The tool steel producer's contribution to successful die casting of structural components

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Die cast structural components for the automotive industry gain more and more importance as they highly contribute to a weight reduction of cars and thus to a reduced fuel consumption as well as CO_2-emission. So today very often die cast aluminium A-, B- or C-pillar, shock towers, or door components replace traditional steel parts. These structural components are often characterised by large dimensions and complicated design. Die casting dies for structural components have to fulfil highest requirements with respect to toughness, high-temperature strength, and thermal fatigue resistance. Often the traditionally used hot-work tool steels like 1.2343 (AISI H 11), 1.2344 (H 13), or 1.2367 cannot fulfil these requirements. Kind & Co. has developed three special hot-work tool steels with significantly improved properties: TQ 1, HP 1, and HTR. The report will not only give a survey on the properties of these steels but also on practical experience gained with these grades. A proper heat treatment is essential for the performance of the dies. Kind & Co has recently set up one of the largest and most modern vacuum hardening furnaces in the world which focuses on these large die casting dies. The report will also show up the contribution of a modern heat treatment facility to an economic die casting process of high-class structural components.

Keywords: Structural components, automotive industry, hot-work tool steel, special hot-work tool steel grades, mechanical properties, heat checking resistance, thermal conductivity, heat treatment

INTRODUCTION

The international automobile industry faces political decisions which drastically restrict the emission of CO_2 from passenger cars. The European Union has set up a high goal for the automotive industry by restricting the CO_2-emissions to an average fleet value of 120g CO_2/km by the year 2012 [1]. The proportion of CO_2-emissions from road traffic is continuously growing. Although the fuel efficiency of automotive engines has been improved in the recent years the average fuel consumption has scarcely changed. Studies of the European Union estimated an average specific CO_2-emission of 186 g CO_2 / km from the current passenger car fleet. In order to reduce the CO_2-emission from new passenger cars the European Community set a target of 120 g CO_2 / km to be attained by 2005, latest by 2012 [2]. Recognizing that this target cannot be achieved within the original schedule the European Commission proposed a mandatory reduction of CO_2-emmissions to 130 g CO_2 / km by better engine technologies and a further reduction by 10 g CO_2 / km by other technological improvements [3].
Many efforts have been done to improve the fuel efficiency as well as the CO_2-emmission of automotive engines. A further approach to this target is weight reduction of the cars as this directly influences the fuel consumption and CO_2-emission. So meanwhile many car producers have been installing die cast structural components in their cars.

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FIG. 1 ***Cast aluminium structural components (red) in the auto body of the AUDI A 8 [4].***
Componenti strutturali di alluminio pressocolati (in rosso) nella carrozzeria della AUDI A 8 [4].

Audi has been a pioneer in the use of aluminium for auto bodies. Figure 1 gives an example of the widespread use of cast aluminium components in the AUDI A8 [4].
Today structural components can also be found within doors or as hatchback support frames in cars (figures 2 – 3).

SOME REMARKS ON DIE CASTING DIES FOR STRUCTURAL COMPONENTS

The figures 2 – 3 clearly underline the large dimensions and the complicated design which modern die cast structural components can achieve nowadays. These structural components often

FIG. 2 ***Door and window frames for a German sports car (Photo: Georg Fischer AG).***

Telai di portiere e finestrini di un'automobile sportiva tedesca (Photo: Georg Fischer AG).

FIG. 3 ***Die cast hatchback support frame (Photo: BMW AG).***

Telaio di supporto di un portellone posteriore pressocolato.

require long flow paths for the melt. This makes it difficult to fill the die casting dies without a pre-solidification of the aluminium. The die casters often help themselves by increasing the casting temperature of the aluminium melt for a complete filling of the die. In relation to their large overall size often only a small part of the surface of the die is in direct contact with the melt. This increases the thermal load on the dies locally and creates intensive thermal inhomogeneities within the dies.
As a properly balanced temperature distribution is difficult to achieve in large dies die casters often face a high risk of thermal stresses within the dies.
Rips which provide the necessary stiffness of the castings are critical with respect to the dies as the die's cavity is weakened by deep notches. This leads to high local stress concentrations during the casting process in these details. So die casting dies for structural components often face a high risk of gross cracking.
For a proper assembly in the auto body the die cast components must have contact surfaces which fulfil highest requirements concerning surface quality. These facts urgently have to be respected in the processes of die design, tool steel selection, die manufacturing, as well as heat treatment. Only an early co-operation of all parties involved guarantees a proper performance of the die casting dies.

