New Developments in Forging Technology

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Requirements on Forging Dies for Aluminium

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Abstract

Reduced exhaust emissions and fuel consumption, improved agility of passenger cars and extended range of electrically driven cars are actual challenges in the automotive industry. The substitution of components which traditionally had been forged of steel by die forged aluminium components contributes to automotive light weight design. Efficient forging of aluminium components requires tools which allow high production numbers. Although the basic properties of forging tools for aluminium are comparable to steel forging dies the specific properties always need to be adjusted individually in order to provide high production numbers. Due to the specific deformation behaviour of aluminium the criteria for tool steel selection and mechanical properties of forging dies cannot be transferred directly from steel forging. With flow stresses higher than carbon steel and simultaneously narrow temperature ranges for forging operations the forgeability of many technically interesting aluminium alloys is significantly different from many steel grades. The comparably slow forging process and long contact time between forging material and die leads to intensive thermal loads of the dies. Suitable tool steels need to withstand stresses in the surface which are caused by sticking and friction between aluminium and forging die.
Based on an analysis of the factors influencing die life in aluminium forging this report introduces hot-work tool steels which are suitable for the special requirements in aluminium forging. The description of the main properties of these steels and information regarding the recommended hardness levels of forging tools help to select appropriate tool steel solutions to comply with the requirements of the forging industry and to provide long tool life.

1 Introduction

Optimizing cars for weight and therefore light weight design is today and tomorrow a topic of vivid interest among the automotive OEMs as it influences fuel efficiency and battery range. While high safety and comfort standards have to be fulfilled many technologies contribute to the goal of automotive light weight. Die cast structural components of aluminium as well as hot-stamped steel sheet components have been successfully used for years in the body-in-white. Also many chassis components which traditionally had been made of forged steel have been substituted by die forged aluminium components. Economic production of die forged components is based on forging tools which provide high productivity and require minimum maintenance. The selection of appropriate tool steels as well as the correct setting of properties such as hardness, toughness, and wear resistance is extremely important for the tool performance.

As the deformation behaviour of aluminium differs significantly from steel the criteria for tool steel selection and mechanical properties of forging dies cannot be adopted from steel to aluminium. The paper therefore describes the basics of the deformation behaviour of aluminium and analyses the specific stresses to which forging dies for aluminium are exposed during operation. The requirements on tool steels for forging dies are described and suitable tool steels proposed.

2 Forging of Aluminium

The automotive industry is facing permanently intensifying regulations regarding exhaust emissions. Beside optimization of combustion engines automotive light weight can contribute to complying with the official regulations. Reducing the weight of a passenger car by 100 kg lowers the fuel consumption by 0,5 l/100 km and automatically the toxic emissions. Battery range of electrically driven vehicles as well as agility of cars is improved. Today several technologies contribute to weight reduction in the automotive industry. Hot-stamping (press hardening) of steel sheets produces structural components of very high strength with reduced wall thickness and reduced weight. Die cast structural components of light metal (door frames, shock towers, cross members etc.) are used in a large scale in modern passenger vehicles. Substitution of forged components which were traditionally made of steel offers further chances to reduce weight.

Nowadays forged aluminium components can be found in wheel suspensions of many modern cars. Aircraft industry is an industrial branch in which light weight has been a permanent topic and modern air planes are mixture of many modern light materials. Here forged aluminium components cover a wide range of dimensions (Figure 1).

Figure 1: Forged aluminium components in the wheel suspension of a passenger car (left) and forged aluminium landing gear of an airplane (right)

2.1 Forging Behaviour of Aluminium

Aluminium alloys are generally considered to be more difficult to be deformed than carbon or alloy steel grades. Flow curves describe the functional relation between flow stress and strain of the material and can be used to characterize the deformation behaviour of a metal. Figure 2, acc. to /1/, presents flow curves of different aluminium alloys in comparison to carbon steel 1.1163 (C25R). The comparison indicates that some curves for low- to intermediate-strength aluminium alloys, e.g. alloy 6061, are lower than of carbon steel. But especially high-strength alloys, particularly of the 7xxx series, reveal flow stresses which are considerably higher than those of carbon steels.

