THE PERFORMANCE OF SPRAY-FORMED TOOL STEELS IN COMPARISON TO CONVENTIONAL ROUTE MATERIAL

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Abstract

The composition, microstructure and homogeneity affect the wear resistance and toughness of highly alloyed tool steels in numerous ways. Heavy hot working of the casting which is necessary to homogenise the material, generally results in a strong dependence of properties on load direction. Powder metallurgy has been shown to overcome these difficulties but requires a sophisticated process to achieve high quality material. Medium-sized spray-formed billets of the steels HS 6-5-2 (M2), X 153 CrMoV 12 (D2) and X 40 CrMoV 5-1 (H13), whose production and primary structure have been described in the paper "spray forming of high-alloyed tool steels at medium size dimensions", were forged to round bars of 60 mm diameter. Stock material of similar size and composition from the conventional and powder metallurgical route was used for direct comparison. Sample production and heat treatment was carried out in such a way as to ensure best possible comparison. Pin-on-disk tests and rubber-wheel tests were applied as well as impact tests. The microstructure and response to heat treatment is presented. As a general test result, spray-formed material produced on a semi industrial scale shows properties that are significantly better than those of conventionally produced material. While PM-material has by far the best results in toughness, abrasive wear behaviour strongly depends on the detailed parameters of the wear tests applied.

INTRODUCTION

As a new technique for processing highly alloyed materials, spray forming has been introduced during recent decades. It has been proven to produce highly alloyed tool steels with interesting properties. In order to evaluate this
new technique it is necessary to directly compare the materials properties with those of material of similar composition produced by the competitive routes, i.e. ingot casting and powder metallurgy.

Previous reports [1, 2, 3, 4] gave indications that spray forming leads to properties close to powder metallurgically produced material for high-speed steels and carbide-rich cold-work tool steels. The main advantages of spray-formed material reported are higher toughness than conventionally produced steels [2, 4] and in some cases higher hardness [2].

INVESTIGATED MATERIAL, SAMPLING AND HEAT TREATMENT

The project focused on the evaluation of standard tool steels for cutting (high-speed steels M2, M3), cold working (D2) and hot working (H13). The manufacturing and basic analysis, especially of the spray-formed material, is described in this compendium under the title “Spray forming of high-alloyed tool steels at medium size dimensions”.

Samples were taken from $\varnothing 60$ mm bar material in the forged/rolled condition. Specimens for the wear tests were manufactured according to the requirements of the test machines. For the toughness measurement, unnotched samples ($7 \times 10 \times 55$ mm) in the longitudinal and transverse directions were used for all grades. Additional V-notched (ISO-V) samples were used for the hot-work tool steel. Heat treatment parameters are given in Table 1. After the investigation of the tempering curves, the final heat treatment parameters were selected as appropriate for typical applications.

Table 1. Heat treatment parameters for the tempering tests

<table>
<thead>
<tr>
<th>AISI</th>
<th>DIN/EN</th>
<th>Austenitising</th>
<th>Hardening</th>
<th>Tempering</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>HS 6-5-2 C</td>
<td>1210°C, 6 min, vacuum</td>
<td>6 bar $N_2$</td>
<td>$3 \times 2$ h</td>
</tr>
<tr>
<td>M3</td>
<td>HS 6-5-3</td>
<td>1210°C, 6 min, vacuum</td>
<td>6 bar $N_2$</td>
<td>$3 \times 2$ h</td>
</tr>
<tr>
<td>D2</td>
<td>X 153 CrMoV 12</td>
<td>1060°C, 10 min, vacuum</td>
<td>6 bar $N_2$</td>
<td>$3 \times 2$ h</td>
</tr>
<tr>
<td>H13</td>
<td>X 40 CrMoV 5-1</td>
<td>I: 1030°C, 10 min, vacuum</td>
<td>6 bar $N_2$</td>
<td>$3 \times 2$ h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II: 1030°C, 30 min, salt-bath</td>
<td>air</td>
<td>$3 \times 2$ h</td>
</tr>
</tbody>
</table>
RESULTS

TEMPERING CURVES

The results from the hardening and tempering tests are shown in Fig. 1. All materials, whether conventionally produced, spray-formed or PM show the typical tempering behaviour of the respective steel grade. For the high-speed steels, the powder metallurgically produced M3 has a higher secondary and hot hardness than the various M2 materials. This is not a result of the PM production route but of the different chemical composition (3 versus 2% vanadium).

Figure 1. Tempering curves of the steels M2 (M3-PM), D2 and H13.

The effect of the higher nitrogen content in one series of the spray-formed materials can just be recognized directly after the hardening. In the M2 and D2 grades the higher nitrogen content leads to a lower hardness, probably related to a higher content of residual austenite. Conversely, the H13 with a higher nitrogen content clearly has a higher hardness directly after hardening. This can be related to a harder martensite containing carbon and nitrogen.
For typical tempering temperatures no effect of the production route on the tempering behaviour was found.

