

ADVANCED TOOL STEELS PRODUCED VIA SPRAY FORMING

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Abstract

During the past decades spray forming has been developed to a technology, which today is suitable to produce high alloyed tool steels on an industrial scale. In 1999 Dan Spray A/S, a subsidiary of Det Danske Stålvalseværk, has opened the first industrial billet spray forming plant for specialty steels in Taastrup (Denmark). Since 1996 Edelstahl Witten-Krefeld GmbH has cooperated with Dan Spray A/S in order to evaluate the state of art of spray forming and to develop new spray formed tool steels.

The report first compares spray forming to commercial metallurgical processes used to produce high grade tool steels. A study on the spray formed cold-work tool steel 1.2379 (AISI D2) describes the state of art of spray forming with respect to the production of high grade tool steels. The spray formed material proved to be extremely homogeneous and revealed a very uniform and fine microstructure. It exceeded conventionally produced cold-work tool steel in many properties. Industrial applications demonstrated that tools made of the spray formed steel had a definitely higher performance than those made of conventional D2 steel.

Based on these results Edelstahl Witten-Krefeld developed the new high alloyed cold-work tool steel Thyrospray 2399, of which the properties are described here. The paper also describes the results of first industrial experience with tools of Thyrospray 2399. Currently Edelstahl Witten-Krefeld GmbH concentrates its activities on the development of a new spray formed high-speed steel and a wear and corrosion resistant tool steel.

Keywords: Spray forming, production methods, solidification, cold-work tool steel, homogeneity, carbide structure, mechanical properties, application tests

INTRODUCTION

The spray forming technology of metallic materials has been developed in the late sixties, early seventies at the University of Swansea, Great Britain. The process was then further developed to industrial scale by Osprey Metals Ltd., founded in 1974 by a group of former students of this university, and licenses have been given worldwide [1].

It is the purpose of the spray forming technology to atomize a metallic melt and to compact the generated droplets to near-net-shape semi- and finished products. The high cooling rates in combination with an extremely fast solidification of the atomized molten particles lead to the formation of a fine-grained microstructure with a homogeneous distribution of the alloying elements. Compared to conventionally cast materials the improved mechanical, technological and processing properties of spray formed materials open chances to many new alloying and application concepts.

Today, after more than 30 years of intensive and worldwide development of the "Osprey-Process", the spray forming technology is mainly used for the production of semi-finished products to be further hot formed by forging, rolling or extrusion as a slight porosity in the spray formed material cannot be completely avoided, yet. For more than 10 years spray forming has been state of the art in the production of certain aluminum- and copper alloys. Spray forming of steel has been studied and further developed in many laboratory and pre-industrial pilot-plants [2, 3, 4, 5, 6, 7, 8, 9, 10]

The opening of the first industrial billet spray forming plant for specialty steels at Dan Spray A/S in Taastrup (Denmark) in 1999 has given the chance to an extensive use of spray formed specialty steels. Since 1996 Edelstahl Witten-Krefeld GmbH has cooperated with Dan Spray A/S in order to evalu-

ate the state of art for spray forming and to develop spray formed tool steels. This report summarizes the state of these activities and developments.

DESCRIPTION OF THE SPRAY FORMING PROCESS FOR THE PRODUCTION OF BILLETS AT DAN SPRAY

Dan Spray's spray forming plant consists of following main components:

- Induction furnace (melt capacity max. 4 t)
- Casting furnace (max. capacity 7 t)
- Spray chamber (max. billet $\varnothing 500$ mm, max. weight 4 t)
- Heat treatment furnace (electric)

A survey of the plant is given in Fig. 1.

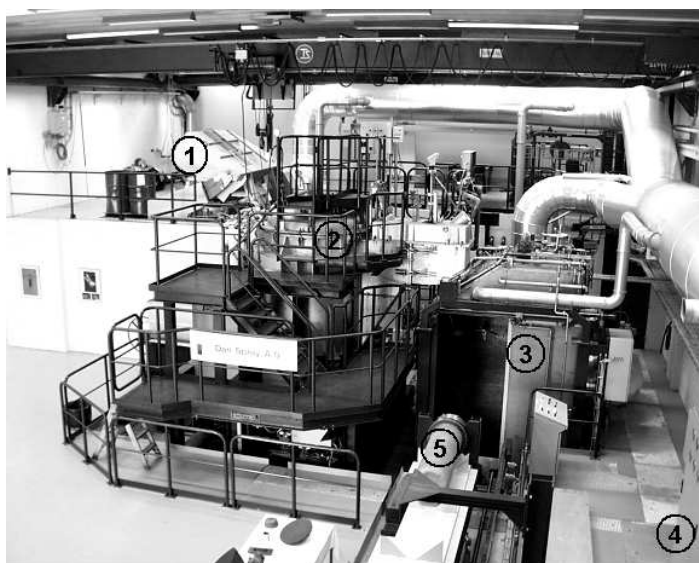


Figure 1. Spray forming plant at Dan Spray A/S in Taastrup, Denmark 1) Induction furnace, 2) Casting furnace, 3) Spray chamber, 4) Heat treatment furnace, 5) Spray formed billet.

