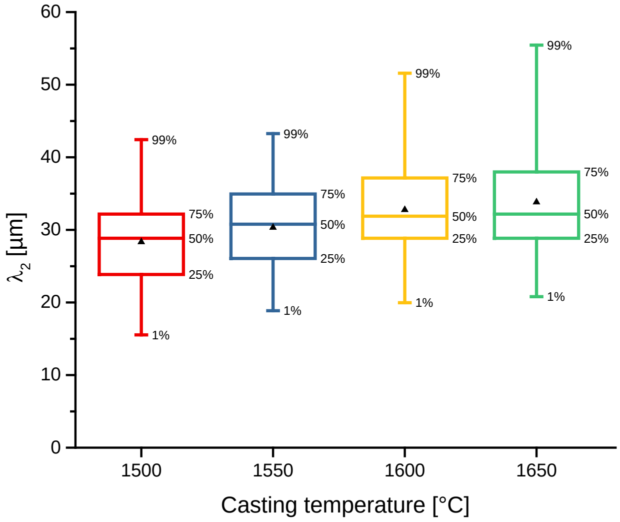


Figure 6: Effect of casting temperature on the secondary dendrite spacing

~~A very~~The obvious change in the solidification structure shows Figure 7. It shows that the primary grains in the ingot cast with a temperature of 1650 °C are much larger and more branched, than the primary grains in Figure 7 a) cast with 1500 °C. This is in a good correlation with the effect of the cooling rate on the nucleation rate discussed in the introduction.

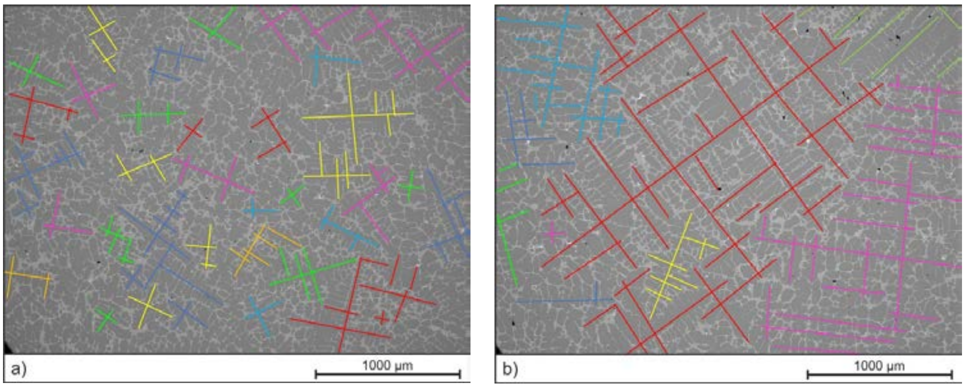


Figure 7: SEM images illustrating the change of primary grain size from **a)** 1500 °C to **b)** 1650 °C

Effect of casting temperature on carbides

Figure 8 shows a typical example of a M_2C in the experimental castings. The structure is lamellar with very fine regions and fairly rough areas. All of these variations of M_2C structure can be found in every ingot and there are no major structural changes towards needle or plate like M_2C as is sometimes reported in literature for AISI M2 [14–16].

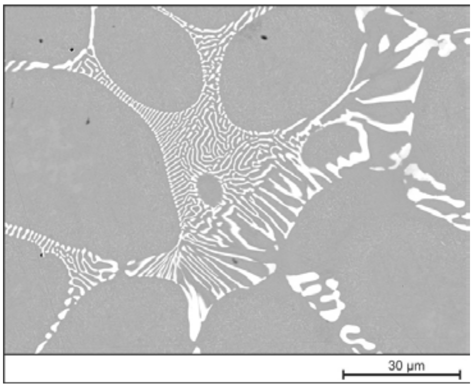


Figure 8: Example for M_2C in AISI M42

SEM images were analyzed with the image analysis software Clemex Vision 7 to investigate the carbide structure and size in more detail. Figure 9 shows two examples of edited images. The eutectic carbides are highlighted in different colors. The fine structures are marked in blue and areas thicker than 1.2 mm are visible in green. Figure 9 a) was taken from a specimen cast with 1500 °C and Figure 9 b) with 1650 °C. In comparison with each other, it is obvious that the green areas in Figure 9 b) are larger and more frequent.

