Investigation of the homogeneity of a spray formed tool steel billet

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Abstract
The deposit conditions regarding spray forming are often shown by heavy FEM-simulations. All of them show that the deposit conditions in the centre are considerably higher in temperature than at the surface, like the accumulated heat is considerably higher at the end of the billet than at the starting plate.

In this paper the homogeneity of a spray formed 3.5 tons industrial produced tool billet has been examined with regard to microstructure and chemical composition as a function of both the length and the diameter of the billet.

The analyses are made on sprayed objects as well as on forged bars.

As basis a new steel has been chosen with high content of alloying elements developed to resist wear in hot working applications.

The paper will also show examples of application experiments of this new steel.

Introduction
During the last 4 years Dan Spray A/S has been spray forming tool steels at the 4 tonnes plant in Taastrup, Denmark. The spray forming know-how was based on trials from the 1 tonnes facilities at Osprey in Wales during several years, and the aim was to build a plant where 4 tonnes billets could be produced and reproduced with a strong degree of automation. In order to gain metallurgical know-how Dan Spray A/S went into close collaboration with costumers to develop new tool steels that takes use of the advantages in the spray forming process. This paper shows a result from a development project performed with Uddeholm Tooling AB and Dan Spray A/S as close partners.

Simulated deposition
Spray forming has been simulated for many years, but within the last few years the computer power has made it possible to simulate many different parameters from models of atomisation, deposition heat balance etc. It has been interesting to follow the development of these models, but difficult to bring the models into the world of 3,5 tonnes billets. [Ped03]
The deposition pattern is often shown with an accumulation of heat in centre of the billet as shown in Figure 1.

Many of these models has been based on observations from laboratory runs where the preform has been photographed thermally or cut into pieces afterwards to see the micro segregation pattern as function of placement in the spray formed product. The photo in figure 2 shows a thermal image taken at the Oxford University.

**Spray forming method at Dan Spray A/S**

The plant at Dan Spray is based on a twin atomiser system spraying up the billets vertically with a flow rate of app. 80 kg steel per minute. The upper atomiser produces the centre of the billet and the lower is responsible for the rim. The atomising pressures in the nozzles can be controlled independently in order to cool down the centre to avoid a deep pool of semi liquid steel.

To get a temperature gradient as low as possible Dan Spray has performed several runs with varying pressures on the upper atomiser. The resulting billets has been cut in order to investigate the solidified structure as function of the billet radius. A typical microstructure is shown in figure 3, where the dendritic cell size is proportional to the time to solidify (time from liquidus to solidus). [Jer77]
Today the parameter set has been optimised to give a solidification structure as equal as possible to fulfil the demands of homogeneity from the customers.

![Solidification structure in a common spray formed Ø500 mm billet. The picture to the left is taken from the centre of the billet and the picture to the right is taken 25 mm below the billet surface.](image)

**Figure 3.**

**Development of a new tool steel for hot working applications**

Spray forming gives a freedom to add alloying elements that under normal casting procedures have a strong tendency to segregate. The alloy chosen in this presentation is a wear resistant hot work tool steel called Toughtec, with chemical composition as shown in table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>1,6</td>
<td>0,25</td>
<td>0,5</td>
<td>5,0</td>
<td>2,3</td>
<td>7,2</td>
</tr>
</tbody>
</table>

This alloy has been spray formed and the homogeneity in the forged bars has been investigated in detail.

**Homogeneity in forged materials**

The spray formed billet (charge DS 390) was made in dimension Ø500 mm and app. 2,3 meters long. After hot forging and fully annealing the diameter was reduced to Ø333 mm.

The chemical composition was measured at the surface, at mid radius and in centre of the forged bar with the result shown in table 2.

<table>
<thead>
<tr>
<th>Charge nb.</th>
<th>Dim. (mm)</th>
<th>Position</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS 390</td>
<td>Ø333</td>
<td>Surface</td>
<td>1,62</td>
<td>0,30</td>
<td>0,57</td>
<td>0,026</td>
<td>0,012</td>
<td>4,94</td>
<td>2,33</td>
<td>7,41</td>
<td>0,08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R/2</td>
<td>1,59</td>
<td>0,30</td>
<td>0,57</td>
<td>0,028</td>
<td>0,013</td>
<td>5,05</td>
<td>2,31</td>
<td>7,36</td>
<td>0,08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>centre</td>
<td>1,59</td>
<td>0,30</td>
<td>0,57</td>
<td>0,027</td>
<td>0,010</td>
<td>5,01</td>
<td>2,33</td>
<td>7,43</td>
<td>0,11</td>
</tr>
</tbody>
</table>
The table shows that no macro segregation has taken place. The composition is very uniform throughout the radius even for vanadium, which has the strongest tendency to segregate.