HOT-WORK TOOL STEELS FOR DIE CASTING DIES OF STRUCTURAL COMPONENTS

The remarks concerning the loads of the dies during the die casting process lead to the inescapable conclusion that dies for these structural components require highly sophisticated hot-work tool steels produced via the Electro-Slag-Remelting (ESR) metallurgy.
Europe's most frequently used hot-work tool steel for die casting dies is the grade 1.2343 (X37CrMoV5-1). It combines good high-temperature strength with a sufficient toughness and heat checking resistance and it fulfils the requirements for many standard components. Alloyed with higher vanadium content the grade 1.2344 (X40CrMoV5-1) is the most frequently used grade for this application in the USA. Compared to 1.2343 it offers a higher high-temperature strength, tempering resistance, and wear resistance but a reduced toughness. The grade 1.2367 (X38CrMoV5-3) was often used in cases when a high high-temperature strength and an increased heat checking resistance was requested.
For higher demands on the properties of the die steels Kind & Co has meanwhile developed three special hot-work tool steels: the grades TQ 1, HP 1, and HTR. Their compositions are listed in table 1. This table also includes the average compositions of established, standardised hot-work tool steels which are well known in the die casting industry.
The three grades TQ 1, HP 1, and HTR represent different ob-

Steel designation			Alloy content in mass-%									
Mat. No.	AISI	Brand name	C	Si	Mn	P	S	Cr	Mo	V	W	Nb
1.2343	H 11	USN	0,37	1,00	0,40	< 0,020	< 0,005	5,20	1,20	0,40	—	—
1.2344	H 13	USD	0,40	1,00	0,40	< 0,020	< 0,005	5,20	1,30	1,00	—	—
1.2367	—	RPU	0,38	0,40	0,40	< 0,020	< 0,005	5,00	3,00	0,50	—	—
—	—	TQ 1	0,36	0,25	0,40	< 0,012	< 0,003	5,20	1,90	0,55	—	—
—	—	HP 1	0,35	0,20	0,30	< 0,012	< 0,003	5,20	1,40	0,55	—	+
—	—	HTR	0,32	0,20	0,30	<0,0125	< 0,005	2,20	1,20	0,50	3,80	—

TAB. 1 ***Chemical compositions of hot-work tool steels for die casting dies.***

Composizione chimica degli acciai da utensili da lavorazione a caldo per stampi di pressocolata.

Mat. No.	AISI	Brand Name	Hardening Temp. °C	Soaking Time min
1.2343	H 11	USN	1000	45
1.2344	H 13	USD	1020	45
1.2367	—	RPU	1030	45
—	—	TQ 1	1010	60
—	—	HP 1	1020	60
—	—	HTR	1060	60

Tab. 2 ***Recommended hardening parameters for hot-work tool steels for die casting dies.***

Parametri di indurimento raccomandati per gli acciai da utensili da lavorazione a caldo per stampi di pressocolata.

jectives of their development processes. TQ 1 was developed in order to combine the specific advantages of the two grades 1.2343 –very high toughness - and 1.2367 – high high-temperature strength - within one new grade. Based on the knowledge about the beneficial results of highest cleanliness and lowest concentration of detrimental trace elements on the steel properties Kind & Co. uses a highly sophisticated metallurgy process. The result is an outstanding combination of high-temperature strength and toughness. The grade HP 1 was developed as an economical alternative to TQ 1. HP 1 had been derived from the composition of TQ 1 by reducing the concentration of the expensive alloying element molybdenum.

