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Alternative alloying concepts of hot work tool steels for application in die casting

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High performance hot work tool steels need to feature complex mechanical and physical properties in order to fulfill the requirements arising from different die casting applications. The required properties depend i.a. on the die casting process and the materials to be cast. They may include e.g. high toughness and strength at elevated temperature in order to be able to withstand thermal shocks occurring during high-pressure die casting. For application in low-pressure die casting, high temperature stability can be important in order to maintain mechanical properties even after long exposure to molten metal. In terms of physical properties, a high thermal conductivity is of particular interest, since on the one hand it increases resistance to thermal shocks, while on the other hand it can help to accelerate cooling of cast parts and thus in turn reduce the process cycle time. In this contribution, different new alloying concepts are presented. These include a specifically developed CrMoV-alloyed hot work tool steel featuring an optimized combination of high temperature strength, toughness, and resistance to thermal shock. A second new development combines superior thermal conductivity, high temperature stability, and high resistance to thermal shock. Furthermore, an additional approach makes use of the beneficial properties of a bainitic microstructure, which results in a combination of high strength at elevated temperatures and high toughness at minor alloying cost. Relevant properties of the alternative alloying concepts are compared to those of standard hot work tool steels, which are conventionally used in die casting applications.

KEYWORDS: DIE CASTING, TOOL STEEL, THERMAL SHOCK, TEMPERATURE STABILITY, THERMAL CONDUCTIVITY, HIGH-TEMPERATURE STRENGTH, TOUGHNESS, MICROSTRUCTURE

INTRODUCTION

During (high pressure) die casting ((HP)DC) of non-ferrous metals like e.g. Al- or Mg-alloys, different environmental conditions occur, which can affect dies and tool steels used for said application. These may include exposure to elevated temperatures due to contact with molten metal for longer duration as well as fast cycles of high and low temperatures due to spray cooling between two parts in HPDC. Furthermore, liquid metal injected with high velocity into the cavities of the die can cause mechanical stresses as well as occurrence of erosive wear (1). In turn, this means that tool steels used for die casting, depending on process parameters, need to exhibit different properties in order to ensure a proper service life.

In the case of low pressure die casting, maintenance of service hardness even during long exposure to elevated temperatures is of particular interest. This is ensured by high microstructural stability, which means resistance to e.g. coarsening of carbides.

In addition, during high pressure die casting, which is fre-

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quently characterized by the intention to produce a large amount of pieces in short cycle times, dies can be stressed by frequent changes in temperature featuring quite large amplitudes (thermal shock), which results in mechanical stresses. In consequence, as explained by the theory of Kindbom (2), the formation of cracks is inevitable (heat checking). However, different material properties can contribute to delay of formation or propagation of cracks (3). These include high strength and toughness at elevated temperatures, since it increases resistance to thermally induced plastic deformation (1) (2) (3) (4). A low coefficient of thermal expansion could also be favorable (3), however, in steel it depends on alloying content. Thus, since for economical reasons it is virtually undesired to further increase the contents of alloying elements in hot work tool steels significantly, this option is rather theoretical. Furthermore, a high thermal conductivity is beneficial since it can reduce thermal stresses during HPDC due to faster compensation of temperature differences (3) (5) (6) (7) (8). Basically, thermal conductivity of steel is linked with the amount of lattice defects, the most severe of which are alloying elements in solid solution. Thus, reduction of alloying contents can increase thermal conductivity, and additionally save cost. However, they are important for aforementioned mechanical properties. Cr for example, which is known to be highly detrimental to heat conduction of steel (9), cannot be neglected in some cases e.g. dies featuring large cross-sections, which need to exhibit uniform hardness distribution (through hardenability) (8), which is ensured by addition of chromium. Consequently, choosing tool steels featuring the required properties based on analysis of process parameters allows for optimized results.