Forgeability of all aluminium alloys improves with increasing temperature but the effect of temperature is different from alloy to alloy. Successful forging of aluminium alloys requires a strict control of the recommended metal temperature which is in the range of 420 – 470 °C for aluminium alloys 2014 and 2219, 430 – 480 °C for aluminium alloy 6061, and 380 – 440 °C for aluminium alloy 7075. Especially the temperature ranges for the technically interesting alloys are comparably low and narrow.

Other important parameters of the aluminium forging process are proper control of the die temperature and of the strain rate. Compared to forging of steel the die forging process of aluminium is comparably slow and is often done in several deformation steps.

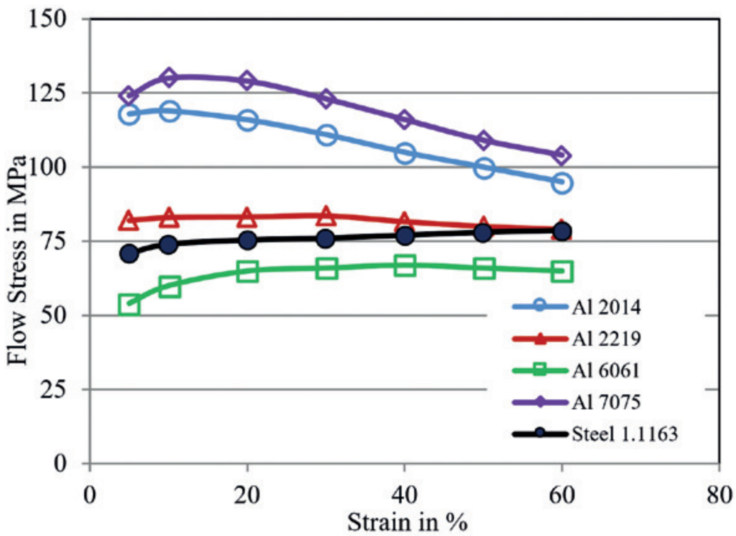

Figure 2:
Flow curves of four aluminium alloys, measured at 370 °C, strain rates 10 s-1, in comparison to carbon steel 1.1163, measured at 1205 °C, strain rate 10 s-1

Aluminium alloys develop a tendency of sticking to tools. This phenomenon is due to metal transfer between aluminium alloy and forging tool during plastic deformation. The extent of this metal transfer depends on factors such as alloy composition, surface roughness, and lubrication. Considerable variations of the coefficient of friction had been observed depending on the aluminium composition and roughness /2/.

Sticking of aluminium on die surfaces hinders the flow of the aluminium within the die cavity. During forging it is responsible for stresses induced surface of the die cavities and for cracks in the forging tools.

2.2 Requirements on Tool Steels for Forging Dies for Aluminium

Efficient forging of aluminium components requires tools which allow high production numbers. Although the basic properties of forging tools for aluminium are comparable to steel forging dies the specific properties always need to be adjusted individually in order to provide high production numbers.

The requirements on tool steels for forging dies for aluminium must be derived from the specific deformation behaviour of aluminium and from the resulting loads to which these dies are exposed during forging.

Compared to forging of steel the process of forging aluminium is comparably slow. And although the forging temperatures of aluminium alloys are considerably lower the long contact time between forged material and die is responsible for a high thermal load of the dies. As aluminium is often forged isothermally /1/ forging dies are heated which exposes them to further thermal loads. Suitable tool steel grades therefore need to have a good tempering resistance in order to avoid softening during the forging operation.

Despite the comparably slow deformation process of aluminium forging suitable tool steel grades need to have high toughness in order to prevent cracking from the friction induced stresses in the surface of die cavities.

Due to the abrasive character of oxide layers on the surface of the forgings sufficient resistance against abrasive wear is a compulsory property for all tool steel grades in forging applications.

3 Tool Steel Selection for Forging Dies for Aluminium

Like a puzzle the performance of a forging tool is the result of complex interaction of many factors (Figure 3). Some of these factors are related to the dies, their design and method of production. Other factors respect the forging process as well as handling of the dies in the forging shop. Quality of the used tool steel means fulfilling reliably specified material requirements like hardness, strength, wear resistance. The best way to achieve satisfying tool performance is to consider the various aspects jointly with all parties involved.

