IMPROVING THE PERFORMANCE OF FORGING TOOLS — A CASE STUDY

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Abstract The drop forging industry as an important partner of the automotive industry is exposed to a high economic pressure. This pressure can be encountered successfully if the forging dies reveal a high productivity and sustain the manifold impacts for a long time.

The main impacts on forging dies are of thermal and mechanical kind. The report briefly describes the main wear mechanisms of forging dies. The hot-work tool steel Thyrotherm 2999 EFS SUPRA has originally been developed for hot forming tools which are exposed to high thermal and mechanical impacts, e.g. forging dies for heavy metals. Thyrotherm 2999 EFS SUPRA combines an excellent tempering resistance, a high hot-strength and thermal conductivity, and finally reveals a high wear resistance. This combination of properties promises a good applicability to forging processes which show a high wear impact. Independent laboratory tests, carried out at the University of Hannover, Germany, proved the great wear behavior in forging and extrusion tests.

During the introduction of Thyrotherm 2999 EFS SUPRA to the market application tests have been carried out with various customers in many different forging operations ranging from press and hammer forging to high-speed forging. The report describes the results and the experience gained in these tests and proves that the use of Thyrotherm 2999 EFS SUPRA directly contributes to an improved tool performance.

Keywords: Hot-work tool steel, drop forging, high-speed forging, tool life, wear mechanism, application test

INTRODUCTION

The drop forging industry has been an important partner of the automotive industry and thus of a vivid branch for a very long time. On the one hand this intensive focus guarantees a high level of capacity utilization in the forging industry, on the other it leads to a strong dependence and to considerable economic pressure. The international competition, new production technologies as well as the omnipresent trend to more complex shapes and simultaneously reduced tolerances require serious efforts of the drop forging industry to reduce the production costs. One promising approach to solve this problem is an improved performance of the forging tools.

As wear is the most important factor limiting the lifetime and performance of forging tools [1] an increased wear resistance directly contributes to economic benefits: a higher number of forged parts per tool, a higher accuracy, and extended operation times. The factors influencing the performance of forging tools are manifold and include material properties of the used hot-work tool steel, mechanical, thermal, and chemical impacts during operation as well as factors derived from the forging machine [2, 3, 4].

All efforts to improve the performance of forging tools require knowledge of the impact and wear mechanisms during operation. A detailed description of the impacts on forging tools is given in [5, 6]. Edelstahl Witten-Krefeld GmbH has developed the hot-work tool steel THYROTHERM 2999 EFS SUPRA which is especially designed for hot forming applications with intensive thermal and mechanical impacts on the tools. It exceeds other hot-work tool steels in tempering behavior, high-temperature tensile strength and in thermal conductivity. The steel excellent wear resistance was proved in independent laboratory tests by the University Hannover, Germany, and has been described earlier [7]. Meanwhile THYROTHERM 2999 EFS SUPRA has been successfully introduced to the market.

After a short summarizing survey of the most important wear mechanisms in forging dies this report will describe the experience gained in various industrial applications of THYROTHERM 2999 EFS SUPRA as a tool material.

FAILURE ANALYSIS OF DROP FORGING DIES

An excellent description of the wear mechanisms of forging dies and the progress of wear during forging dies is given in [5]. The development of wear on forging tools is mainly determined by microstructural alterations in the outmost surface of forging tools. The first forging cycle immediately influences the microstructure in the surface of a forging die (Fig. 1 [5]). This

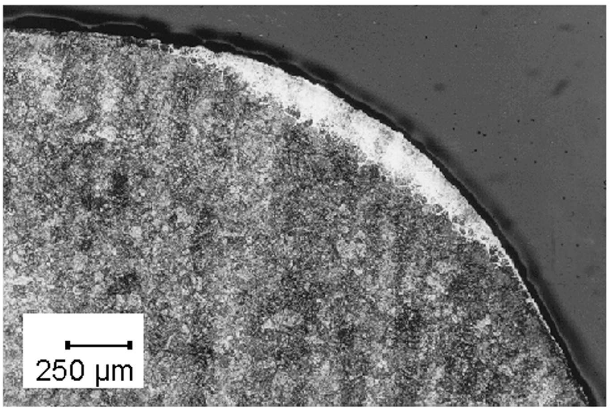

Figure 1. Microstructure of a forging die after the first forging stroke.

photo gives an impression of the microstructure in the surface of a forging tool after one single forging cycle. The surface of the tool clearly reveals a white area with a thickness of up to 140 µm after the first forging operation. This zone grows during the following 100 cycles to approx. 200 µm. This particular zone has an extremely fine grained and martensitic microstructure indicating that it has undergone a new hardening process.