Melting occurs in the induction furnace under an inert gas atmosphere (nitrogen) using classified scrap, pre-alloys and further additions. After

melting the melt is poured into the casting furnace. Via the casting furnace's bottom-tapping the melt is transferred into the atomizing unit with oscillating atomizing nozzles ("Twin Atomizer"). Here the gas stream atomizes the melt into droplets of approx. $\varnothing 50 - 500 \mu\text{m}$. Usually nitrogen is used as the atomizing gas in the spray chamber. The stream of droplets is accelerated from the two oscillating nozzles to a rotating target. The adjustable oscillation of the nozzles and the rotation of the target allow a uniform compaction of the atomized particles and thus homogeneous growth of a round billet. A properly adjusted downward movement of the growing billet allows for a permanently constant distance between the atomizing unit and the billet during spray forming.

The orientation of the billet production at the Dan Spray Plant is with the long axis vertical, the billet growing upwards as it is spray formed. The billet dimension is a maximum of 500 mm in diameter and 2,5 meter in length, with a weight of approximately 4 tons.

Depending on its chemical composition it can subsequently be heat treated or cooled under controlled conditions, adjusted as well as inspected (ultrasonic test). Edelstahl Witten-Krefeld as a partner of Dan Spray is then responsible for the forging of the billets presently using the world's largest forging machine [11] as well as its heat treatment, adjusting, machining, and inspection facilities.

THE SOLIDIFICATION PROCESS DURING SPRAY FORMING

The complex process during spray forming has been studied and described by Apelian [12], Conelly [13], Bauckhage [14, 15] and others. Numerous parameters such as the steel's chemical composition, properties of the melt, melt temperature, atomizing gas, number, design, and alignment of the nozzles as well as the sizes of the droplets, the distance between nozzles and target, and geometry and movement of the target influence the process. An optimum and reproducible process needs a well-defined set of parameters.

The presently most discussed model of deposition and solidification of the atomized melt droplets is described in Fig. 2. The globular droplets with diameters varying between 50 and 500 μm solidify at different rates. As small particles might solidify completely during the flight medium sized particles might be partly solidified and larger still completely liquid.

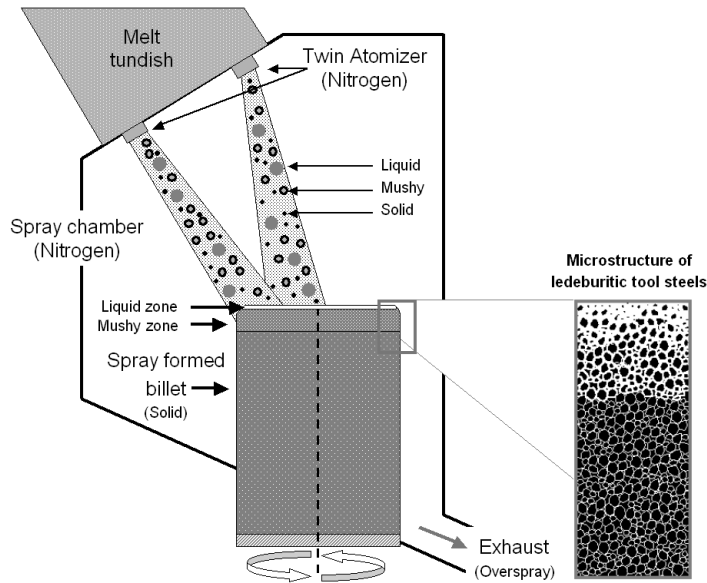


Figure 2. Solidification process during spray forming.

The particles hitting the surface of the target have a high velocity and a high energy. Ideally they build a layer, which consists of both liquid and solidified metal and has a thickness of only a few mm on the target ("mushy zone"). This layer is expected to exist during the entire spray forming process. Due to their high kinetic energy smaller dendritically or semi solidified particles get smashed during their impact on the target and melt up again. Those dendritic fragments, which do not melt up, again are nuclei for the now starting rapid solidification which is promoted by the comparably cold atomizing gas, thermal flow into the spray chamber as well as into the solidified billet. Besides, the impact of the droplets causes turbulences in the mushy zone leading to a homogeneous thermal balance and a homogeneous chemical composition. Therefore the rapid solidification does not start dendritically but mainly globulitically. The remaining melt enriched with segregating alloying elements forms a liquid network and solidifies at a lower rate than the globulitic particles.

Figure 3 shows the typical solidified structure of the ledeburitic cold-work tool steel X155CrVMo12-1 (Mat.-No. 1.2379, AISI D2). It reveals a fine and homogeneous globulitic structure with an extremely fine ledeburitic carbide network with a mesh size of approx. 5 – 40 μm .

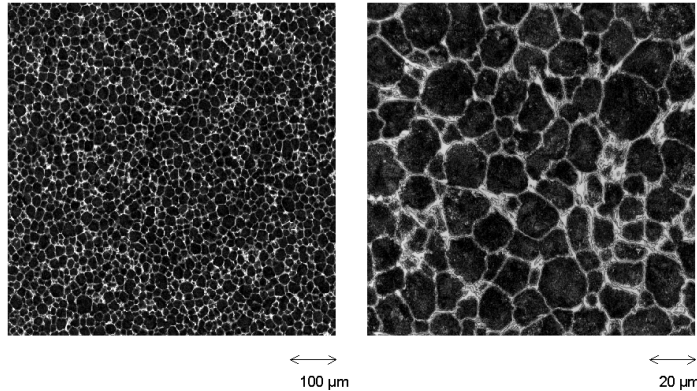


Figure 3. Microstructure of a ledeburitic cold-work tool steel in the as sprayed condition.

