HIGH SPEED STEEL PRODUCED THROUGH CONVENTIONAL CASTING, SPRAY FORMING AND POWDER METALLURGY

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Abstract

Powder metallurgy (PM) and spray forming (SF) have been reported as important alternative routes for tool steel production. The ability to promote refined and more uniform microstructures is their main advantage, leading to improved properties and higher isotropy. While PM application is a completely established technology, the SF process may be considered as a not totally explored field. Therefore, the present work aimed to study the potential of both processes, focusing in high speed steel (HSS) production. AISI M3:2 high speed steel was produced by conventional casting, spray forming and powder metallurgy. Conventional ingots and a 400 mm diameter SF billet were rolled to large diameter bars, with cross section around 110 mm. The PM material was evaluated in the as-HIPed condition, in comparative diameters. Large diameter HSS bars are used mainly in cutting tools, but are also applied in cold work tooling when higher wear resistance is required. In the present characterisation, microstructures and bend test analysis were used, both in transverse and longitudinal directions. The results show that the as-HIPed PM material presents finer and more uniform carbide distribution, leading to a complete isotropy and higher toughness than the conventional steel. In the SF material, carbides are also finer, have good distribution and the isotropy is considerably higher than that for conventional HSS.

Introduction

High speed steels (HSS) forms a special class of highly alloyed tool steels, combining properties such as high hot hardness and high wear resistance. The cast structure of conventional HSS contains coarse carbide arranges, which makes the material useless. After certain hot working degree, carbides cells are broken and properties are enhanced. However, the carbide particles remain distributed in bands or cells parallel to the working direction, reducing transverse toughness and causing anisotropy.

The above discussion is based on the assumption that cooling rates were reasonably slow. Present-day techniques are available to cover an extremely wide range of cooling rates, which can have a deep effect on as-cast structure. Powder Metallurgy (PM) was the first industrial application of the increase in the cooling rate during solidification for high speed steels products. Finer primary carbides, smaller grain sizes and absence of carbide stringers are some characteristics attained. As a result of such microstructure, they have higher toughness, higher hardness after heat treating and higher isotropy. Another advantage of PM is the possibility of producing any alloy design. For conventionally produced HSS, however, some highly alloyed grades are not feasible due to their poor hot ductility.
In spite of its better performance in many applications, PM HSS has normally high cost especially due to the hot isostatic pressing (HIPing) step. The advantage of Spray Forming process (SF) in relation to PM is to combine rapid solidification (gas atomisation) and direct method for bulk components production. The absence of HIPing process lead to substantial cost reduction. Although this technology is not as disseminated as powder metallurgy, there are several reports of its use in highly alloyed steels [7-9], and recently have been industrially applied for HSS rolling mill rolls [10] and tool steels [11] production. With single atomiser, the billet size was limited to 175 mm diameter [12]. Considering the initial porosity, such small billet diameters could be a problem for the production of fully dense bars, especially in larger sizes (higher than 50 mm). However, in 1995, the development of twin spray atomiser made the production of billets of diameters up to 400 mm possible [13]; today toll steels can be spray formed in billets up to 500 mm [11].

Therefore, due to the advances of PM on HSS quality and the possibility of large billet production in spray forming, the present work aimed to compare microstructures and mechanical properties of AISI M3:2 produced through these two processes. The PM material was produced through APM [5] process, being in the as-HIPed condition. All results are compared to conventional wrought HSS of the same grade.

Materials and Methods

All materials studied were in bar diameters around 110 mm. The SF M3:2 billet, with 400 mm round billet, was spray formed through a twin atomiser equipment and hot forged and rolled to a 116 mm bar. Part of the rolled bar was also rolled to 11 mm. As-HIPed M3:2, produced through APM process [5], was also evaluated in an 80 mm bar. As the PM steel is in the as-HIPed condition, the diameter is less important than that of conventional or spray formed steels.

The chemical compositions of all materials are presented in Table 1. It is important to mention that, although the vanadium content of SF material is in the middle of the AISI range, the carbon content is in the minimum limit. The SF material is thus expected to have higher tendency to VC carbide formation and, as a consequence, its equivalent carbon content in solution after austenitizing is lowered. This material is thus less able to promote hardness, by secondary hardening, than the others are.