The first forging cycle immediately increases the hardness in the outmost surface (Fig. 2 [5]). Then the progressing forging operation leads to a further

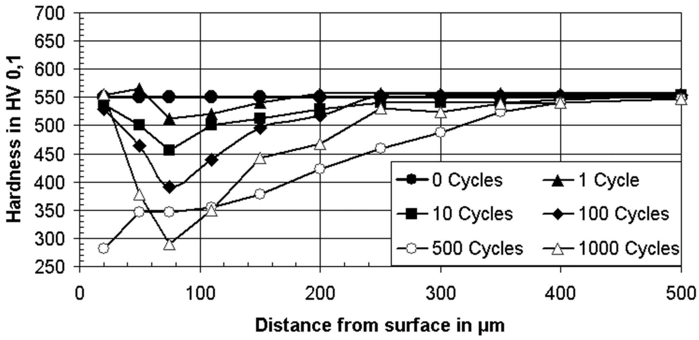

Figure 2. Influence of forging operations on hardness profiles in the surface of forging die.

increase of the hardness in the outmost surface. Here the high thermal impact on the tool austenitizes the hot-work tool steel again which is then subsequently quenched by the sprayed lubricant. Approximately 100 µm below the tool´s surface the hardness drops to a minimum. This is directly related to the thermal influence on the tool. The thermal influence is no longer high enough to re-harden the steel but as the temperature still exceeds the tool´s final tempering temperature the hot-work tool steel softens.

A considerable plastic deformation on the tool surface after 500 strokes coincides with an extreme loss in hardness. During the previous forging operation the high thermal impact generated a zone of approx. 80 µm thickness with a ferritic, soft microstructure which thus favored the plastic deformation of the surface.

After 1000 forging cycles the hardness in the surface increases again. The softened surface observed after 500 cycles could not withstand the subsequent mechanical impacts any longer so that it was worn off during the following forging cycles. The newly created surface was then subjected to the same impacts and changes mentioned before.

A forging die is exposed to a continuous thermal impact (basic temperature of the die, ideally within the range of 200–300 °C). This temperature can be regarded as a balance between the thermal energy input during forging and the loss of energy between two forging cycles due to thermal conduction and cooling. As a general overheating of the die has to be avoided an appropriate cooling of the die has to be secured.

Forging dies are also exposed to an intensive cyclic thermal impact which results from the contact with the hot forged parts (1100–1200 $^\circ C$) and the subsequently sprayed lubricant. Figure 3 [8] schematically shows the cyclic thermal impact of the surfaces of forging dies. Due to the contact with the

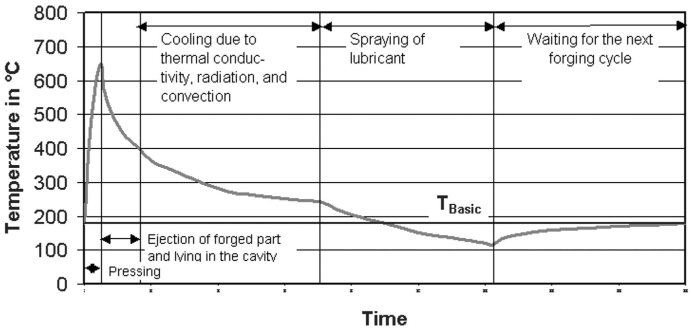

Figure 3. Time-temperature-profile in the surface of a forging die (schematic).

material to be forged the surface temperature of the die rises drastically to temperatures between 650 and 700 $^\circ C$. The lubricant sprayed onto the die's surface cools the outmost surface of the die immediately. This thermal cycle is repeated with every forging cycle and finally supports thermal fatigue within the die´s surface. Thermal fatigue finally results in a network of cracks which occurs on the surface. These cracks not only reduce the quality of the forged parts but as the number and depth of these cracks grow during further forgings they are also an origin of further damage.