COMPARISON OF TECHNOLOGIES FOR THE PRODUCTION OF HIGH-GRADE TOOL STEELS

The traditional and most frequently used method to produce tool steels is conventional ingot casting or alternatively continuous casting of the melt followed by forging or rolling processes. Tool steels produced in that way cover a wide range of applications. If higher demands on properties such as ductility, homogeneity or cleanliness have to be fulfilled usually remelted tool steels are applied. The used metallurgical technologies are the electro-slag-remelting (ESR) or the vacuum-arc-remelting (VAR) process. In all these technologies the range of producible steel compositions is limited. Segregations, which are unavoidable during the solidification, limit the steel's hot formability and thus the industrial applicability of such steel. The development of powder metallurgy (PM) allowed to intensively widen up the limits of steel compositions. Due to the rapid solidification of the powder particles the development of segregations is suppressed to a high extend. Therefore the development of PM tool steels concentrated on high alloyed steel compositions with very high carbide contents.

Spray forming has now been developed to a new and important technology for the production of tool steels. Similar to the PM technology spray forming is based on the atomization of a melt, which allows using the benefits of a rapid solidification. The main difference to PM is that spray forming directly produces a solid billet whereas in PM the powders have to pass a complex and expensive process of classification, mixing, and compaction in order to achieve a solid block of steel. As a new technique spray forming is able to provide materials with well-balanced compositions allowing to meet customers demands with a spectrum of properties between conventional and PM tool steels.

A general comparison of the three metallurgical technologies described here is given in Fig. 4. One of the most evident differences between these technologies is the number of process steps required to produce a forged or rolled bar of tool steel. Most critical in the PM-process are the various steps of powder handling, in which the highly reactive metal powders are endangered to oxidation or contamination. As spray forming is performed in a closed system under protection by an inert gas this risk does not exist here. These three production routes result in different macro- and microstructures. With respect to the solidifying volumes ESR materials usually still have a higher level of segregations than spray formed or PM material. Highest homogeneity can be expected from PM and spray formed steels. Examples of typical microstructures of steels produced via these three methods are given in Fig. 5. The differences in carbide size and distribution are most evident and most likely to influence the mechanical properties of the steels.

The wear resistance of a tool steel is closely related to the amount, size, and distribution of the carbides embedded in the steel's matrix. An increasing amount of carbides improves the wear resistance of a steel, an increasing size of the carbides reduces it. The influence of the carbide size also explains the different behavior of conventional and PM tool steels. The very fine distribution of fine carbides lowers the wear resistance of the PM tool steels. [16].

As shown in Fig. 6 a very uniform distribution of fine carbides offers almost no resistance against abrasive wear. Larger carbides in a network structure do not improve the wear resistance as the network does not protect the matrix against wear. Best wear resistance can be achieved if the carbides have reached a certain size and are evenly distributed in the steel.

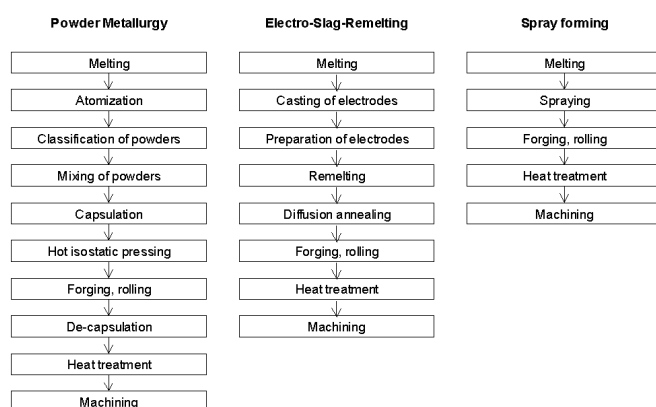


Figure 4. Comparison of production routes for high-grade tool steels.

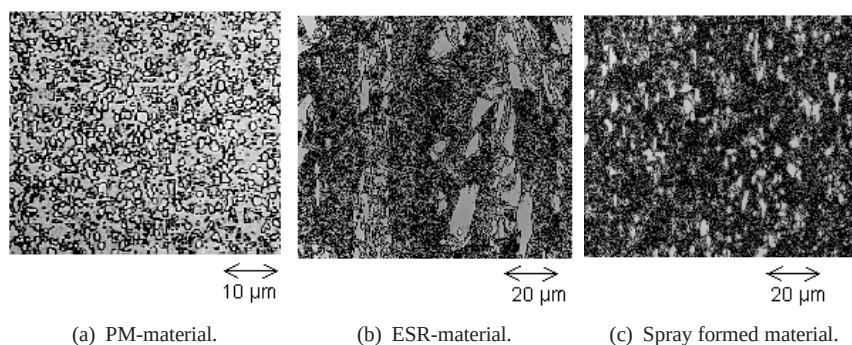


Figure 5. Microstructures in forged bars of cold-work tool steel 1.2379 ($\varnothing 150$ mm).