Five images of every experiment were examined and the results are summarized in Figure 10. While the overall carbide content stays the same for all four castings, the ratio of coarse carbides is increasing 11 %.

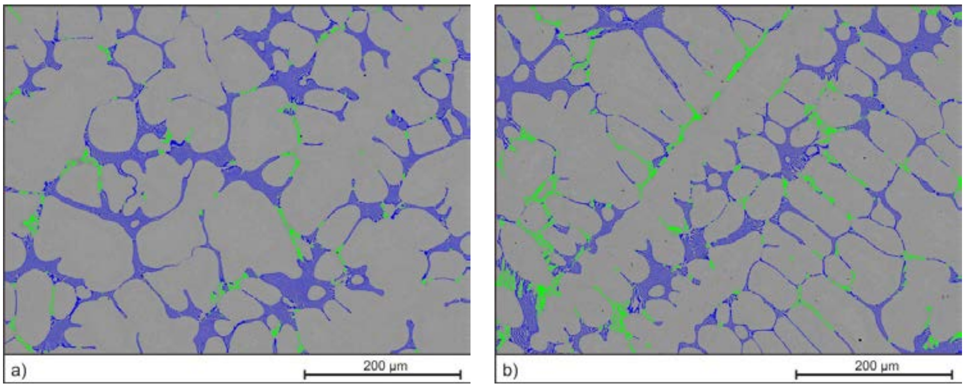


Figure 9: SEM images with highlighted eutectic carbides in blue and coarse carbides in green at **a)** 1500 °C and **b)** 1650 °C casting temperature

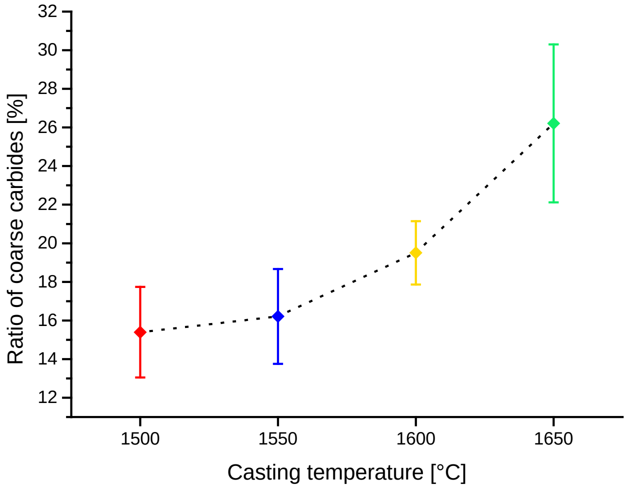


Figure 10: Effect of casting temperature on the ratio of coarse carbides

Summary & Conclusion

The effect of overheating of the melt before casting on AISI M42 high speed steel was tested in four experiments. Before performing the castings a simulation of the solidification had suggested noticeable higher cooling rates for low casting temperatures and vice versa. The solidification process is known to have a determining effect on micro- and macrostructure of a cast-steel. The secondary arm spacing as well as the CET are a result of the conditions during solidification.

Every class of high speed steel has their specific way of solidification and carbide formation. With medium solidification rates the only eutectic carbide in AISI M42 is M_2C. The immediate effects of casting temperature on the solidification structure and especially on the carbide morphology have been documented in this paper.

The following conclusions have been reached:

1.) An exact measurement of the CET is very complex, but there is a clear change between lower (1500 and 1550 °C) and higher casting temperatures (1600 and 1650 °C). The part of the cross section consisting of columnar dendrites increases from 30 to 60 %.
2.) The secondary arm spacing λ_2 is increasing slightly with increasing casting temperature.
3.) The primary grain size is massively influenced by the casting temperature. Increasing the overheating leads to a small number of huge and highly branched primary grains. This also confirms that at higher casting temperatures the nucleation rate in the center of the melt is low and only a few nuclei are able to survive.
4.) As the overheating grows the amount of carbide lamellas thicker than 1.2 mm rises significantly as well, future research shall be conducted if this is purely an effect of the solidification rate or if the primary grain size influences the carbide formation as well.
5.) If there is a possibility for an adjustment of the casting temperature, it should be considered for improvements of micro- and macrostructure.

Acknowledgement

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