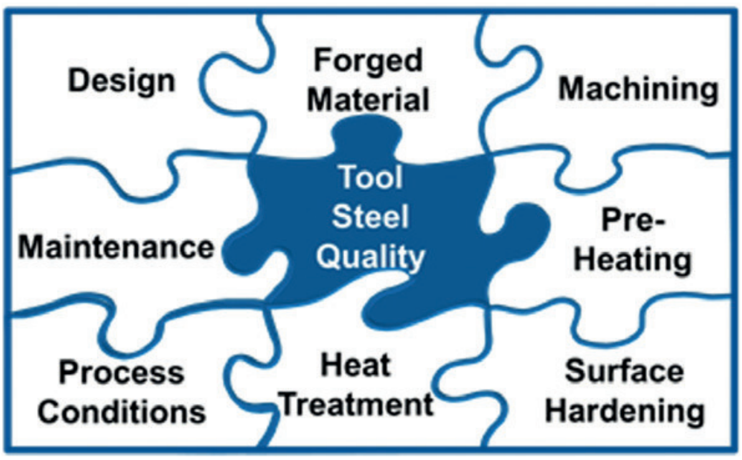

Figure 3:
Factors influencing the lifetime and performance of forging tools

For more than 130 years Kind & Co. has been a producer of tool steels specialized in the development and production of hot-work tool steels. In close contact with tool makers and forging shops Kind & Co. has learned the needs of the forging industry. The tool steel recommendations listed in Table 1 are based on long-time experience.

Steel designation			Alloy composition in mass.-%						
Brand	Mat.-No.	AISI	C	Si	Mn	Cr	Mo	V	Nb
USN ESR	1.2343	H11	0,37	1,00	0,40	5,20	1,20	0,40	-
HP1	-	-	0,35	0,20	0,30	5,20	1,40	0,55	+
CS 1	-	-	0,50	0,30	0,40	5,00	1,90	0,55	+

Table 1: Chemical compositions of hot-work tool steels for forging dies for aluminium

The chemical compositions of the grade USN ESR is internationally standardized in ISO 4957 Tool Steels /3/. While the alloying concept is standardized, heat treatment, alloying point within standard bands, forging strategy etc. are not. Therefore, even a “standard” grade from Kind & Co. provides better than average behaviour during operation because of excellent execution in all process details. USN ESR is produced via Electro-Slag-Remelting (ESR). This remelting process not only purifies the steel but also drastically improves its homogeneity and provides improved toughness.

The special grades HP 1 and CS 1 have been developed by Kind & Co. and are exclusively produced via ESR. Both grades are based on the principle of highest cleanliness. The concentrations of phosphorus and sulphur as well as of detrimental trace elements such as aluminium, copper, zinc have been drastically reduced providing these grades extreme toughness. HP 1 and CS 1 aim at improved high-temperature strength. The addition of niobium (Nb) prohibits grain growth during heat treatment which would negatively influence the toughness of these grades.

Tempering is the final step in heat treatment of forging dies. This process determines the final hardness, strength and high-tempering strength, and toughness of the steel. Tempering curves like those shown in Figure 4 describe the individual response of the steel to tempering. They serve as an instrument for the heat treater of forging dies. They are also helpful to select suitable tool steels. The more a die is exposed to high temperature the more important is a high tempering resistance. High tempering resistance protects forging dies against undesired softening during operation.

Figure 4 displays the tempering curves of the tool steel grades listed in Table 1. The three grades develop the typical tempering behaviour of high alloyed hot-work tool steels with a secondary hardness maximum between 500 and 550 °C tempering temperature. The decline of the curves at tempering temperatures above the secondary hardness maximum describes the tempering resistance – resistance against softening during operation. The tempering resistance of these grades increases in this sequence: USN ESR => HP 1 => CS 1. High-temperature strength and toughness are measured in tensile tests at elevated temperatures (Figure 5). The reduction of area Z can be used to describe the toughness of the steels. Abrasive wear resistance is a further property which influences the performance of forging tools (Figure 6). Wear resistance is not only a matter of hardness but depends to a high degree on the content, size, and distribution of hard phases like carbide precipitations.