PROPERTIES OF SPRAY FORMED COLD-WORK TOOL STEEL

Edelstahl Witten-Krefeld evaluated the potential of spray forming as a new production technique for tool steels on the high-alloyed ledeburitic tool steel X153CrMoV12 (Mat.-no. 1.2379; AISI D2). The composition of this steel is listed in Table 1.

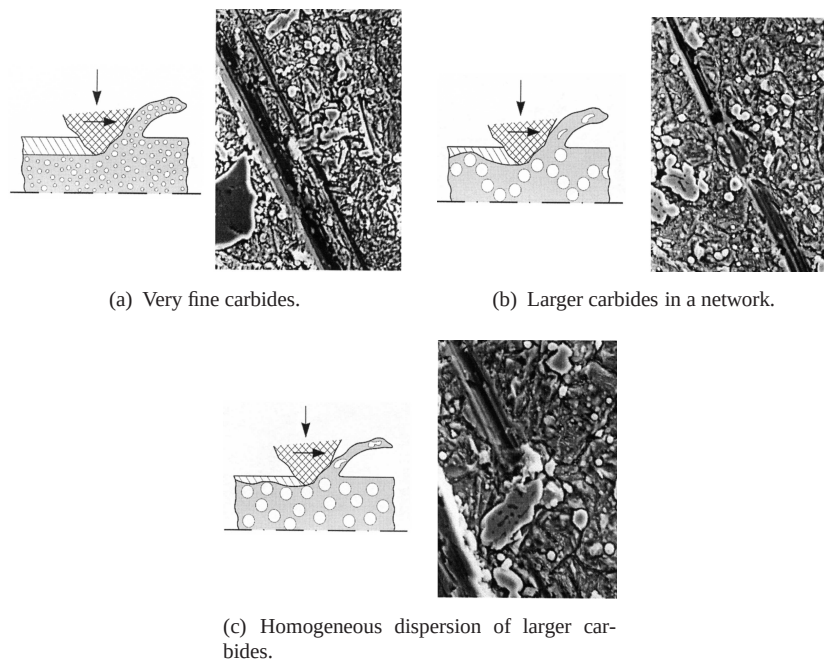


Figure 6. Influence of carbide size and distribution on wear resistance of tool steels (acc. to Berns).

Spray formed billets of this steel having the dimensions of $\varnothing 500$ mm $\times$ 2.500 mm were forged at Edelstahl Witten-Krefeld to bars of $\varnothing 250$ mm, $\varnothing 182$ mm, 160 mm sq., and $\varnothing 105$ mm.

Table 1. Chemical composition of a studied spray formed billet of cold-work tool steel 1.2379 and limits of chemical composition according to DIN EN ISO 4957

Heat number	Alloy content [wt%]									
	C	Si	Mn	P	S	Cr	Mo	Ni	V	N
013258	1,49	0,20	0,25	0,023	0,014	11,62	0,71	0,14	0,98	0,070
DIN EN ISO	1,45 –	0,10 –	0,20 –			11,0 –	0,70 –		0,70 –	
4957	1,60	0,60	0,60			0,030	0,030		1,00	

Macroetched slices taken from the bottom and the top of the billets reveal a very dense and homogeneous constitution. Indications of porosity or segregations did not show up, Fig. 7. Concentration profiles measured on the cross-sections of the forged bars underline the steel's high homogeneity. An example, which describes the distribution of the elements C, Cr, Mo, and V over the cross-section of $\varnothing 182$ mm is given in Fig. 8.

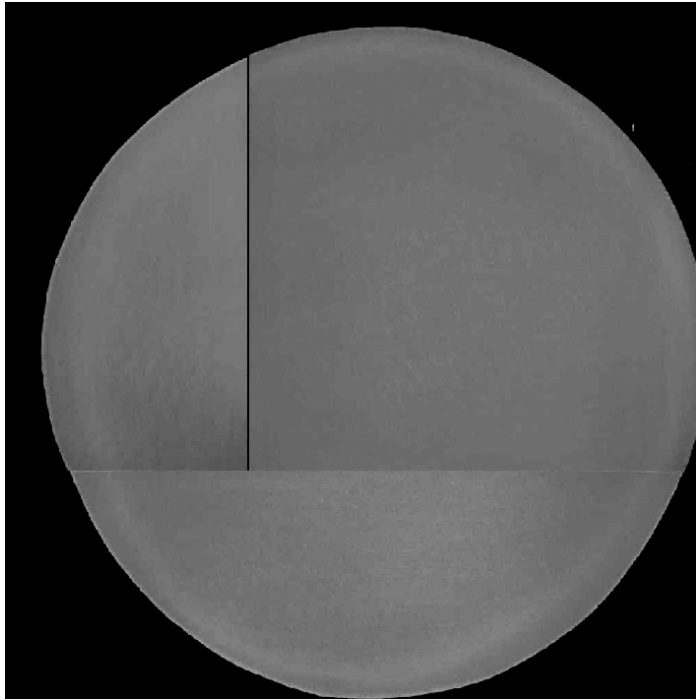


Figure 7. Macrostructure of a spray formed billet of cold-work tool steel 1.2379 ($\varnothing 500$ mm; as-sprayed).