THYROTHERM 2999 EFS SUPRA

The invention of the hot-work tool steel Thyrotherm 2999 EFS SUPRA was based on the knowledge of these impacts. As mentioned in [7, 9] Thyrotherm 2999 EFS SUPRA was originally developed for hot forming applications with high demands on wear resistance.

The steel´s chemical composition is given in Table 1.

Its tempering behavior, its hot-strength, and its thermal conductivity are characteristic properties of this hot-work tool steel (Figs. 4–6) [7].

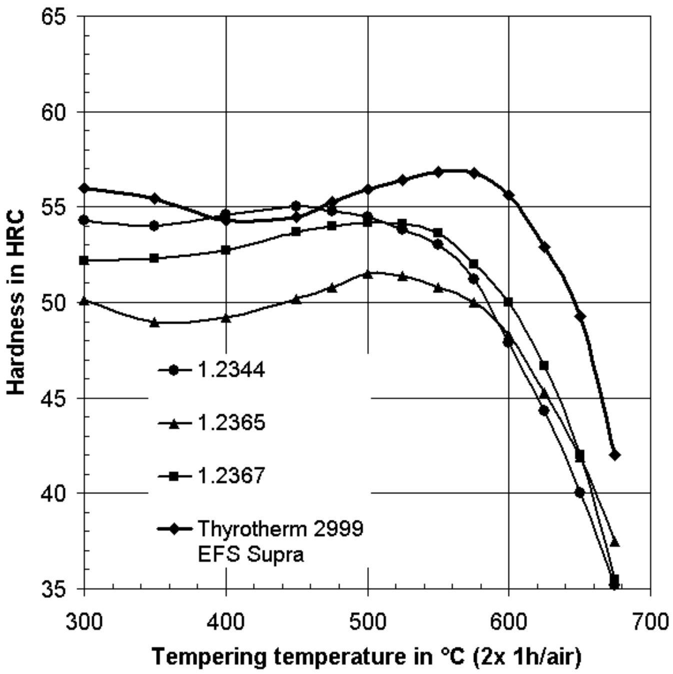

Figure 4. Tempering response of several hot-work tool steels (all steels hardened from their usual hardening temperature).

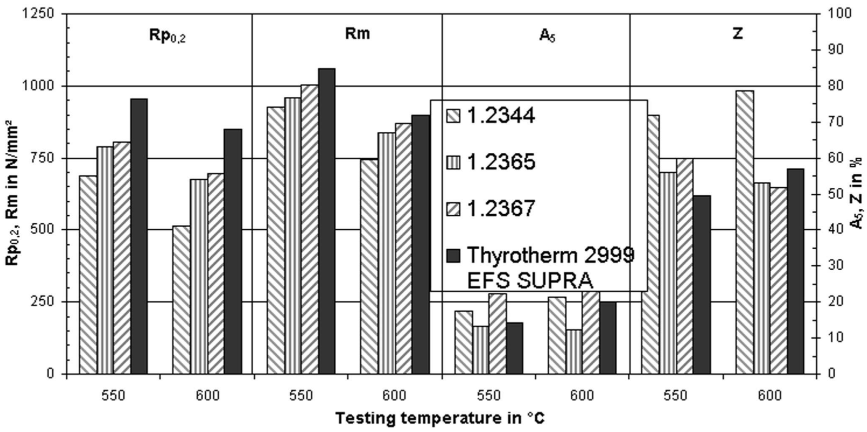

Figure 5. Hot-strength and ductility of several hot-work tool steels (all steels hardened and tempered to $R_m = 1450$ N/mm^2).