The addition of a small dose of niobium helps to prevent grain growth during hardening from the higher specific hardening temperature of the steel. The latest development of Kind & Co. is the steel grade HTR. This steel aims at applications which require an extreme high-temperature strength and heat checking resistance. This can be seen in the different alloy concept of HTR. The reduction of the chromium content contributes to an improved thermal conductivity. The alloying element tungsten improves the high-temperature strength as well as the thermal conductivity.

The specific properties of these special grades will be described in the following paragraphs.

PROPERTIES OF HOT-WORK TOOL STEELS FOR DIE CASTING DIES

The steel grades listed in table 1 develop their properties only after proper hardening and tempering.

The recommended hardening temperatures and soaking times for the hardening process are listed in table 2.

Tempering curves (figure 4) help to select the best suitable steel for the individual die casting application as they describe the steel's tempering resistance. A high tempering resistance has a beneficialeffect on the performance of die casting dies for large structural components as it helps to withstandthe high thermal loads of the dies. As the curves of the grades 1.2343 and 1.2344 are very similarthis diagram displays only grade 1.2343 for a better readability. It is evident that steel 1.2367 exceeds the grades 1.2343 and 1.2344 in the secondary hardness maximum and in the tempering behaviour. Grade TQ 1 develops nearly the same high tempering resistance as 1.2367. Although HP 1 has a slightly lower secondary hardness maximum than 1.2343 or TQ 1 it develops in the technically interesting temperature range nearly the same high tempering resistance as TQ 1. The tungsten alloyed special steel grade HTR develops a secondary hardness maximum nearly as high as HP 1 but at a clearly higher tempering temperature. The decline of the tempering curve indicates

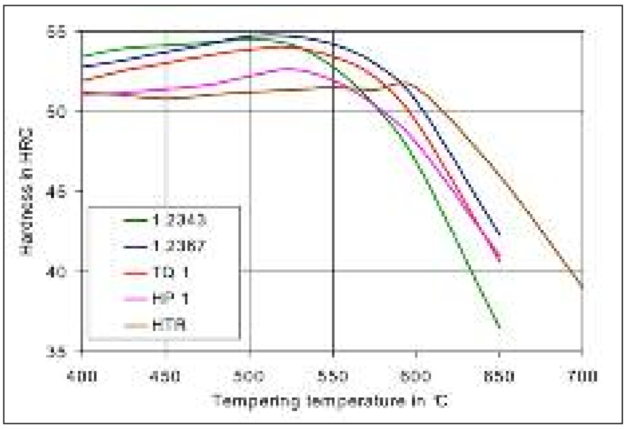

FIG. 4 ***Tempering curves of standard and special hot-work tool steels for die casting dies.***

Diagramma di rinvenimento di acciai standard e acciai speciali da utensili per lavorazione a caldo per stampi da pressocolata.

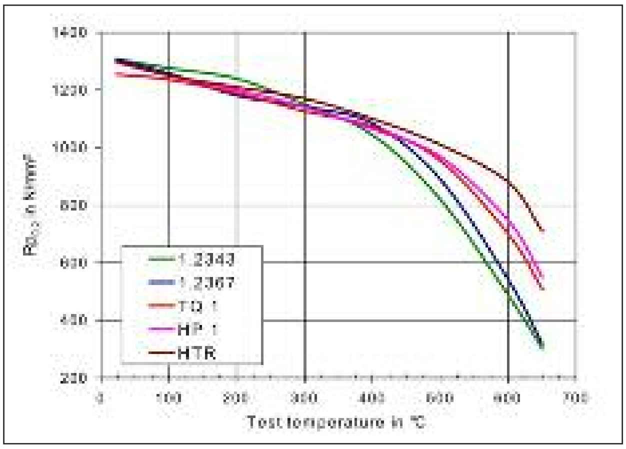

FIG. 5 ***High-temperature strength of standard and special hot-work tool steels for die casting dies.***

Resistenza meccanica alle temperature elevate di acciai standard e acciai speciali da utensili per lavorazione a caldo per stampi di pressocolata.

the steel's very high tempering resistance.