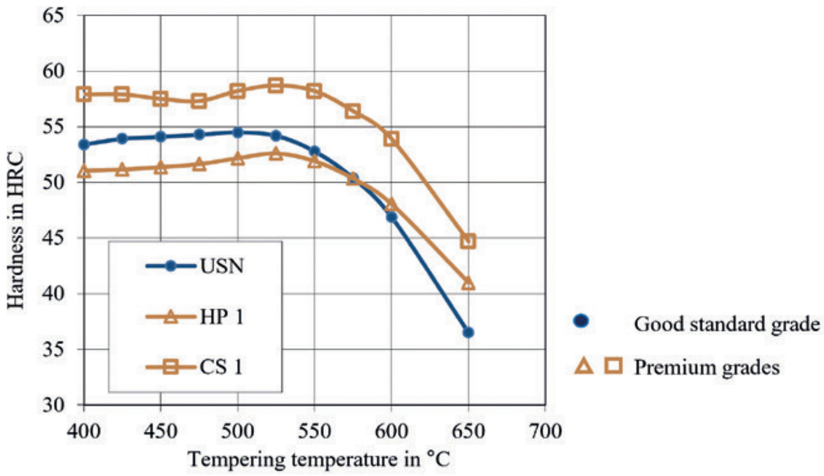

Figure 4:
Tempering behaviour of hot-work tool steels listed in Table 1

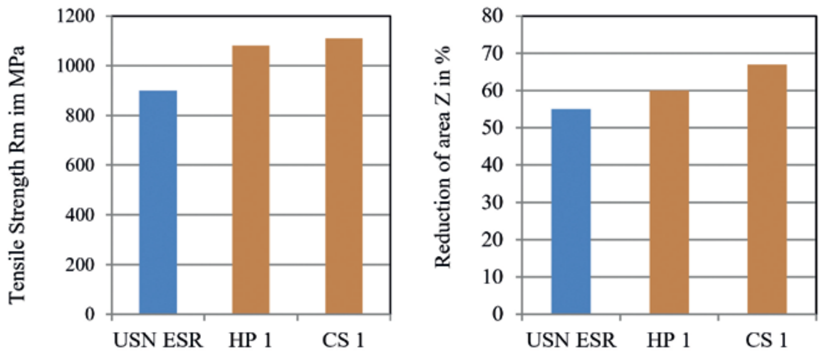

Figure 5:
High-temperature strength and toughness of hot-work tool steels for forging dies, measured at 550 °C (all steels hardened + tempered to Rm = 1500 MPa)

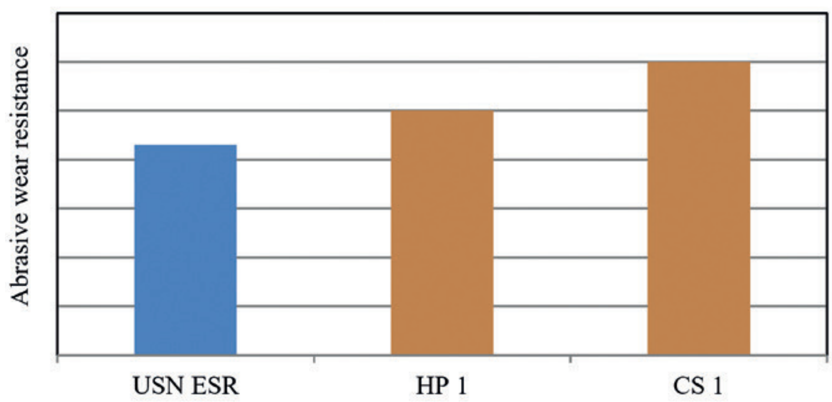

Figure 6:
Abrasive wear resistance of hot-work tool steels (qualitative comparison)

The microstructure of these steels consists, if hardened and tempered correctly, of tempered martensite and very fine homogeneously dispersed secondary carbide preciptitations. Representative for the three grades discussed here Figure 7 displays the microstructure of USN ESR in the hardened and tempered condition.