In the as-sprayed condition the microstructure consists of fine primary grains, which are surrounded by a fine network of ledeburitic carbides. The size of the primary grains is relatively constant over the cross-section as well as over the length of the billet. The forging operation breaks up the fine carbide network and aligns the remaining fine ledeburitic carbides in longitudinal direction. In the investigated bars these carbides are evenly distributed, Fig. 9.

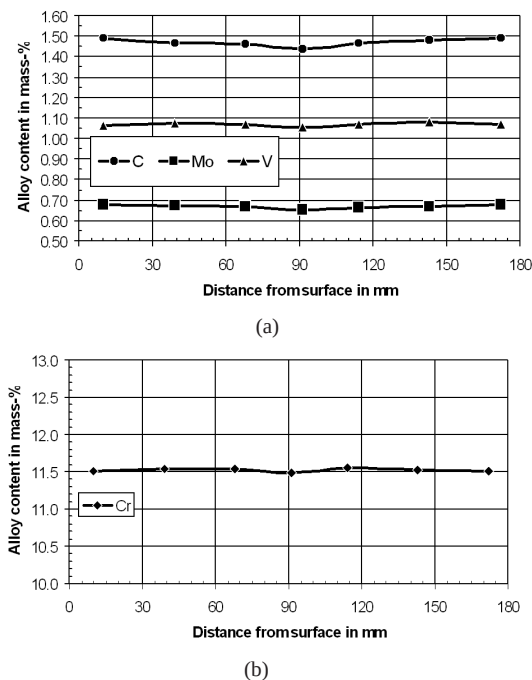


Figure 8. Concentration profiles over the cross-section of a forged bar of steel 1.2379 (forged to $\varnothing 182$ mm).

In the forged bar ($\varnothing 105$ mm) the average carbides size was $8 - 14 \mu\text{m}$ near the surface and $25 - 30 \mu\text{m}$ in the center indicating the rather homogeneous carbide sizes of the spray formed steel. The spray formed steel had a very good cleanliness ($K1 = 0,33$ for sulfides and $K1 = 1,33$ for oxides, according to DIN 50 602). This is also expressed in the low oxygen contents of approximately 30 ppm.

The fine and homogeneous microstructure of a spray formed cold-work tool steel is of advantage for many properties. Figure 10 clearly points out that the spray formed cold-work tool steel reveals a better ductility even if it was less deformed. This improvement is related to both the elastic as well as plastic deformation of the steel.

The steel proved its outstanding performance in an industrial application: a comparison of the spray formed steel 1.2379 with conventionally produced

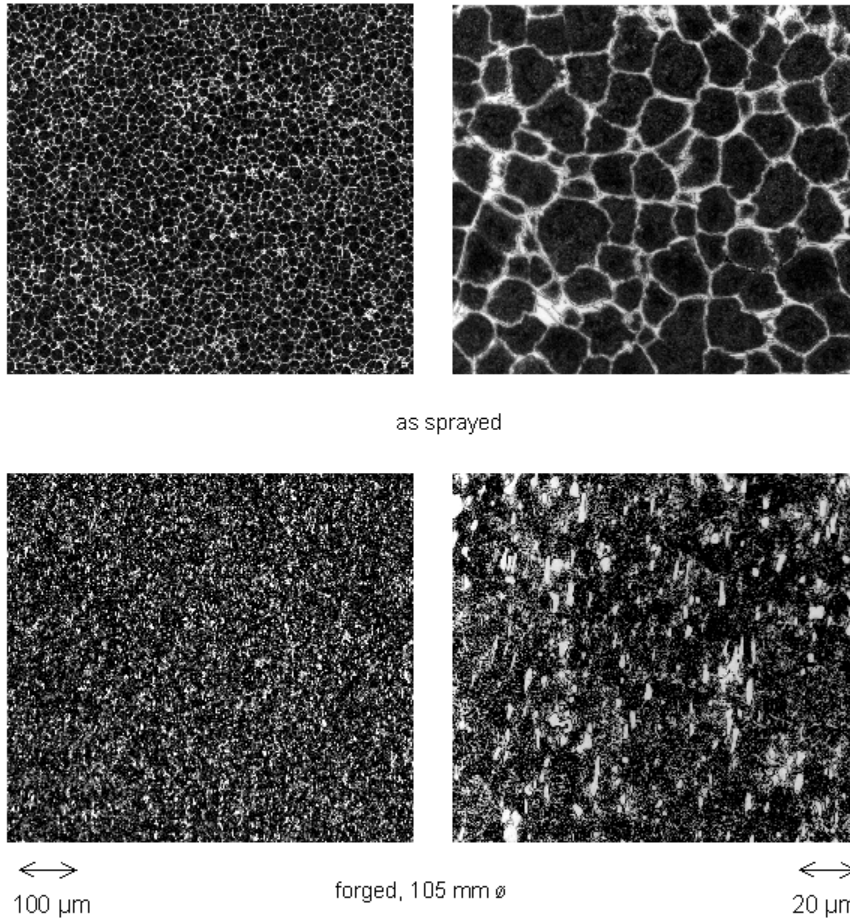


Figure 9. Microstructure of a spray formed billet of cold-work tool steel 1.2379 top: as-sprayed condition, bottom: forged to $\varnothing 105$ mm