In order to withstand the high mechanical impacts during the pressure die casting process the suitable hot-work tool steels must provide sufficient high-temperature strength.

The high-temperature strength of the steels is expressed by the 0,2-% Yield Strength measured at elevated temperatures (figure 5). In the temperature range below 400 °C the discussed steel grades develop a similar behaviour, but at higher temperatures the differences between the grades become more evident. While the standard grades 1.2343, 1.2344, and 1.2367 loose their high-temperature soon above 400 °C the special grades TQ 1 and HP 1 exceed these grades clearly. The tungsten alloyed grade HTR has the highest high-temperature strength among the discussed grades.

Toughness is a very important property which is needed to withstand the sudden mechanical loads of the die casting process. A high toughness helps to compensate local stress concentrations and to prevent stress cracks in critical segments of the die inserts. Figure 6 compares the toughness potentials of the discussed hot-work tool steels. The values have been measured on ISO-V-Notch samples taken in transverse orientation from the centre of forged bars and hardened to 45 HRC.

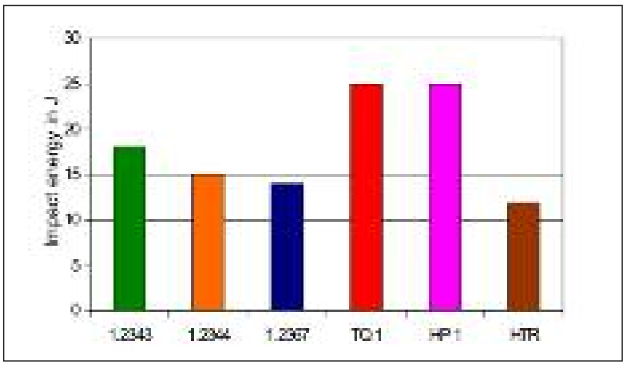

FIG. 6 ***Toughness of hot-work tool steels for die casting dies (ISO-V-Notch samples, transverse, centre of forged bars, approx. 320 mm dia., 45 HRC).***

Tenacità di acciai da utensili per lavorazione a caldo per stampi di pressocolata (provini per la prova di intaglio a V-ISO, sezione trasversale, centro di barre forgiate del diametro di ca. 320 mm, 45 HRC).

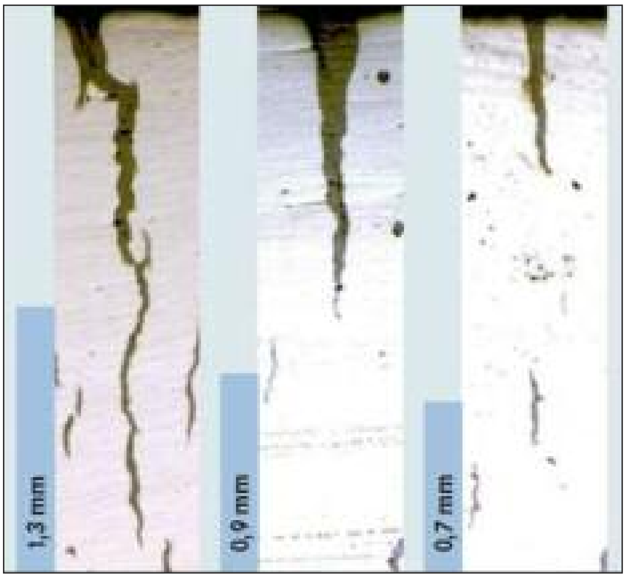

FIG. 7 ***Appearance of heat-checking cracks after 4.000 cycles 600 °C / water - a): steel 1.2343; b): steel HP 1; c): steel HTR.***

Aspetto delle cricche superficiali da fatica termica dopo 4.000 cicli a 600 °C / acqua - a): acciaio 1.2343; b): steel HP 1; c): acciaio HTR.