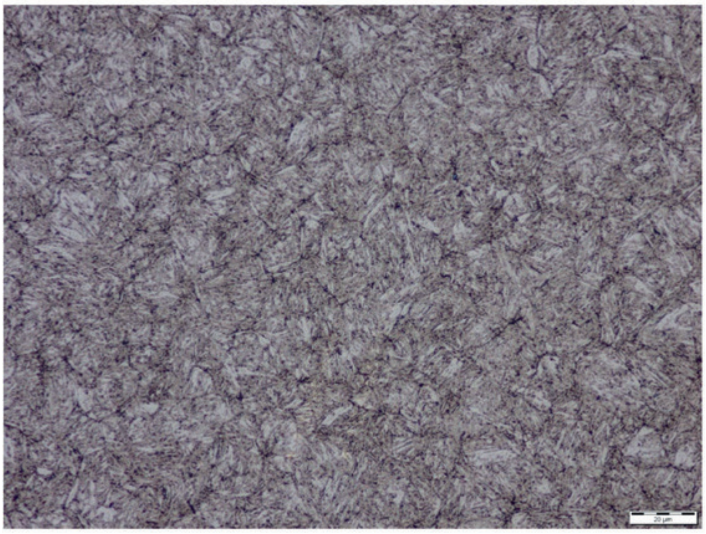

Figure 7:
Microstructure of hardened and tempered hot-work tool steel USN ESR

As shown above Kind & Co. provides hot-work tool steels with a wide range of properties according to the demands of the customers.
The selection of the best suitable tool steel as well as the determination of hardness ranges for forging dies for aluminium has to respect the design of the cavity, the aluminium alloy and specific aspects of the forging operation.
In order to assist customers in the decision for the best suitable too steel and hardness Kind & Co has developed a schematic guide which respects forging equipment, forged material, type and design of the die cavities (Figure 8).

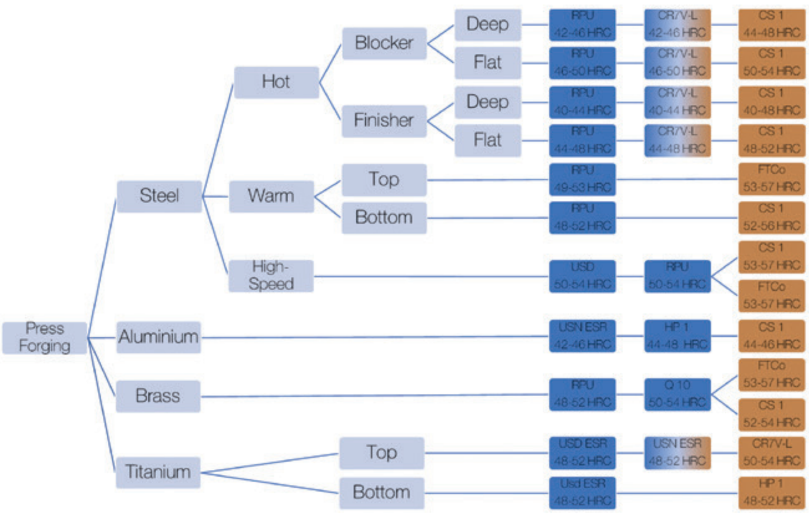

Figure 8:
Schematic guide to suitable tool steel grades in die forging applications

The specific aspects of aluminium forging are shown in Figure 9.