steel in the fine blanking process of chain components. Plain carbon steel sheet metal of 4,5 mm thickness and a hardness of 230 – 269 HB was stamped. Tools, made of conventional 1.2379 and hardened and tempered to 58 – 60 HRC, usually produce approximately 100.000 parts before they have to be reground. The tools of the spray formed steel produced 150.000

parts before they had to be reground. This already leads to an improvement of the performance by 50 %. Tools of conventional 1.2379 usually need a regrinding by 7 mm. In this case the first repair of the tool required only 1 mm of regrinding. Due to the application of the spray formed cold-work tool steel the customer could improve the tool life by the factor 7.

NEW DEVELOPMENTS

The positive results gained on the spray formed cold-work tool steel 1.2379 were motivation to further investigations on spray formed tool steels. Edelstahl Witten-Krefeld GmbH never intended to use the spray forming technology for the production of commercially available tool steels. On the contrary, the use of the spray forming technology promises various chances to break up the limits of traditional tool steel compositions and to develop new tool steels having properties well adjusted to customers requirements. Based on studies of the international tool steel market Edelstahl Witten-Krefeld GmbH decided to begin its activities with spray formed cold-work tool steels as these offer various facilities to establish new steel grades, which can fill the technological gap between conventionally produced and PM tool steels. Here spray forming can be used to maximum benefit as it combines technological and economic advantages. It allows to produce tool steels similar to PM tool steels requiring considerably less process steps.

The following paragraphs give a first description of the new cold-work tool steel developed by Edelstahl Witten-Krefeld. As the developments are presently being continued further details will be presented during the conference.

THE NEW COLD-WORK TOOL STEEL "THYROSPRAY 2399"

The invention of a new spray formed cold-work tool steel aimed on a well balanced combination of a high hardness and wear resistance, and a toughness superior to conventionally produced cold-work tool steels.

The postulation of a secondary hardening characteristic and a secondary hardness maximum of around 65 HRC lead to the chemical composition shown in Table 2. Vanadium, molybdenum, and especially niobium were added in order to give the steel the desired high wear resistance due to the

presence of fine dispersed MC-carbides. With reference to the spray forming technology the new cold-work tool steel was named Thyrospray 2399.

Table 2. Average chemical composition of the spray formed cold-work tool steel Thyrospray 2399

Alloy content [wt%]							
C	Si	Mn	Cr	Mo	V	Nb	N
1,55	1,00	0,65	9,00	2,00	1,95	1,00	0,10

The steel is composed of a high content of carbon as well as carbide and nitride forming elements. Thus nitrogen – used as a process gas during spray forming – can easily be solved in the steel giving the steel a high content of carbides and carbonitrides simultaneously. The predominant carbide phases are of the MC ($M = V, Nb, W$) and the M_7C_3 -type ($M = Cr, Mo$) whereas the carbonitrides precipitate mainly as $M(C, N)$ ($M = V, Nb, W$) and $M_7(C, N)_3$ ($M = Cr, Mo$).

A macroetched slice (Fig. 11) as well as a concentration profile for carbon measured on a forged bar of $\varnothing 230$ mm demonstrate the high homogeneity of the material. The fine carbides are homogeneously dispersed over the cross-section and do not show any preferred orientation as usually known from commercially produced and forged ledeburitic cold-work tool steels, Fig. 12.

Due to the spray forming process carbides as well as carbonitrides are optimized with respect to their size and homogeneously dispersed in the microstructure. Despite the very high alloy content but due to its high homogeneity the steel is still forgeable.

Hardened from 1080°C the steel gains a hardness of 64 HRC. The tempering behavior of the steel reveals a secondary hardness maximum 65 HRC after hardening from 1140°C and triple tempering at 540°C , Fig. 13.

The high hardness and the homogeneous distribution of carbides and carbonitrides results in a high wear resistance. The results of wear tests in comparison of three other steel grades is shown in Fig.14, the chemical compositions of the three other steels listed in Table 3. The wear tests were carried out on an Amsler-machine with rolls of the tested steels having a hardness of 62 HRC. These rolls rotated against rolls of high-speed steel HS

10-4-3-10 (Mat.-no. 1.3207) with a hardness of 67 HRC under the influence of a normal force.

Table 3. Chemical composition of other tool steels compared in Amsler wear tests

Steel grade	Alloy composition [wt%]							
	C	Si	Mn	Cr	Mo	V	Nb	N
A	1,02	0,98	0,40	8,13	2,02	0,45	0,155	-
B	1,54	0,35	0,33	11,3	0,75	0,17	-	-
C	0,97	0,32	0,48	5,25	0,93	0,32	-	-

First industrial experience with tools of Thyrospray 2399 was gained on thread rolling-tools producing screws of the stainless steel X5CrNiMo19-11 (1.4401). Tools made of Thyrospray 2399 produced 140.000 screws whereas tools of conventional cold-work 1.2379 failed after 70.000 screws. All tools made of Thyrospray 2399 proved an excellent stability of their geometry, which proves that size, shape, and distribution of the carbides are well adjusted to the demands.