After the examination of the tempering behaviour the following tempering parameters were selected for the heat treatment of samples for toughness and wear tests:

Table 2. Heat treatment parameters applied for the wear and toughness tests

<table>
<thead>
<tr>
<th>AISI</th>
<th>DIN/EN</th>
<th>Tempering</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>HS 6-5-2 C</td>
<td>3 × 2 h at 575°C</td>
<td>approx. 63 HRC</td>
</tr>
<tr>
<td>M3</td>
<td>HS 6-5-3</td>
<td>3 × 2 h at 575°C</td>
<td>approx. 64 HRC</td>
</tr>
<tr>
<td>D2</td>
<td>X 153 CrMoV 12</td>
<td>3 × 2 h at 510°C</td>
<td>61–62 HRC</td>
</tr>
<tr>
<td>H13</td>
<td>X 40 CrMoV 5-1</td>
<td>I: 3 × 2 h at 585°C</td>
<td>47–48 HRC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II: 2 × 2 h at 585°C + 1 × 2 h at 550°C</td>
<td>49–50 HRC</td>
</tr>
</tbody>
</table>

MICROSTRUCTURE

The figures presented here show the carbide distribution of the ledeburitic steel grades M2 (M3) and D2 in dependence of their respective production routes (Figs. 2 and 3). The basic effect of the spray forming process on

Figure 2. Microstructures of M2 (M3-PM) steel produced by different routes.
the carbide structure in comparison to conventionally produced material was found, primarily, not to be the reduction of the carbide size but to be the more even distribution of the carbides throughout the ingot.

While the microstructure in the edge area of the material does not differ significantly between conventionally produced and spray-formed materials, the centre regions of the conventionally produced material are dominated by long carbide stringers and larger areas with a reduced carbide content between these. The spray-formed materials has a similar microstructure in the edge and in the centre with only very short carbide stringers. This effect of the production route is more strongly pronounced for the D2-grade where comparatively large and long carbide stringers can be found.

The powder metallurgically produced material is mainly characterised by an even more fine and homogeneous carbide structure. This difference is, again, more pronounced in the D2-steel.

**IMPACT TOUGHNESS**

Figures 4 and 5 show the impact toughness of the ledeburitic grades M2 (M3) and D2 for the following production routes: conventional; spray-formed; and powder metallurgically produced. For the spray-formed material, the results of the material with usual nitrogen content (M2-SF, D2-SF)
and the material with higher nitrogen (M2-SF (N), D2-SF (N)) content are presented. For both, the high-speed steel and the cold-work tool steel grades

**Figure 4.** Impact toughness of M2 steel (M3-PM) produced by different routes.

There is a significant improvement in impact toughness due to spray forming in comparison to conventionally produced material. The spray-formed steels with a higher nitrogen content exhibit slightly lower values than the material with the usual nitrogen content. Clearly the highest toughness was measured on the powder metallurgically produced steels. This is seen in the longitudinal direction as well as in the transverse direction where it is

**Figure 5.** Impact toughness of D2-steel produced by different routes.
more pronounced. This effect of the production route is also stronger in the D2-grade than in the M2-grade. The large difference between longitudinal and transverse directions in the D2 PM-steel compared to the M2 PM-steel is particularly noticeable. The higher hardness and carbide content of the M3-PM steel in comparison to the M2-steel, which also may have affected the results, must also be taken into account. While the impact toughness of the ledeburitic grades is mainly affected by the carbide distribution and therefore has rather low values, the impact toughness of the hot-work tool steel H13 is much higher and mainly influenced by segregations and impurities. For this material V-notched samples were used in two different heat treatment conditions.

The first series (Fig. 6) shows the results for the spray-formed material (usual nitrogen content: H13-SF, higher nitrogen content H13-SF (N)) in comparison to conventional material after vacuum hardening. Again, a clear advantage of the spray-formed material compared to the conventional material and slightly lower results for the material with higher nitrogen content can be seen. The effect is again more pronounced in the transverse direction.

In the second series, an additional comparison was made with electro-slag-remelted (ESR) material, which is usually regarded as the premium grade of hot-work tool steels. In this second series a specially heat treated (diffusion annealed) conventionally produced steel was also used (H13 conv.DA). This second series also had a slightly higher hardness. Figure 7 shows the somewhat surprising results. The spray-formed material, which did not undergo diffusion annealing, exhibits the worst results. In both, the ingot-cast and the spray-formed material, the transverse direction showed clearly lower toughness values than the longitudinal direction. As for the electro-slag-remelted steel the toughness can be regarded as more-or-less independent of the testing direction and shows the highest values.

**ABRASIVE WEAR RESISTANCE**

Abrasive wear tests were performed using two different methods:

- pin-on-disc tests of $\varnothing$ 8 mm samples against SiC-grinding paper (120 grit)
- rubber-wheel tests according to ASTM 65.94 with $\mathrm{SiO}_2$
The results are shown as the inverse value of the measured wear rate (weight loss [1/g]), meaning that the highest values represent the highest wear resistance (Fig. 8 and 9). Both tests gave a similar basic result with some differences in detail, proving the transferability of the results but also the limits of their interpretation. Generally, spray-formed materials show a similar wear resistance to their conventionally produced counterparts. Significant exceptions are the spray formed M2 steels. The higher nitrogen material had a lower wear resistance in the pin-on-disc test, while both spray-formed materials had a higher wear resistance in the rubber-wheel test. Larger deviations from the results of the conventional material were found for the powder metallurgically produced grades. In both tests the D2-PM steel showed a lower wear resistance than the material from the other production routes. This is more dominant in the pin-on-disc test. The M3-PM steel showed a similar wear resistance to the M2 steels produced by the other production routes in the pin-on-disc test. However, a somewhat surprising result with the highest wear resistance value was found in the corresponding rubber-wheel test, showing the effect of the higher content of hard monocarbides.
Figure 7. Impact toughness of D2 steel produced by different routes (salt-bath hardening and tempering to 49-50 HRC).