Thus, the use of common premium hot work tool steel grades like e.g. 1.2343, 1.2344 or 1.2367 may result in sufficient service life of dies in many cases. However, there can be applications where, based on a systematical analysis of parameters and conditions, significant improvements can be achieved by using special hot work tool steels, which in turn may tentatively feature rather unconventional alloying concepts.

In this contribution, recently developed special tool steels are presented focusing especially on their properties related to application in die casting.

EXPERIMENTAL

The chemical composition of the investigated special tool steels as well as reference materials is listed in Tab. 1. Thermodur E 40 K Superclean is based on a conventional 5 mass% chromium hot work tool steel and is characterized mainly by addition of 2 mass% molybdenum as well as low silicon content and lowest amounts of tramp elements. In combination with the vanadium content, it features an optimized combination of high-temperature strength and toughness. Thermodur 2383 Supercool was originally developed for application in hot stamping tools. Due to the well-balanced chemical composition, which mainly features the lack of chromium and silicon, it is characterized by very high thermal conductivity yet still showing good mechanical properties. Thermodur 2322 exhibits a bainitic instead of a martensitic microstructure, which results in a good combination of high toughness and remarkable strength at elevated temperature. Furthermore, in deviation from all other hot work tool steels investigated in this study, 2322 was not electroslag-remelted (ESR). Specimens were taken from transition areas of large blocks and heat treated. Parameters were chosen from preliminary investigations on tempering behavior as shown in Fig. 2. Consequently, the following investigations were performed. Toughness (Charpy-V as well as unnotched specimens), tensile testing, and thermal shock resistance (self-constructed test rig, details i.a. in (3) as shown in Fig. 1). The latter allows for thermal cycling of specimens between inductive heating and a cooling bath, which was performed from 2,000 up to 8,000 cycles, followed by microscopic evaluation of cracking (number and length of cracks).

Tab.1 - Chemical analysis of investigated materials in mass%.

STeel Grade	C	Si	Mn	Cr	Mo	Ni	V	Others
Thermodur E 40 K Superclean	0.36	0.3	0.3	4.8	1.8	-	0.8	+
Thermodur 2383 Supercool	0.45	-	0.9	-	1.5	0.9	1.5	-
Thermodur 2322	0.18	0.55	0.8	2.0	0.7	0.2	0.1	+
Thermodur 2343 Superclean	0.37	1.0	0.4	5.3	1.3	-	0.4	-
Thermodur 2344 Superclean	0.4	1.0	0.4	5.3	1.4	-	1.0	-
Thermodur 2367 Superclean	0.37	0.3	0.4	5.0	3.0	-	0.6	

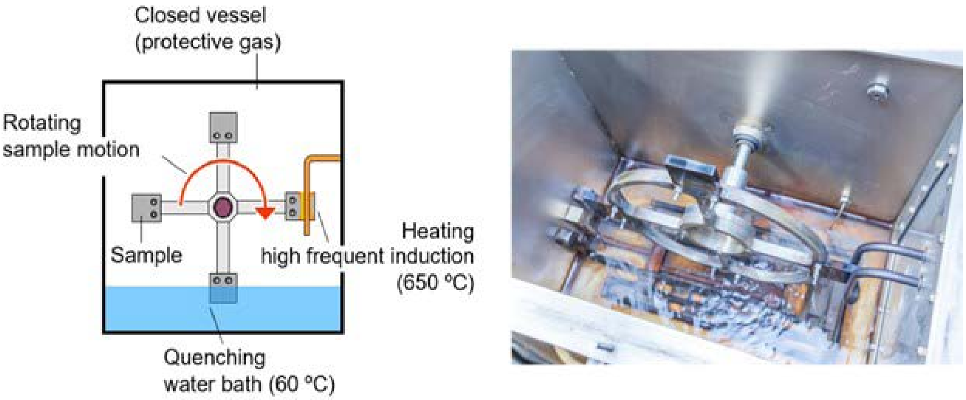

Fig.1 - Test rig for determination of heat checking resistance.