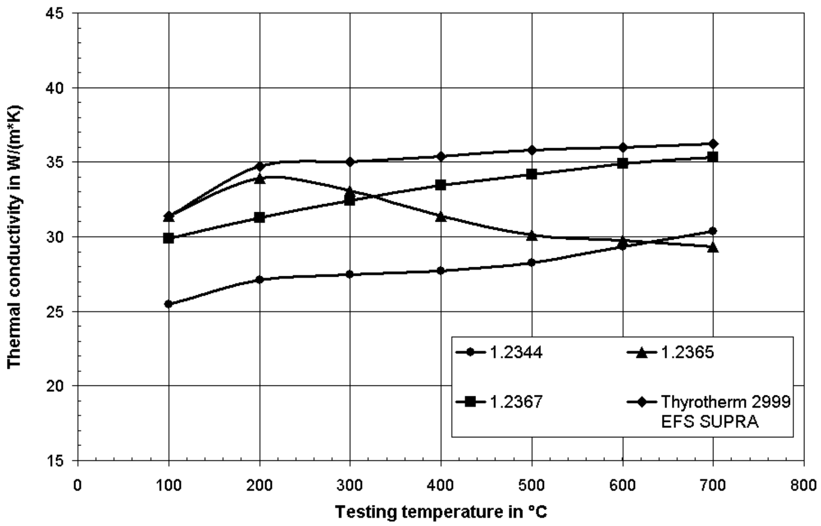

Figure 6. Thermal conductivity of several hot-work tool steels (hardened and tempered to 44 HRC).

Table 1. Chemical compositions of studied hot-work tool steels

Steel Designation			Chemical composition in Mass- %				
Name	German Mat.-№	AISI	C	Si	Cr	Mo	V
Thyrotherm 2999 EFS SUPRA	—	—	0.45	0.30	3.00	5.00	1.00
X38CrMoV5-1	1.2343	H11	0.38	1.00	5.30	1.30	0.40
X40CrMoV5-1	1.2344	H13	0.40	1.00	5.30	1.40	1.00
X32CrMoV3-3	1.2365	H10	0.32	0.30	3.00	2.80	0.50
X38CrMoV5-3	1.2367	—	0.37	0.40	5.00	3.00	0.60

Independent laboratory tests of the University of Hannover, Germany, proved the excellent wear resistance of Thyrotherm 2999 EFS SUPRA (Fig. 7) [7, 10] and were a stimulus for various industrial application tests.

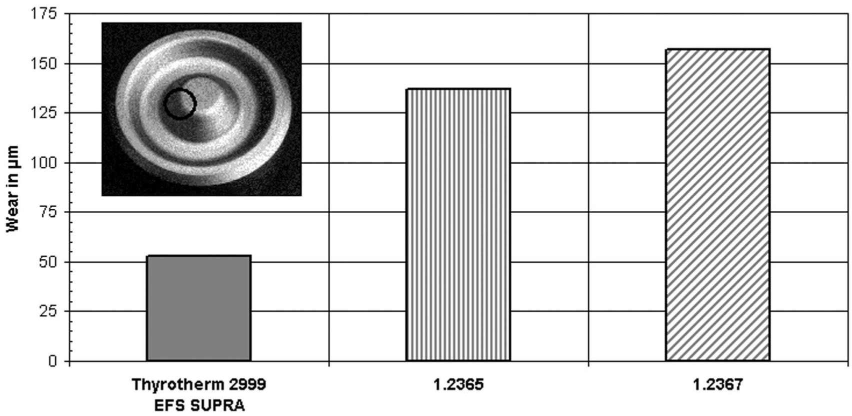

Figure 7. Wear of forging dies made of different hot-work tool steels after 1000 strokes (laboratory tests).

CASE STUDIES ON HAMMER AND PRESS FORGING APPLICATIONS

Hammer and press forging were among the first industrial applications of Thyrotherm 2999 EFS SUPRA. Typically components for the automotive industry of low alloyed steel are forged, but the tests also included applications with austenitic stainless steels and through-hardening bearing steels. In all cases the dies are exposed to very high forging temperatures which promote thermal fatigue of the tool steels. High demands for accuracy of the forged parts strictly limit the tolerable wear of the forging dies. Typical hot-work tool steels for these applications are the grades 1.2343, 1.2344, or 1.2367 with a hardness between 45 HRC and 48 HRC. In order to limit the adhesion of the forged material and to reduce the wear of the tools the cavities of the dies are often nitrided. A survey of the chemical compositions of these hot-work tool steels is given in Table 1, of the forged steels in Table 2.

