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

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Abstract

Powder Metallurgy and Spray Forming 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 Osprey process may be considered as a not totally explored field. Therefore, the present work aimed to study the potential of both processes, focused in high speed steel (HSS) production. VWM3C (AISI M3:2) was produced by conventional casting, Osprey process and powder metallurgy (Sinter 23). Conventional ingots and a 400 mm diameter Osprey 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 mainly employed in cutting tools, but are also applied in cold work tooling when higher wear resistance is required. In the present characterization, microstructures and bend test analysis were employed, 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 Osprey material, carbides are also finer, well distributed and the isotropy is considerably higher than that for conventional HSS.

Keywords: High speed steel, Powder metallurgy, Spray forming, Isotropy, Bend test
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. These properties are possible to be attained due to a special microstructure, composed of a matrix around 65 HRC and hard primary carbides, rich in molybdenum, tungsten and vanadium.

The cast structure of conventional HSS contains coarse carbide arranges, which makes the material not useful [1]. After certain hot working degree, the carbide particles are finer and more separated, but are contained in bands or cells parallel to working direction [1]. These carbide arrangements reduce toughness and produce anisotropic properties, which may also cause distortion after heat treating [1, 2].

The above discussion is based on 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 profound effect on as-cast structure. In normal ingot casting practice the cooling rate may be as low as $10^{-3} \, ^\circ\text{C}$/per second. In the consumable electrode processes such as ESR or VAR, the values are of the same order [2]. However, in powder production and spray deposition, cooling rates up to $10^5 \, ^\circ\text{C}$/s may be attained [2]. A relative comparison of all these processes is shown in Fig. 1 [3]. The right axis makes an approximate relation regarding the dimension produced.

Powder Metallurgy (PM) was the first industrially application of the benefits of refining by expressive increase in cooling rate during solidification. Finer primary carbides, smaller grain sizes and absence of carbide stringers are some characteristics attained [4, 5]. As result of such microstructure, they have higher toughness, higher hardness after heat treating and are more isotropic [4, 5]. Another advantage of PM is the possibility of producing any combination of alloy composition; for conventionally produced HSS, however, the chemical composition arrange is limited by hot workability [1, 2].

PM HSS may be produced by various processes, being the most usual the ASP, CPM and APM process. The differences in PM processes mainly regards to Hot Isostatic Pressing (HIP) techniques. As discussed in previous works [6, 7], the APM process has some advantages, since it is able to produce as-HIPed PM HSS free from porosity and with no segregation of S, O or C. This is possible thanks to a cold loaded mega-HIP system, where
PM has been applied in several situations due to success in refining HSS microstructure. In spite of its better performance in many cases, wide application of PM HSS is limited by the relatively elevated cost of such products. The large number of operations, especially the HIPing step, has considerably high cost, which impairs the total PM material cost.

The advantage of spray forming process (also known as Osprey process) in relation to PM is based on this point. As shown in Fig. 1, PM or other rapid solidification techniques, the refined microstructure always relate to reduced sizes. On the other hand, the Osprey Process is unique in combining a rapid solidification process (gas atomization) with a direct method for making bulk components. Since its development [8], Osprey process has been widely studied in several types of alloys, being today presented in usual books and handbooks [1, 2, 9]. Although this technology is not as technologically applied as powder metallurgy, there are several reports of its use for high speed steel production [10, 11, 12]. Besides, Osprey process
has been used industrially applied in Rolling Mill Rolls, of high speed steels, definite chilled iron or spheriodal graphite iron [13].

There are four main stages in Osprey Process, including melting and dispersing, gas atomization, deposition and collector manipulation. An overview of the Process, with a single atomizer and applied to billet production, is shown in Fig. 2 [14]. For HSS production, the melt is normally atomized by supersonic $\text{N}_2$ gas. With the single atomizer, the billet size was limited to 175 mm diameter [15]. Considering the relatively high initial porosity, such small billet diameters could be a problem for production of fully dense bars, specially in sizes higher than 50 mm. However, in 1996, the development of double atomized spray forming made possible the production of billets in diameters up to 400 mm.

Therefore, due to the advances of PM on HSS quality and the possibility of large billet production in Osprey process, the present work aimed to compare microstructures and mechanical properties of AISI M3:2 produced from these two processes. The PM material, named Sinter 23, was produced
through APM process, being in the as-HIPed condition. All results are compared to conventional wrought HSS of the same grade, which is named VWM3C.

MATERIALS AND METHODS

All materials studied here were in bar diameters around 110 mm. The conventional M3:2 (VWM3C) parted from cast ingots, which were wrought conformed to 116 mm square bars. The Osprey M3:2 was produced in a 400 mm round billet, spray formed through a double atomizer equipment. The as-cast billet was forged to 200 mm squared bar, and rolled to 116 mm. One rolled bar was also rolled to 11.11 mm. Some properties of this material are also presented. As-HIPed M3:2 (Sinter 23), produced through APM process, was also evaluated, in a finished 76 mm bar. As Sinter 23 is in the as-HIPed condition, the diameter is less important than that of conventional or even that of spray forming. This size is thus perfectly comparable.