Tools made of Thyrospray 2399 were also tested in blanking components for chains of a micro-alloyed steel (sheet metal, $s = 4$ mm). Tools made of Thyrospray 2399 did not only increase the number of blanked parts by 45 % but did also reveal a significantly higher stability of the cutting edges.

FURTHER ACTIVITIES

Current research activities on spray formed tool steels at Edelstahl Witten-Krefeld concentrate on the development of a new high-speed steel as well as on a corrosion- and wear resistant tool steel.

CONCLUSION

The report demonstrates that spray forming has been developed to a new and interesting technology for the production of high grade and high alloyed tool steels. The chances to establish spray forming as a commercially available production technology in addition to conventional metallurgy and powder metallurgy are high. The investigation on the ledeburitic cold-work tool steel 1.2379 proved that the specific characteristics of the spray forming

process lead to remarkable properties of the spray formed tool steels. In first application tests tools made of the spray formed cold-work tool steel 1.2379 achieved a definitely higher performance than those made of the conventional steel.

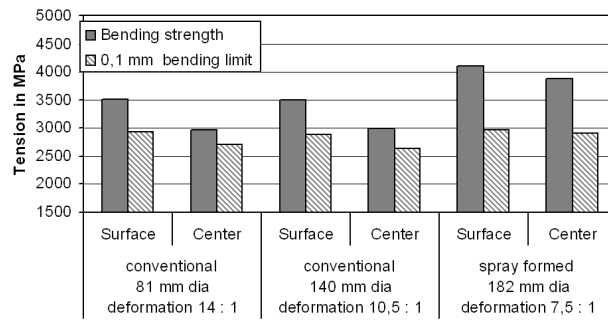
Encouraged by these positive results Edelstahl Witten-Krefeld GmbH developed in close cooperation with Dan Spray A/S the new cold-work tool steel Thyrospray 2399. Its properties have been described here. First industrial applications show very positive results in thread-rolling and blanking operations. The investigations will be continued.

Further activities at Edelstahl Witten-Krefeld focus on the development of a new spray formed high-speed steel and a corrosion- and wear resistant tool steel. A description of these steels will be given later.

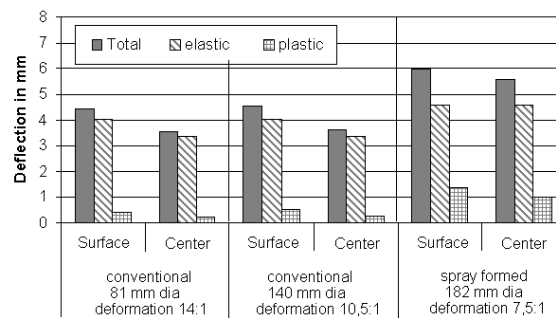
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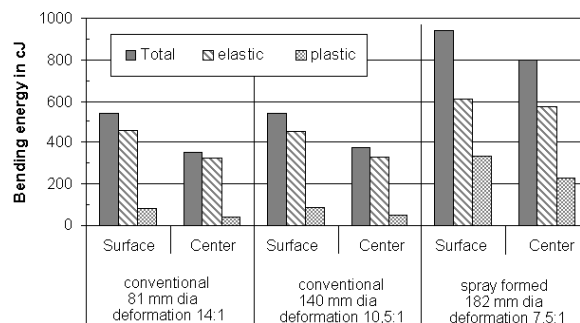
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(a)



(b)



(c)

Figure 10. Ductility of cold-work tool steel 1.2379, measured in static bending tests – spray formed vs. conventional production (hardness: 58 HRC).

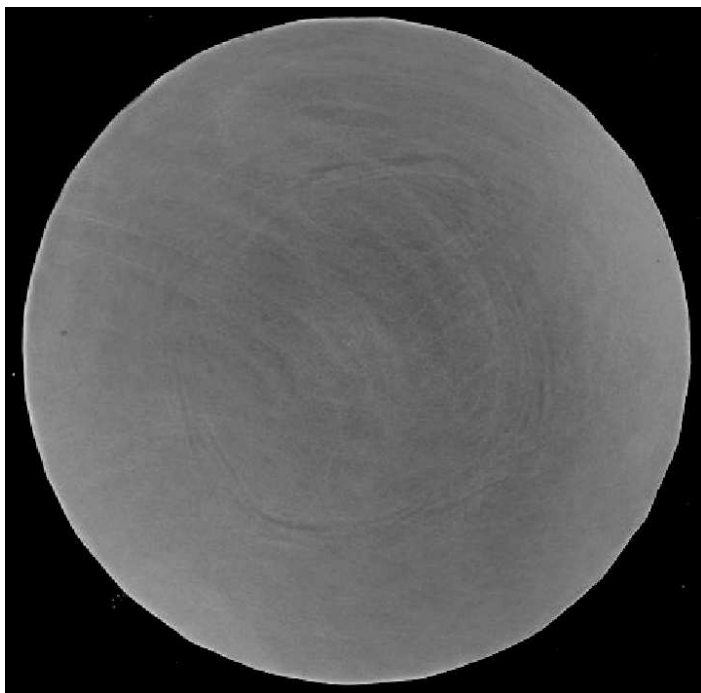


Figure 11. Macroetched slice describing the homogeneity of a forged bar of $\varnothing 230$ mm (Thyrospray 2399).