The hot-work tool steel 1.2343 is the toughest grade among the three discussed standard grades.
The special grades TQ 1 and HP 1 exceed the toughness of 1.2343 by approx. 25 %. This expresses the highly improved ability of these steels to endure sudden mechanical loads as well as to compensate high stresses in the dies. As the grade HTR aims at increased high-temperature strength it cannot develop the same high toughness level as the other special grades.
A high resistance of the steels against heat checking cracks is essential to produce cast components with best surface quality. The formation of heat checking cracks is a thermo-mechanical fatigue process of the steel. As the resistance against heat checking is to a certain degree related to the high-temperature strength of the steel an increase of the hardness / strength can improve the heat checking resistance to a certain extend. On the other hand it must be respected that an increase of hardness is automatically combined with a reduction of the overall toughness potential of the steel. So with the intention to improve one property one can easily impair a second property. A helpful alternative can be the selection of a steel grade with improved heat checking resistance.
In a laboratory test samples of 45 HRC were exposed to 4.000 cycles of heating up to 600 °C and water quenching. The photos in figure 7 display the characteristic appearance of the heat checking cracks in the tested steels. Among the steels described here the grades 1.2343 and 1.2344 developed the same maximum crack length of approx. 1,3 mm. With definitely less and shorter thermal fatigue cracks the grades TQ 1 and HP 1 achieved a much higher resistance against thermal shocks. The best resistance was observed in samples of grade HTR.
The thermal conductivity is responsible for the heat transfer from the cavity's surface into the cooling channels. Table 3 gives a survey on the thermal conductivity of the discussed steels. All data are valid for the hardened and tempered condition (45 HRC).
Due to its high molybdenum content steel 1.2367 offers the best thermal conductivity among the standardized hot-work tool steels. The two special grades TQ 1 and HP 1 develop nearly the same high level which is on the other hand exceeded by the tungsten-alloyed steel HTR.
A high thermal conductivity helps to reduce the thermal load in the cavity of the die. It also lowers thermally induced stresses and helps to create a well balanced thermal distribution within the dies.
This is for example important in dies for frame-like components like doors or hatchback support frames where an uneven thermal load of the dies is very likely.
At least hot-work tool steels with a high thermal conductivity can also contribute to an increased productivity due to reduced cycle times.

Steel designation			Test temperature in °C		
Mat.No.	AISI	Brand name	100	400	600
1.2343	H 11	USN	26,8	27,3	29,3
1.2344	H 13	USD	25,5	27,7	29,3
1.2367	—	RPU	29,9	32,4	34,0
—	—	TQ 1	29,5	30,5	31,5
—	—	HP 1	29,8	31,4	33,0
—	—	HTR	35,2	34,6	33,0

TAB. 3 ***Thermal conductivity λ in W / (m * K) of hot-work tool steels.***

*Conducibilità termica γ in W / (m * K) di acciai da utensili per lavorazione a caldo.*

PRODUCTION OF SUITABLE HOT-WORK TOOL STEELS

Although it should be a well-known fact it has to be repeated again that the high requirements concerning homogeneity, cleanliness, and toughness can only be fulfilled with grades that have been produced via the electro-slag-remelting (ESR) process. The super-clean grades like TQ 1 and HP 1 furthermore require special metallurgical processes to provide the low concentrations of detrimental trace elements already in the first melting process.
Structural components like door or window frames or hatchback support frames require even larger die inserts. Today dimensions such as 1400 mm x 1750 mm x 475 mm are among the

usual dimensions for those die inserts. Producing the required large steel blocks also requires an adequate forging technology. Kind & Co recommends for these large die blocks the so called three-dimensional forging technology. In comparison to the conventional bar forging the three-dimensional forging process leads to a much higher and more homogeneous plastic deformation of the steel. This has a very positive effect on mechanical properties such as toughness.