Table 2. Chemical compositions of the forged steels

Steel Designation		Chemical composition in Mass- %			
Name	German Mat.-no	C	Si	Mn	Cr
C15	1.0401	0.15	$\leqslant 0.40$	0.45	—
C35	1.0501	0.35	$\leqslant 0.40$	0.65	< 0.40
C45	1.0503	0.45	$\leqslant 0.40$	0.65	< 0.40
16MnCr5	1.7131	0.16	$\leqslant 0.40$	1.15	0.95
100Cr6	1.3505	1.00	0.25	0.35	1.50
St 52	1.0421	$\leqslant 0.22$	$\leqslant 0.55$	0.85	—

CASE 1

The first case study was an application on a forging die used on Maxi press. The customer produces components for drive shaft of automobiles. The forged steel was the plain carbon steel C45 (1.0503) requiring a forging temperature in the range of 1200 ℃.

The forging die (Fig. 8) was originally made of hot-work tool steel 1.2343, hardened and tempered to 46–47 HRC without any further surface treatment. Usually the wear of these dies grew to an intolerable extend after 6.000–7.000 forgings so that the dies had to be exchanged and to be revised. In case that a repair of the die could guarantee the required accuracy of the forged parts the tools were used again.

Here Thyrotherm 2999 EFS SUPRA was used in the hardened and tempered condition (46–47 HRC) without any further surface treatment. In several trials each of the tools made of Thyrotherm 2999 EFS SUPRA pro-

Figure 8. Studied forging die.

duced more than 10.000 forgings which means that the productivity of the tools had been improved by more than 60%.

As in almost each series of tests complications occurred also during this case study. One tool failed rather early due to total fracture. The analysis of the defect tool easily and clearly proved the reason of this unexpected failure: the tool failed due to insufficient pre-heating prior to operation.

CASE 2

In this case a customer produces components of the drive shaft for an automobile. The carbon steel C35 was forged at a temperature of 1250 ℃ on a 10 MN-excenter press.

The edges of the cavity are the most critical areas of the die (Fig. 9) as they are exposed to extreme mechanical and thermal impacts. Originally the dies were made of the hot-work tool steel 1.2367, hardened and tempered to 48–52 HRC and finally nitrided. These tools produced an average of 2.500 parts before wear grew to an intolerable extend. Here Thyrotherm 2999 EFS SUPRA was also used in the hardened and tempered condition (48–52 HRC) and subsequently nitrided. With an average production of 3500 parts per die the tools made of Thyrotherm 2999 EFS SUPRA improved the productivity by approximately 50%. Another positive effect was that due to Thyrotherm

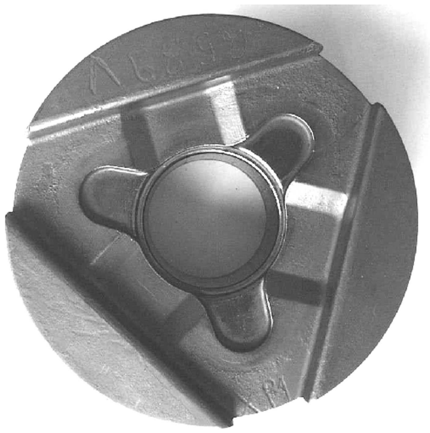

Figure 9. Studied forging die (courtesy of Galladé Umformtechnik, Witten, Germany).

2999 EFS SUPRA the customer could save at least one forging die and the required installation time per production lot.

CASE 3

In this case the customer produces large series of parts of the carbon steel C45. The most critical part of the investigated tool is the concentric ring on the face of the die which is exposed to extreme thermal and mechanical impacts (Fig. 10).