Furthermore, thermal conductivity was determined by means of indirect method, which included measurement of thermal diffusivity (laser flash analysis), specific heat capacity (differential scanning calorimetry), and density (buoyancy principle, dilatometry). Multiplication of said values, which all depend on measurement temperature, results in thermal conductivity.

RESULTS AND DISCUSSION

Tempering behavior

Fig. 2 shows on the left side the tempering curves of the investigated special hot work tool steels in the region of secondary hardness maximum. While it becomes clear that 1.2344 exhibits the highest secondary hardness due to increased amounts of carbon and vanadium, the hardness peaks of 1.2343 and 1.2367 are slightly lower. The latter shows increased hardness at temperatures above approximately 600 °C, which means less hardness decrease due to higher microstructural stability. E 40 K features slightly lower secondary hardness but comparable values above 600 °C when compared to 1.2343, which indicates high microstructural stability in the case of E 40 K as well. Because of the different alloying systems, 1.2383 and 1.2322 show different tempering behavior. The first exhibits significantly more intense secondary hardening behavior, which in addition is shifted to higher temperatures, which in turn means that 1.2383 at temperatures above 650 °C shows the highest hardness. The latter in contrast features significantly lower hardness in the secondary hardness maximum region, but it seems noticeable, that the hardness drop at higher temperatures is less pronounced as compared to conventional hot work tool steels.

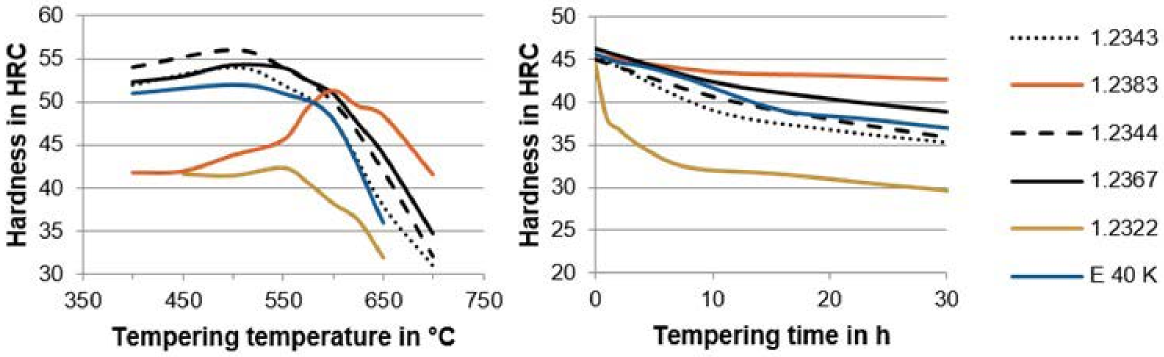

Fig.2 - Tempering behavior of investigated special hot work tool steels.

Long-term tempering behavior

As shown in Fig. 2 on the right side, microstructural stability of the special hot work tool steels was investigated by performing tempering experiments for longer durations at 600 °C. The specimens were either used in quenched and double tempered ("qt", all except of 1.2322) or just quenched (1.2322) to 45 HRC condition. In the case of tempering to 45 HRC, this means that temperatures larger than 600 °C were applied prior to long-term tempering. Thus, the initial tendency for microstructural changes during long-term tempering at 600 °C is reduced due to qt. By trend, the tendencies seen in the tempering curves shown in Fig. 2 are confirmed. After 30 h of testing, 1.2343 and 1.2344 show similar hardness, while that of E 40 K is slightly higher. Due to higher microstructural stability, 1.2367 shows less decrease in hardness, while 1.2383 exhibits the best results expressed by lowest reduction of hardness by long-term tempering. Because of the lack of tempering, 1.2322 features highest reduction of hardness at longer exposure to 600 °C. However, when comparing the inclination of curves of the investigated materials at durations between 10 and 30 h, these seem to be quite comparable. Thus it can be concluded, that 1.2322 shows quite comparable endurance, but at a lower level of hardness, which, for some applications however may be sufficient.