As shown earlier in this paper the heat is concentrated in centre of the billet. This has an impact on the microstructure development as is visualized in figure 4 for a bar of Ø333 mm. The microstructure at surface is fine with a gradual increase of the carbide microstructure towards centre of the bar. The material has been hardened at 1050 °C for 30 minutes followed by tempering at 525 °C/2x2 hours.

Figure 4. The photos shows the coarsening of the primary carbides as function of distance from the surface of a bar with a diameter of 333 mm.
It is clear that the carbides are larger in centre of the bar, and figure 5 shows the maximum carbide size as function to the radius.

![Figure 5](image_url)

**Figure 5.** Maximum carbide size between surface and centre for Ø333 mm. Toughtec, charge DS 390.

The same charge has been heat-treated to a hardness of app. 54.5 HRC at 1050 °C followed by 2x2h at 525 °C. If carbon has been removed from the matrix in order to produce larger amounts of carbides the hardness should be affected. As shown in figure 6 the hardness is not affected by the coarsening of carbides.

![Figure 6](image_url)

**Figure 6.** Hardness between surface and centre for Ø333 mm - Toughtec, charge DS 390.
Toughtec can be heat-treated to working hardness varying from 45 to 60 HRC. This can be seen in figure 7 where the resulting hardness from four different austenitizing temperatures followed by tempering at varying temperatures is given.

![Tempering graph showing the hardness after proper heat treatment.](image)

When forging/rolling Toughtec into smaller dimensions the structure becomes more uniform. The photo in figure 8 shows the microstructure of a bar rolled to Ø35 mm. The material has been hardened at 1150 °C for 30 minutes followed by tempering at 550 °C/2x2 hours. The carbide size and distribution is similar to the structure seen in figure 4 comparing to the centre of the bar.

![Microstructures at centre of a Ø35 mm bar after hardening to 59 HRC – Toughtec, charge DS 324.](image)

**Properties**
The alloy Toughtec has been developed to have an excellent performance in hot working applications. Traditionally hot working steels contain only small amounts of primary carbides which decrease the abrasive wear resistance in comparison with a material containing more carbides. With more that 7% vanadium, Toughtec has wear properties even better than the wear
resistance cold work tool steels AISI D6 as shown in figure 9. The wear tests have been performed as pin-on-disc against SiO₂-paper with grit size 120 at room temperature.

Figure 9. Wear sheet comparing Toughtec with traditionally cold working tool steels.

Further, compared to the cold working tool steels the toughness of Toughtec is considerable higher. This can bee seen in figure 10, where the impact strength is shown both in longitudinal and transversal direction. The impact strength has been measured on unnotched specimens with dimensions 7x10x55 mm.
Figure 10. Impact energy, unnotched specimens, in longitudinal and transverse direction for Toughtec, A2, D2 and D6.

Cases
Material properties given in laboratory tests can be difficult to transform into specific applications at the end users. Therefore a series of application tests has been carried out, and one of the results is shown below.

Guide rolls case
When rolling steel plates their position shall be carefully controlled in proportion to the major rolls. In this application guide rolls as shown in figure 11 are used.

Table 3. Results from guide roll case where Toughtec was compared with AISI D2.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Dimension interval</th>
<th>Location</th>
<th>Work period</th>
<th>Wear result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughtec</td>
<td>47 – 58 mm</td>
<td>First roll against the heat</td>
<td>9100 m</td>
<td>No wear at all</td>
</tr>
<tr>
<td>AISI D2</td>
<td>47 – 58 mm</td>
<td>Second roll against the heat</td>
<td>9100 m</td>
<td>Abrasive wear at the contact points</td>
</tr>
</tbody>
</table>
As shown in table 3 the wear resistance is much better for Toughtec compared to AISI D2 though the most severe wear should appear on the first roll against the hot plates.

**Conclusion**

The results given in this paper shows that a very satisfactory degree of homogeneity can be achieved in highly vanadium alloyed tool steels when using spray forming as the manufacturing process. The combination of large amounts of vanadium carbides, the size of the carbides and a specific chosen matrix gives a tool steel with excellent performance in hot working applications.

**References**


[Ox03] Oxford University homepage: [http://users.ox.ac.uk/~pgrant/sfintro.html](http://users.ox.ac.uk/~pgrant/sfintro.html) 27.01.2003

[Jer77] Jernkontoret: *A guide to the solidification of steels*, 1977, p. 11-16