First own experiments of the customer aiming at an improved performance of the dies started with tools made of hot-work tool steel 1.2343. The critical areas were additionally cladded with UTP G3 which increased the average number to 9.000 parts per tool. Further improvements were achieved with dies of the hot-work tool steel 1.2343 cladded with stellite 21 and finally nitrided. The production nearly doubled to approximately 17.000 parts / tool.

As Thyrotherm 2999 EFS SUPRA itself possesses a very high wear resistance this steel was tested in the hardened and tempered condition without any further surface treatment. The average production of these tools was about 13.000 parts per tool.

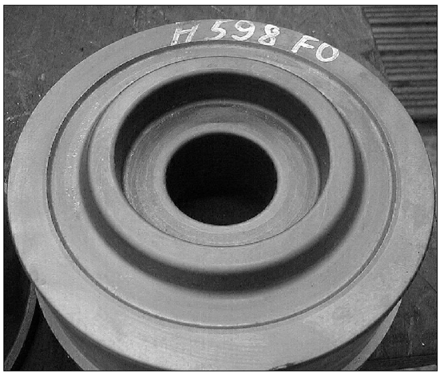

Figure 10. Studied forging die (courtesy of Johann Hay GmbH & Co. KG, Bad Sobernheim, Germany).

On the first view these results could be regarded as negative results. But an evaluation of the whole process easily explains the advantage of Thyrotherm 2999 EFS SUPRA. Tools made of Thyrotherm 2999 EFS SUPRA forged nearly the same number of parts as those tools did which received a rather complicated and expensive treatment.

CASE 4

Gear levers of steel grade St 52 were forged at a temperature of $1150\,^{\circ}C$ using dies of hot-work tool steel 1.2367 (ESR quality). The nitrided dies with a hardness of 48–50 HRC produced an average number of 12.000–13.000 parts. Dies made of Thyrotherm 2999 EFS SUPRA produced 14.000–16.000 parts, in one case even 18.000 parts.

CASE 5

The die shown in Fig. 11 was used to forge fasteners of a titanium alloy. The specific problems of this application arose from the poor hot forming properties of this titanium alloy in combination with the narrow and deep cavity of the die. In order to fill the complete cavity the titanium had to be pressed extremely slowly which on the other hand caused long contact times between forging and die and thus a high thermal impact (forging temperature: $930\,^{\circ}C$).

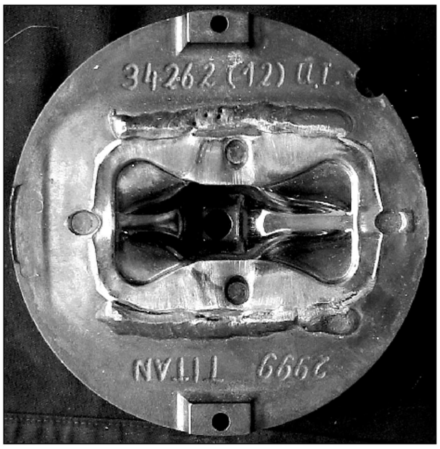

Figure 11. Studied forging die.

The original tools of hot-work tool steel 1.2343 were hardened and tempered to 48 HRC and finally nitrided what enabled them to produce an average of 1.000 parts per tool. The equivalent tools of Thyrotherm 2999 EFS SUPRA hardened and tempered to 46–47 HRC and finally nitrided produced 3.700 parts in average.

CASE STUDIES HIGH-SPEED FORGING

A high-speed forging machine consists of several forging stations which produce in a highly automated process large lots of 100.000–1.000.000 parts. The process is characterized by a forging frequency of 100–200 parts / min and an intensive water cooling of the tools in order to sustain the extreme impacts.

As any interruption of the forging process reduces the productivity of the process it is usual practice that whenever a tool change is required the complete set of tools is exchanged. This clearly points out the importance of a long tool life.

Until recently the most common hot-work tool steel for high-speed forging was the grade 1.2365 which combines a good hot strength and a sufficient thermal conductivity to allow water cooling. The tools are either used in the hardened and tempered condition or in the additionally nitrided condition depending on the customer's philosophy.