Table 1: Chemical composition of PM, SF and conventionally cast AISI M3:2 high speed steel. For comparison, the AISI range for M3:2 steel is also presented. Weight percent and iron balance.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>V</th>
<th>N</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder Metallurgy (PM)</td>
<td>1.32</td>
<td>0.63</td>
<td>0.35</td>
<td>4.02</td>
<td>4.95</td>
<td>6.00</td>
<td>2.97</td>
<td>0.061</td>
<td>0.005</td>
<td>0.025</td>
</tr>
<tr>
<td>Spray Forming (SF)</td>
<td>1.14</td>
<td>0.54</td>
<td>0.26</td>
<td>4.04</td>
<td>4.91</td>
<td>5.86</td>
<td>2.94</td>
<td>0.034</td>
<td>0.005</td>
<td>0.025</td>
</tr>
<tr>
<td>Conventional</td>
<td>1.17</td>
<td>0.51</td>
<td>0.25</td>
<td>4.11</td>
<td>4.94</td>
<td>5.87</td>
<td>2.75</td>
<td>0.011</td>
<td>0.001</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Austenitizing temperatures between 1080 to 1220 °C for 5 min were employed, and tempering was fixed at 560 °C, being double of 2h for conventional and SF M3:2 and triple 1.5 h for the PM steel. All heat treatments were performed under vacuum. Three tempering treatments were employed to PM material due to its finer structure that leads to intense carbide dissolution and retained austenite formation.

The toughness was evaluated in transverse and longitudinal directions, using the static bend test method, which was developed [14] and is commonly applied [6, 15-17] in hardened tool steels. Fracture energy was calculated through the area bellow the force-dislocation curve. For toughness evaluation specimens with 5 mm x 7 mm x 65 mm were heat treated to 64.5 HRC.
Results and Discussion

The as-cast microstructures of conventional HSS, PM and the SF M3:2 can be compared in Fig. 1. The finer microstructure of PM material is clearly visible (compare Fig 1a and 1d). This is a result of the higher cooling rate applied during atomisation.

The SF microstructure shows differences between the dense and porous regions (Fig. 1b and 1c). In spray forming, it is well established \cite{7, 12, 18} that porous regions result from particles that solidified large part of their volume during the flight, i.e. in contact with the gas, and reach the substrate with few liquid. As a result, microstructures become finer (Fig. 1b), approaching those of PM material (Fig. 1d), which is fully solidified in gas atomisation. In spite of the differences in some regions, the as-cast SF M3:2 presented a microstructure considerably finer than that of conventional material, as a result of the high cooling rate applied during atomisation.

Fig. 2 presents annealed microstructures of SF and conventional M3:2 with 116 mm square size and considerable differences in relation to carbide distributions are observed. The 116 mm section is considered a large size for high speed steels, and the conventional high speed steel remains coarsen carbide distributions, in cellular arranges. Core microstructures are considerably coarser, with less broken carbide cells. In spite of being common in conventional high speed steels, this arrange is not desired, because the continuous carbide distributions are preferable regions to crack propagation. They are thus the microstructural aspects determining tool failure, when failure by chipping or fracture is considered. In practical applications, this situation is important for large diameter cutting tools, such as large milling cutters and large broaches. The low toughness determined by such coarse carbide arranges also limits the applications of high speed steel in cold work tooling.

On the other hand, the microstructure of PM steel (Fig. 1d) is constant throughout the transverse section, because as-HIPed PM high speed steel presents primary carbides in a totally individualised arrange. As it will be shown later, this microstructure leads to higher and more uniform properties, especially in terms of toughness.

The microstructure of the SF material can thus be considered an intermediary behaviour between conventional and PM. Different from conventional HSS, carbides in SF M3:2 do not form coarsen morphologies. Most primary carbides are individualised and finer. Besides, SF M3:2 HSS shows less variation in microstructure between the core and the surface (compare Fig. 2d, 2e and 2f). This fact is strictly related to the spray forming process. As considerable amounts of particles solidify during the “flight” period, the final microstructure is less dependant on the position of the section than that of conventional HSS. Because of the coarseless microstructure and small variation throughout the section, the SF material is considered to be close to PM HSS. However, some differences still remain.

In Fig. 3, carbides scanning electron microscopy of is presented. By EDS, all the carbides may be divided in two types: V rich and W-Mo rich carbides. According to the literature \cite{1-2}, the stoichiometry of these carbides are MC and M\textsubscript{6}C respectively.
In Fig. 1, carbides of SF material are much finer than conventional steel ones. On the other hand, the same comparison in Fig. 2 and Fig. 3 shows that carbides sizes in SF material, although more distributed, have individual size close to the conventional steel. This microstructural variation of SF high speed steel indicates the possibility of carbide coarsening after hot working, especially during the heating previous to forging and rolling. This fact was evaluated in previous work \cite{19} and it was shown that carbide coarsening can actually occur, depending on hot working time and temperatures. Therefore, SF HSS is shown to be able to present more refined microstructures, if lower temperatures were employed to its conformation, indicating one possibility of process optimisation.