HEAT TREATMENT OF DIES FOR STRUCTURAL COMPONENTS

A well adjusted heat treatment is the key to a proper performance of die casting dies. The vacuum hardening technology is state-of-the art for the heat treatment of dies. The most important step is the hardening process in combination with the tempering to the correct hardness. The austenitization process as well as the carbide precipitation during the tempering is diffusion controlled so that it is absolutely important to follow the time-temperature-regimes advised by the steel producers. Kind & Co. therefore recommends the hardening temperatures and soaking times listed before in table 2.

The choice of the best suitable hardness is always a matter of the die design, die size, individual loads of the die during the casting process, and of the used hot-work tool steel. A general recommendation cannot be given. For most smaller and medium sized die casting dies a hardness of 44 - 46 HRC is regarded as the best suitable range. In case of large die inserts, e.g. for door components, it can be very beneficial for the die performance and die lifetime to reduce the hardness down to 40– 42 HRC as this increases the steel's toughness. Another beneficial contribution to an improved die performance is the use of steel grades with an improved toughness potential, e.g. TQ 1 or HP 1.

The best toughness values can be achieved after a complete martensitic transformation of the steel in the hardening process. The necessary minimum quenching rates for the martensitic transformation depend on the transformation behaviour of the steels individually described in the TTT-diagrams of the steels. Some die casters or technical organizations define minimum quenching rates in order to achieve a fully martensitic transformation. The North American Die Casting Association NADCA as well as FORD recommends a minimum cooling rate of 28 °C / min for the temperature range between the austenitizing temperature and 540 °C, measured near the surface of the die [5, 6]. General Motors [7] claims a slightly higher cooling rate of 30 °C / min.

Martensitic hot-work tool steels tend to precipitate carbides during cooling within the temperature range between 1000 and 700 °C. The highest precipitation rate for these steels has to be expected between 800 and 900 °C. These carbide precipitations negatively influence the toughness of the steels but they can be suppressed by a high cooling rate. This explains why die casting dies have to pass this temperature range during the quenching process as fast as possible in order to develop best toughness [8, 9].

Die inserts for structural components today easily achieve dimensions and weights which exceed the usable dimensions and quenching capacities of most vacuum hardening furnaces. So it can be a challenge for the die makers to find vacuum hardening furnaces large enough for these die inserts.

Kind & Co. has set up one of the world's largest and most powerful vacuum hardening furnaces (figure 8) in order to provide the full service of a reliable heat treater to the die casting industry. The chamber of the furnace offers usable dimensions of 1600 mm x 1430 mm x 2000 mm (w, h, l) and a maximum load capacity of 5.500 kg. It is suitable to harden large die inserts as those shown in figures 9 – 10.

FIG. 8 ***New vacuum hardening furnace Ipsen Turbo Treater ST6672 at Kind & Co.***

Nuovo forno di trattamento termico in vuoto Ipsen Turbo Treater ST6672 at Kind & Co.

FIG. 9 ***Die insert for a passenger car door, 3.820 kg.***

Inserto di stampo di una portiera di automobile, 3.820 kg.

FIG. 10 ***Die insert for a hatchback support frame, 1.350 mm x 1.720 mm x 440 mm, 5.440 kg.***

Inserto di stampo di un telaio di portellone posteriore, 1.350 mm x 1.720 mm x 440 mm, 5.440 kg.

Die inserts of these large dimensions and weight can only be hardened successfully if the furnace has a sufficient cooling capacity. The high quenching pressure of max. 15 bar can be kept up during the complete quenching process as the powerful cooling turbine (560 kW) circulates the pressurized nitrogen gas through large heat exchangers. This guarantees the necessary fast heat removal from the dies. Specially designed cooling nozzles inside the chamber allow adjusting the gas flow in various