Due to its high high-temperature strength and thermal conductivity the use of Thyrotherm 2999 EFS SUPRA offers a great potential for an optimized tool performance in high-speed forging applications.

The case studies to be described in this report are listed in Table 3. Different tool components of various dimensions were tested forging mainly automotive parts at forging temperatures in the range between 1100 and 1250 ℃. The tools of Thyrotherm 2999 EFS SUPRA were hardened and tempered to 47–54 HRC and finally nitrided. They were compared to tools of hot-work tool steel 1.2365 with an equivalent hardness and nitrided surface. The comparison of the production figures given in this table clearly reveals that tools made of Thyrotherm 2999 EFS SUPRA at least led to an improvement by 35% and also demonstrates that improvements of more than 150% could be achieved.

CONCLUSIONS

Forging — die forging as well as high-speed forging — is a widely used technology to shape solid metallic components. To a high extend the forging industry produces components for the automotive industry which requires highest accuracy at lowest costs. Among the different efforts to optimize forging processes those which concentrate on an extended tool life are highly important.

These case studies clearly demonstrate that the hot-work tool steel used in forging applications has a great influence on the die life. Important properties are the hardening and tempering response, strength and ductility at forging temperatures, thermal fatigue resistance, as well as thermal conductivity. Thyrotherm 2999 EFS SUPRA exceeds commonly used hot-work tool steels in these properties by far.

Industrial application tests with customers proved the outstanding behavior of Thyrotherm 2999 EFS SUPRA as a tool material in press forging and high-speed forging applications. The case studies also demonstrated that the success of trials can have various influences. The thermal balance of a forging tool can be rather complicated and should always be respected, especially if — as described here — a tool steel with an improved thermal conductivity is tested. A proper pre-heating of the tools tremendously extends the tool life as it reduces the tensions within the forging tools and thus

Table 3. Parameters and results of forging tests on high-speed forging machines

Case	Machine	Tool Dimension in mm	Produced Component	Forged Material	Forging Temperature in ℃
1	AMP 40	Die 132 dia.	automotive component	100Cr6 (1.3505)	1150
2	AMP 70	Die 202 dia.	bearing component	100Cr6 (1.3505)	1125
3	AMP 20	Punch 31 dia.	automotive component	16MnCr5 (1.7131)	1200
4	AMP 20	Piercer 33 dia.	automotive component	C22 (1.0402)	1100
5	AMP 50 HFE	Extrusion die 100 dia.	stub shaft	Ck45 (1.1191)	1250

Case	Previous Tool System		
	Hot-work Tool Steel / Condition	Hardness in HRC	No of Forged Parts
1	1.2365 nitrided	47	13,000
2	1.2365 ESR nitrided	53	17,000
3	1.2365 nitrided	52	20,000
4	1.2365 nitrided	50 - 52	4,000
5	1.2365 case-hardened + nitrocar-burized	54 - 57	7.600 Failure: spallings

Case	Thyrotherm 2999 EFS SUPRA			Improvement of Performance	
	Condition	Hardness in HRC	No of Forged Parts	No of Forged Parts	%
1	nitrided	47	17,500	4,500	35
2	nitrided	53	23000	6,000	35
3	hardened+ tempered	52	33,000	13,000	65
4	nitrided	54	10000	6,000	150
5	plasma nitrided	53	11000	3,400	45

directly contributes to avoid brittle fracture. It should be regarded that an increase in hardness is not the only way to improve the wear resistance of a forging tool. The wear resistance depends on various factors. Often the selection of a hot-work tool steel such as Thyrotherm 2999 EFS SUPRA which has a higher "natural" wear resistance than other hot-work tool steels promises better results even at a reduced hardness. Here the relation between hardness and ductility has to be kept in mind. Another important factor influencing the die life is the degree of automation in the forging shop. The highly automated high-speed forging applications clearly demonstrated that the scattering of the achieved results was remarkably lower than in press forging applications.

The different case studies described in this report point out that Thyrotherm 2999 EFS SUPRA can be the key to an improved die life if wear of the tools limits the performance of forging tools.

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