Strength and toughness at elevated temperatures

As can be derived from Fig. 3, both tensile strength as well as toughness (Charpy-V) testing were performed at 600 °C in order to illustrate the properties at elevated temperatures. Results described in the following were obtained using specimens heat treated as described before except of 1.2322, which was used in qt condition as well. It becomes obvious that 1.2383 and 1.2367 exhibit highest strength at this temperature, which once again underlines their high microstructural stability, which has already been indicated. However, the differences in strength are quite low. Especially 1.2322, which features lower hardness and thus strength in qt condition at room temperature, shows quite high strength at 600 °C. The same holds true for the high temperature toughness, which is remarkably high in the case of 1.2322, while the reference materials exhibit slightly lower values.

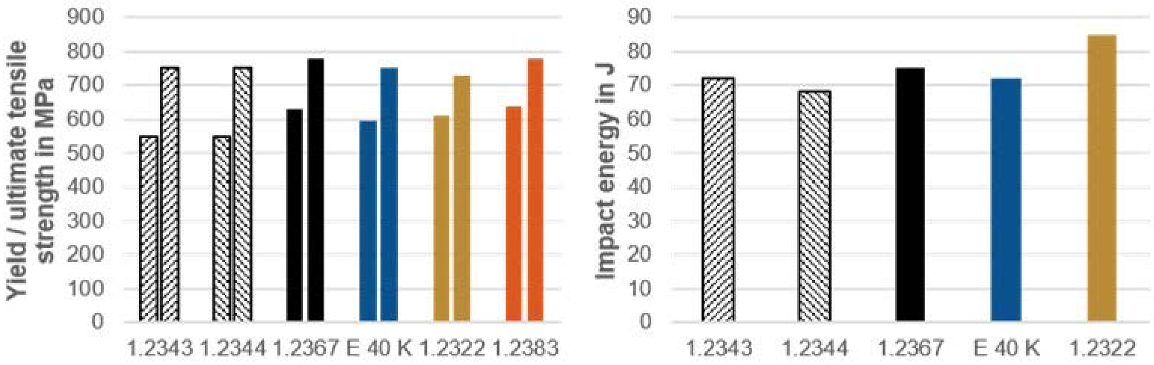

Fig.3 - Strength and toughness at elevated temperature.

Thermal conductivity

While, as already mentioned, a reduction in coefficient of thermal expansion would require significantly higher amounts of alloying contents than hot work tool steels usually have, thermal conductivity can be influenced more unpretentiously. Due to the optimized alloying concept, 1.2383 at similar hardness level shows considerably increased thermal conductivity (Fig. 4), while, as already described, showing good mechanical properties. E 40 K, like the conventional 5 % chromium hot work tool steels, features lower values of heat conduction, yet, similar to 1.2367, they are slightly increased as compared with 1.2343 and 1.2344, respectively.

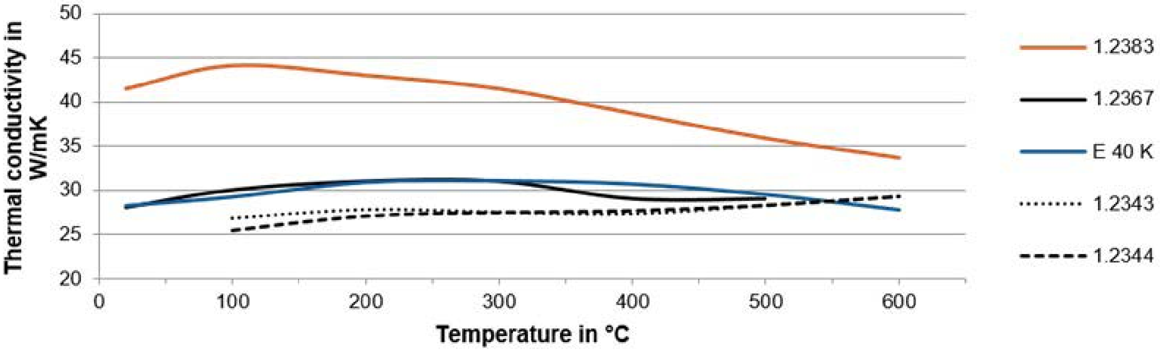

Fig.4 - Thermal conductivity of investigated special hot work tool steels.