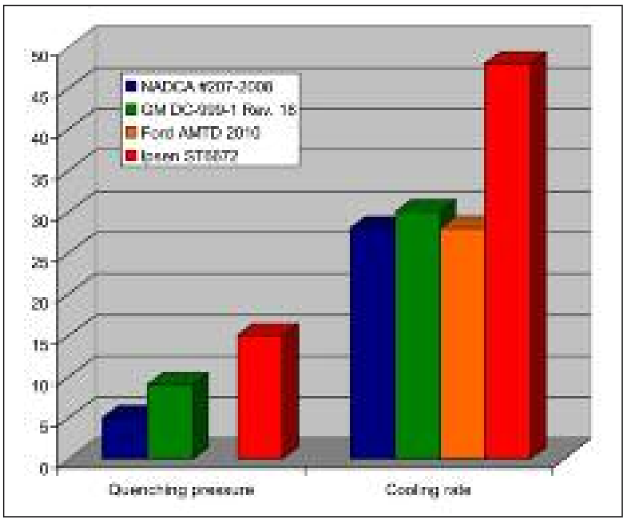

FIG. 11 ***Properties of the furnace compared to requirements.***

Confronto fra caratteristiche del forno e requisiti.

ways according to the geometry of the die to be hardened and help to minimize the distortion of the dies as well as to reduce the crack risk during the hardening process.
The furnace provides the high thermal homogeneity which is necessary to properly harden these large die inserts. Figure 11 compares the values of the quenching pressure and cooling rate of this new furnace with the requirements of the NADCA, Ford and GM specification [5, 6, 7]. The new vacuum hardening furnace at Kind & Co. exceeds their requirements by far.

RESULTS OF INDUSTRIAL HEAT TREATMENTS

The microstructure of a hardened and tempered tool allows a good control of the heat treatment.
Grain size, carbide solution as well as carbide precipitations, and the appearance of the martensitic microstructure are very good indicators for the quality of the vacuum hardening process. As one example showing the potential of the new furnace to harden large dies the microphotographs in figure 12 display the microstructure of the die insert shown in figure 9. The soft annealed material revealed a homogeneous microstructure with fine dispersed secondary carbides. After the hardening and tempering process the grain size was measured acc. to Snyder-Graff Number 8 – 10. The martensitic microstructure is fine and very homogeneous. Toughness values of the steel measured after the vacuum heat treatment exceeded the requirements of the specifications mentioned here by far.

DISCUSSION AND CONCLUSION

The use of die cast aluminium structural components in modern passenger cars is an important contribution to weight reduction, less fuel consumption, and finally reduced CO2-emissions from cars.
These structural components often require large die inserts which are often close to the limits of availability and producability. The specific shapes of these components often create problems like inhomogeneous temperature distribution in the dies or thermal stresses so that the standardized hot- work tool steels like 1.2343 or 1.2344 are at their limits of applicability. Specially developed hot-work tool steels like TQ 1, HP1, and HTR offer optimized properties, such as improved high-temperature strength and tempering resistance simultaneously with an improved toughness and heat-checking resistance. HTR offers drastically improved high-temperature strength and tempering resistance as well as thermal conductivity. Due to its comparably low toughness it should be used in partial inserts which are exposed to extreme thermal loads. The hardness should normally not exceed 43 HRC.
The new vacuum hardening furnace IPSEN Super Turbo ST6672 does not only offer sufficient space to harden the very large die inserts, it also comes with a very unique and high quenching capability. The achievable high quenching rate is responsible for the suppression of pre-eutectoid carbide precipitations as well as a fine martensitic microstructure in the hardened and tempered dies.
This way even large die inserts with a weight of more than 5 tons can develop excellent toughness values.
The combination of modern hot-work tool steels with improved properties and of modern heat treatment facilities offer the best chance for a sufficient performance of die casting dies for these complicated components.