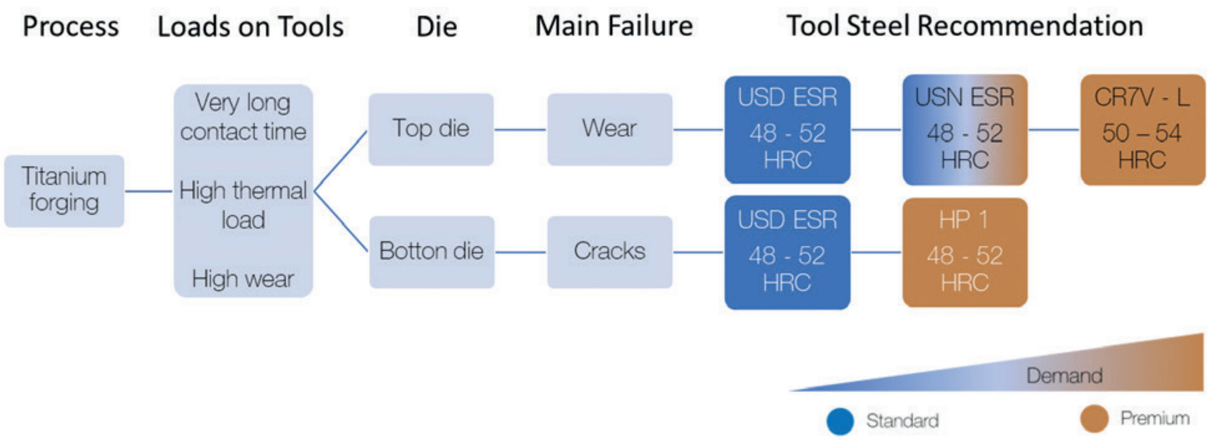

Figure 9: Schematic guide to suitable tool steel grades for aluminium forging

Simple requirements in aluminium forging can be fulfilled using the grade USN ESR with a hardness of 42 – 46 HRC. Compared to USN ESR the special grade HP 1 provides an improved high-temperature strength and toughness level. This allows raising the hardness of dies of HP 1 to a range of 44 – 48 HRC so that the higher hardness further contributes to wear resistance of the forging dies. Due to their specific combinations of properties USN ESR and HP 1 have developed to be good standard grades for aluminium forging dies. the latest development of Kind & Co., special grade CS 1, is characterized by a unique combination of very high high-temperature strength and toughness. This allows setting the hardness to 44 – 48 HRC and providing a further improvement in wear resistance. This way special grade CS 1 can be used as die material if highest requirements for wear resistant forging have to be fulfilled.

4 Conclusion

Due to its low density aluminium gains more and more importance in automotive light weight design as well as in aeronautical applications. Die forged components of aluminium substitute more and more traditional steel parts. Efficient die forging production of aluminium parts depends to a high degree on reliable tools. Therefore the selection of suitable tool steels as well as the determination of optimum hardness ranges plays an important role. As the deformation behaviour of aluminium is significantly different from steel the criteria for the selection of tool steels cannot be transferred from steel.

Forging dies for aluminium require hot-work tool steels with sufficient tempering resistance, high-temperature strength, and toughness in order to withstand the stresses during forging operation. Due to the high requirements of toughness Kind & Co. recommends the hot-work tool steels USN ESR, HP 1, and CS 1. These three grades are produced via Electro-Slag-Remelting in order to guarantee the necessary homogeneity and cleanliness of the tool steel grades.

Chemically grade USN ESR corresponds to the internationally standardized in ISO 4957 Tool Steels but the production process at Kind & Co. provides better than average behaviour during operation. HP 1 and CS 1 are hot-work tool steel grades which Kind & Co. has developed for highly stressed tools.

With hardness ranging from 42 to 46 HRC USN ESR can be recommended as die material for standard applications. The improved high-temperature strength and toughness level of HP 1 allows increasing the hardness of the dies to 44 – 48 HRC contributing to improved wear resistance in combination with simultaneously very high toughness. This combination of properties allows HP 1 to be used for more demanding forging dies.

For even higher requirements in wear resistance special grade CS 1 can be used with a hardness of 44 – 48 HRC.

In any case, using tailored tool steel solutions according to the demands of the part and the series depth provides an economic advantage to the producer of forged parts. Initially higher tool steel costs for specific solutions like HP 1 and CS 1 pay easily off on higher life time of the dies.

Literature

/1/	Kuhlman, G.W.	Forging of Aluminium Alloys In: ASM Handbook, Vol. 14A, Metal Working: Bulk Forming, 2005, pp. 299 – 312
/2/	Schey, J.A., Nautiyal, P.C.	Effects of surface roughness on friction and metal transfer in lubricated sliding of aluminium alloys against steel surfaces In: Wear, 146 (1991), pp. 37 – 51
/3/	N.N.	ISO 4957: Tool Steels, 1999