Heat checking resistance

As already described, resistance to thermal shock, which is a crucial property especially in the case of hot work tool steels applied in high pressure die casting, was investigated as well. The results are shown in Fig. 5. The evaluation of specimen was performed by counting the number of cracks as well as measuring their length in the cross-section of a predefined surface area. By trend, when focusing on the longest test duration (8,000 temperature cycles) the following conclusions can be drawn, taking a certain measurement uncertainty of the test setup into account. The reference materials 1.2343, 1.2344, and 1.2367 can be considered as showing quite comparable behavior, which is characterized by formation of similar numbers of cracks (little less in the case of 1.2343) that exhibit approximately the same maximum depth and consequently by a comparatively high value of total crack depth. The lowest crack depth among the reference alloys in this study can be seen in the case of 1.2343, which shows similar values compared to E 40 K after 8,000 cycles. The difference between these two grades is, that E 40 K shows more, but less deep cracking. Even more cracks were discovered in the case of 1.2383, however, these were exceptionally short, thus resulting in a small total crack depth. In contrast, 1.2322 shows occurrence of less but deeper cracks, thus resulting in a considerably small total depth of cracks as well. The very good heat checking resistance of special steels 1.2383, 1.2322, and E 40 K can be explained by the improved thermal conductivity of the first and second, respectively, while the latter shows an optimized combination of high temperature strength and toughness.

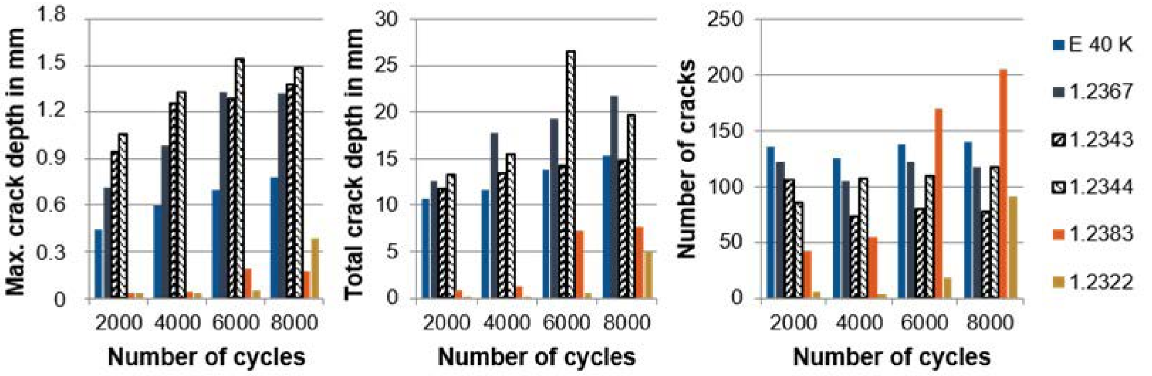

Fig.5 - Heat checking resistance of investigated special hot work tool steels.

CONCLUSIONS

In this study, different special hot work tool steels were characterized with special focus on properties relevant for application in die casting. A specifically developed CrMoV-alloyed hot work tool steel (E 40 K) features an optimized combination of high temperature strength, toughness, and resistance to thermal shock compared with conventional hot work tool steels. A second new development (1.2383) combines superior thermal conductivity, high temperature stability, and high resistance to thermal shock. In an additional approach, a bainitic hot work tool steel (1.2322) was developed, which, based on the beneficial properties of this kind of microstructure, results in a combination of high strength at elevated temperatures and high toughness at minor alloying cost. Thus, the alloying concepts presented are suitable for application in various die casting processes, which will be verified by industrial trials.

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