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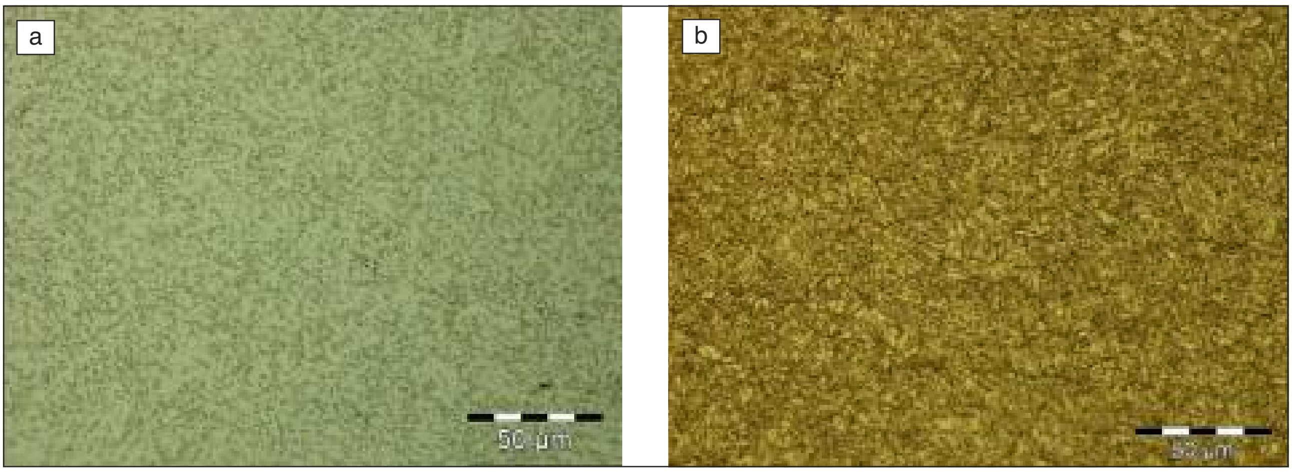

FIG. 12 ***Microstructure of a die casting die insert made of USN ESR (1.2343 ESR), 3820 kg. a: soft annealed microstructure; b: microstructure after vacuum heat treatment in the new hardening furnace.***

Microstruttura di un inserto di stampo da presso colata di acciaio USN ESR (1.2343 ESR), 3820 kg. a: microstruttura dopo ricottura dolce; b: microstruttura dopo trattamento in vuoto nel nuovo forno.

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Abstract

Il contributo dei produttori di acciai da utensili al successo dei componenti strutturali pressocolati

Parole chiave: pressocolata – automotive – acciaio – trattamenti termici –proprietà

La pressocolata di componenti strutturali per l'industria automobilistica acquisisce sempre più importanza in quanto contribuisce fortemente alla riduzione del peso degli autoveicoli e quindi alla riduzione dei consumi di carburanti e delle emissioni di CO2. Per questo motivo oggi molto spesso i componenti in alluminio pressofuso sostituiscono le parti in acciaio tradizionale dei pillar A-, B- C-, di parti degli ammortizzatori e delle portiere. Questi componenti strutturali sono spesso caratterizzati da grosse dimensioni e da forma complessa. Gli stampi per componenti strutturali pressocolati devono soddisfare i più elevati requisiti di tenacità, resistenza a temperature elevate, e resistenza alla fatica termica. Spesso gli acciai da utensili tradizionalmente utilizzati per la lavorazione a caldo come gli acciai 1,2343 (AISI H11), 1,2344 (H13), o 1,2367 non sono in grado di soddisfare questi requisiti. La società Kind & Co. ha sviluppato tre acciai speciali da utensili per lavorazione a caldo che offrono caratteristiche notevolmente migliorate: gli acciai TQ 1, HP 1 e HTR. Il presente lavoro non solo offre una panoramica sulle caratteristiche di questi acciai, ma anche sull'esperienza pratica acquisita con questi gradi di acciaio. Per la realizzazione degli stampi è necessario eseguire un trattamento termico adeguato. La Kind & Co ha recentemente costruito uno dei forni per trattamento termico a vuoto più grandi e moderni al mondo studiato per questi grandi stampi pressofusione. Il presente studio descrive anche il contributo di un moderno impianto di trattamento termico ad un processo economico di pressofusione di componenti strutturali di alta qualità.