The hardness after tempering is shown in Fig. 4, in relation to austenitizing temperature. For all the materials, an increase in the austenitizing temperature leads to increased hardness. The PM material leads to higher hardness levels, even in low austenitizing temperatures. Similarly, the SF material presents the same hardness levels than conventional HSS, in spite of having considerably smaller...
equivalent carbon content. All these phenomena are to carbide dissolution kinetics and reprecipitation during secondary hardening. Finer carbides are more prone to dissolve and thus are indeed more able to promote higher secondary hardening.

Fig. 5 presents bend test results for all the materials. As these materials present linear stress-strain curves, the fracture energy, calculated by the area below the stress-strain curve, is proportional to bend strength (which coincides with rupture stress). From the results of bend test, fracture energy was calculated but the error was very high, around 20%. However, in all cases it was found that the higher the bend strength the higher the fracture energy. This agrees with other reports, which show the correlation between bend strength and toughness \[ 15-17 \] for high hardness (>62 HRC) steels.

In Fig. 5, PM steel attains approximately 40% higher bend strength. In high speed steels, it is considered \[ 17 \] that fracture occurs after cracking of carbides, which forms subcritical cracks that propagate with an increase in loading. Therefore, the improved toughness of PM high speed steel results directly from its microstructure: smaller grain sizes and more uniform and finer distribution of primary carbides.

Under working condition, tools are stressed in a complex arrange of forces and they must resist, regardless the stressing direction. A high degree of isotropy in mechanical properties is thus important. Comparing longitudinal and transverse bend strength, it is shown that PM steel is fully isotropic, while SF M3:2 presents 87% of isotropy and conventional high speed steel have only 54% of isotropy.

The full isotropy of the PM high speed steel results from its fine microstructure and as-HIPed condition, as shown in previous work \[ 6 \]. In conventional cast steel, the reduced isotropy is related to the coarsen carbide network in the microstructure (see Fig 2). For longitudinal stressing, the cracks propagate throughout the material crossing the carbide cells. Based on some reports \[ 7, 17 \], longitudinal toughness may be attributed to general carbide sizes, being less sensitive to the coarse morphology. As SF and conventional M3:2 do not have strong variation in this aspect, the comparable bend strength attained may be understood. In transverse directions, however, coarsen carbide networks of conventional material are preferential ways for cracking propagation. In the SF M3:2, carbide arranges are less oriented (see Fig. 3), leading to similar strength for longitudinal and transverse direction strength. Therefore, in real tooling conditions, PM and SF steels higher isotropy can improve tool performance, retarding failures by chipping or cracking, either in cutting or cold working tools.
Coarsen carbide arranges also have consequences for heat treatment, and can cause distortion. The non-oriented carbide microstructures of PM and SF M3:2 lead to more isotropic expansion/contraction and thus cause less distortion or other heat treatment problems.

It is important to note that the present work evaluated only one SF billet processed in the same conditions as usual high speed steels. Therefore, optimisation of spray deposition and, as already discussed, billet hot working conditions can produce results even better than the ones showed here.

The Comparison of the microstructure of conventional and SF material in small sizes (Fig. 6) showed that the carbide distribution of SF material is absolutely uniform. It was not verified indications of carbide stringers or differences for regions related to different billet height position. As it is usual in conventional wrought HSS, all the regions of conventional cast steel presented carbide stringers, which are thicker for regions related to hot top ingot positions. The absence of carbide stringers is another advantage of spray forming for HSS production.

Fig. 6: Microstructures of 11 mm round bars: a) conventional (region related to hot top ingot position) and b) SF M3:2 (region related middle of billet height). Light microscopy of annealed samples in longitudinal direction.

Conclusions

- Powder metallurgy high speed steel presents fine carbides, distributed in non coarsen morphologies and without orientation throughout longitudinal direction. This microstructure leads to improved properties and full isotropy. The fully isotropic properties of PM high speed steel is important for tools performance and reliability in heat treatment.

- Carbides in SF material are better distributed than conventional HSS, without coarsen arranges. In small diameter bars, SF material has no carbide stringers. In relation to conventional steel, SF material has higher bend strength for the transverse direction toughness, with 87% of Isotropy.

- SF HSS microstructure, properties and isotropy are close to the PM HSS ones. Considering the higher simplicity of the spray forming, it is shown as an interesting route for production of high speed steel and highly alloyed steels.

References