Figure 8. Wear resistance of the steels M2 (M3-PM), D2 and H13 produced by different routes (pin-on-disc test).

in M3 versus M2 in respect of the hardness of different abrasive media (SiC versus SiO₂). Generally the results show a tendency of rising wear resistance
with more homogeneous carbide distribution and of falling wear resistance with smaller carbide size. The positive effect of the homogeneous carbide distribution is more pronounced in the rubber-wheel test with SiO$_2$. The negative effect of smaller carbide size is more pronounced in the pin-on-disc test with SiC.

Conversely, the lower wear resistance, especially against the hard SiC, can always be regarded as a better grindability.

**DISCUSSION**

The behaviour of the different steels during heat treatment gave no indication of an effect of the production route chosen. Only the steels with higher nitrogen content showed different hardness values directly after hardening. Even in these cases, no significant differences between the different production routes could be found in the typical tempering temperature range. This corresponds to the results on T15 high speed steel reported in [4]. Reports of a higher hardness of spray formed steels in [2, 5] could not be verified.

Investigations on the effect of the production method on the microstructure of steels with primary and ledeburitic carbides verified the known relationships. The main advantage of the spray-formed material over the conventionally produced material was found in the even distribution of the carbides over the whole cross section without major segregation areas. [1, 2, 4].

![Figure 9.](image) Wear resistance of the investigated steels M2 (M3-PM), D2 and H13 produced by different routes (rubber-wheel test).
pared to powder metallurgically produced material, the carbide size seems to be significantly larger in spray-formed material. In this regard, reports about PM-like fine carbides [1, 4, 6] could not be completely verified for the alloys investigated.

The main interest was focused on the mechanical properties of the materials. Therefore the toughness and wear resistance were investigated most intensively. Figure 10 shows the overall relationships between the reported test results. For this diagram the values of the wear resistance from the two different tests as well as the toughness results from the longitudinal and transverse directions were combined in average values. For H13 only the results from the series with lower hardness were included and the values for the ESR-material are estimated from the results of higher hardness.

The figure shows clear dependencies of the material properties on the production method. While PM-material shows the best results, especially regarding toughness properties, spray forming has a clear advantage over conventionally produced material. Within the group of spray-formed ma-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10}
\caption{Correlation of wear resistance and impact toughness for the steels M2 (M3-PM), D2 and H13 produced by different routes.}
\end{figure}
terial, the results from material with higher nitrogen content always show lower toughness values than the material with the usual nitrogen content.

The results of the wear tests show no clear trends – once again verifying the effects of the various influencing factors i.e. the microstructure in connection with the test parameters, on the test results – as reported in the literature [7]. Optimised carbide microstructures, and thereby statements on the best production route can only be evaluated in relation to specified wear conditions. Therefore comparisons with other wear or grindability tests [2, 4] are difficult. Furthermore, only abrasive and no adhesive wear tests have been performed so far. Later tests will be part of a continuing ECSC project.

Reports of various toughness tests on carbide-rich tool steels [1, 2, 4] generally give similar results. Spray-formed material always ranks between conventional production and powder metallurgy, with a tendency to be closer to powder metallurgy [4]. In this investigation programme the toughness results from spray-formed material were found to be about half-way between conventional and PM material.

For the hot-work tool steel H13, the spray-formed material did not achieve the good results of the electro-slag-remelted steel. It is a well known fact that not just the solidification process but also special heat treatments such as diffusion annealing can improve the toughness properties of hot work tool steels (i.e.: [8, 9, 10]. This point is still under investigation as no diffusion annealing has been performed on the spray formed billets up to now.

SUMMARY

Spray forming as a new method for the production of tool steels on an industrial scale was investigated under semi-industrial production condition and compared with results from established production routes. A clear classification seems to be possible from these results. Powder metallurgically produced ledeburitic cold-work tool steels and high-speed steels show the best combination of toughness and abrasive wear resistance, with a dominating advantage in toughness properties. Spray-formed tool steels have properties between conventionally produced material and PM material, closing a loop which has existed until now from the technological point of view. For hot-work tool steels, spray forming seems to have the potential to become an equivalent to ESR-material. Additional investigations both on the effect
of different wear mechanisms and the effect of diffusion annealing on the properties still have to be carried out and are in progress.

ACKNOWLEDGMENTS

The working group kindly acknowledges the European Commission for funding the ECSC programme research project 7210PR-173, upon which this paper is based. Many thanks also to the many colleagues involved in this work who are explicitly not named here.

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