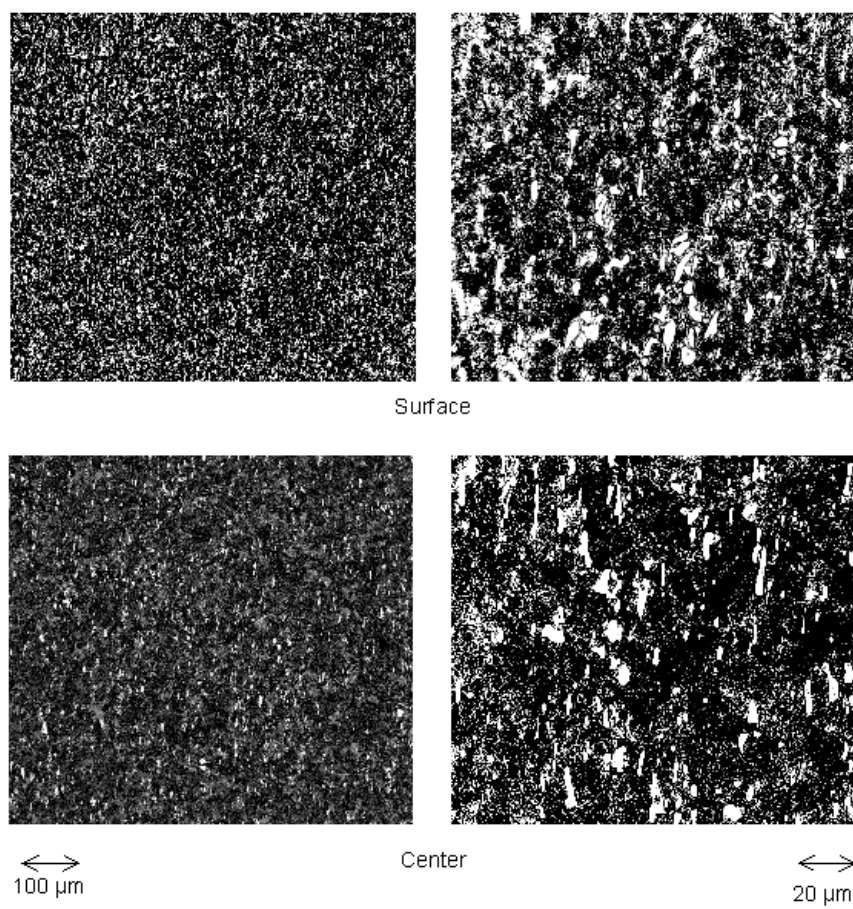


Figure 12. Carbide structure in a forged bar of Thyrospray 2399 ($\varnothing 230$ mm).

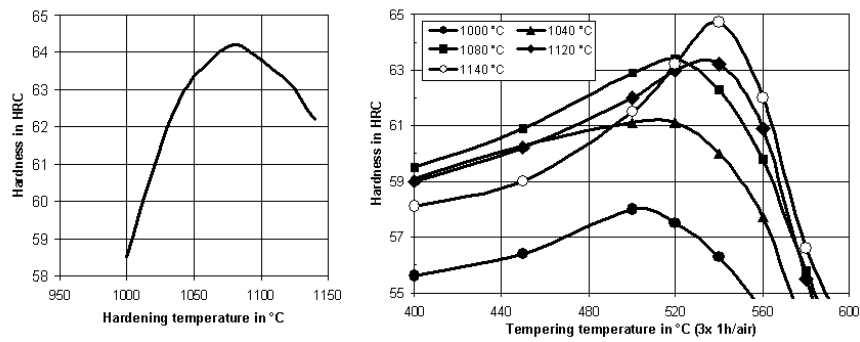


Figure 13. Hardening and tempering behavior of Thyrospray 2399.

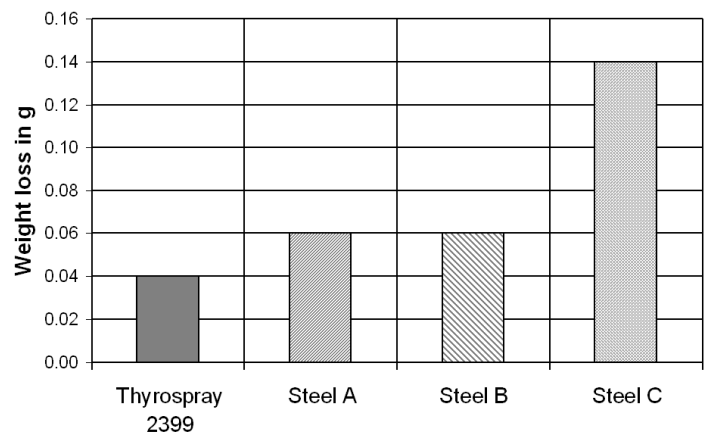


Figure 14. Results of Amsler wear tests.