Chemical compositions of all materials are presented in Table 1. The

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<th>C</th>
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<th>Mn</th>
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<td>Sinter 23</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>
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<td>OspreyM3:2</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>0.005</td>
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<tr>
<td>VWM3</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>0.001</td>
<td>0.027</td>
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<tr>
<td>AISI M3:2 Min</td>
<td>1.17</td>
<td>≤ 0.45</td>
<td>≤ 0.40</td>
<td>3.80</td>
<td>4.70</td>
<td>6.00</td>
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<td>≤ 0.03</td>
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AISI M3:2 composition is also presented for comparison. It is important to mention that, although the vanadium content of Osprey material is in the middle of the AISI range, the carbon content is in the minimum limit. The Osprey material is thus expected to have higher tendency to VC carbide formation. As a consequence, the equivalent carbon content in solution after austenitizing, is lowered. This material is thus less able to promote hardness, by sencondary hardening, than the others.

The heat treatment consisted in heating in the range of 1080 to 1220 °C for 5 min, followed by oil quenching. All tempering treatments were conducted at 560 °C, being a double of 2h for conventional and Osprey M3:2 and triple 1.5h for Sinter 23. As will be discussed later, Sinter 23 presented
higher carbide dissolution, which can increase the retained austenite content. Because that, three tempering treatments were employed to this material. All heat treatments were performed under vacuum.

The maximum austenitizing temperature for Sinter 23 was 1180 °C, because this temperature is able to produce considerably high hardness, adequate for all applications. As presented later, the hardness levels attained after hardening at 1180 °C and tempering are higher than those of Osprey or Conventional VWM3C hardened from 1220 °C and tempered. Besides, as Sinter 23 is a PM HSS, temperatures higher than 1180 °C are inadequate, causing excessive grain and carbide coarsening.

Toughness evaluation was conducted using the bend test method developed [16] and commonly applied [7, 17, 18, 19, 20] to hardened tool steels. Bend strength values can be directly related to toughness, as shown in other reports [17, 18, 19, 20]. Bend specimens with dimension 5 mm × 7 mm × 65 mm were employed, and bend toughness was evaluated in transverse and longitudinal directions, in order to quantify the anisotropy. Toughness was analysed in specimens with hardness around 64.5 HRC.

RESULTS AND DISCUSSION

The as-cast microstructures of a conventional HSS, Sinter 23 and the Osprey M3:2 can be compared in Fig.3. The finer microstructure of PM material is clearly visible (compare Fig.3a and 3d). This is a result of the higher cooling rates, discussed before (see Fig.1).

The Osprey material microstructure shows considerable differences between the dense and porous regions (Fig.3b and 3c). In spray forming, it is well established [10, 15, 21] 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 just a small amount of liquid left. As result, microstructures become finer (Fig.3b), approaching to that of PM material (Fig.3d), which is fully solidified in gas atomisation. Higher density is provided when particles reach the substrate with more liquid. However, the cooling rate is decreased and the carbide arranges are coarser (Fig.3c). A macrographic view of Osprey billet cross section is presented in Fig.4, where the dense or porous regions can be identified. Dense regions form a ring like distribution, near the surface. As discussed, dense regions are result of liquid concentration occurring during the spray forming process. This phenomenon is named as shadow and may happen when two atomizers
Figure 3. As-cast structures of a) Conventional VWM3C, b) porous and c) dense regions of Osprey M3:2 billet and d) PM Sinter 23.
Figure 4. Macrographic aspect of cross sectioned Osprey billet. Porous and dense regions are indicated, including relative density.

are employed in spray forming. In dense parts, particles proceeding from the two atomizers may be concentrated, provoking liquid accumulation and forming, as a consequence, a dense region in the as-sprayed structure.

In spite of the differences in some regions, the as-cast Osprey M3:2 presented a microstructure considerably finer than that of conventional material (see Fig. 3). This results from the better capacity of heat extraction, during solidification in the Osprey process. The ability of production of such fine microstructures in a single process, without HIPing processes, is the main goal of Osprey process.

Figure 5 presents annealed microstructures of Osprey and Conventional M3:2 rolled to 116 mm square size. Surface, mid-ray and core regions microstructures were analysed. The PM material, in the as-HIPed condition, can be compared by microstructure of Fig. 3d, which is constant throughout transverse section.

Comparing Osprey and Conventional M3:2, considerable differences in relation to carbide distributions are observed. The 116 mm section is considered a large size for high speed steels, and conventional VWM3C remains coarsen carbide distributions in cellular or Hooky arranges. In spite of being usual to conventional high speed steels, this arrange is not desired. Because of carbides’ high hardness and brittleness, their continuous distributions are
Figure 5. Microstructure of conventional and Osprey M3:2 in annealed condition. a)/b) are relative to surface, c)/d) to mid-ray and e)/f) for core regions. All micrographs are relative to longitudinal orientation.
preferable regions to crack propagation. They are thus the microstructural aspects determining tool failure, when failure by 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 limit high speed steel applications in cold work tooling. As discussed before, cold work dies normally employ tool steel bars in diameters over 60 mm and, in such dies, the low toughness of conventional HSS is inevitable. Besides, conventional HSS also present strong variations throughout transverse section. Core microstructures are considerably coarser, with less deformed carbide cells.

As-HIPed PM Sinter 23 presents primary carbides in a totally individualized arrange. As will be shown later, this microstructure leads to higher and more uniform properties, specially regarding toughness.

Osprey material microstructure can be target between conventional and PM material ones. In the opposite of conventional HSS, carbides in Osprey M3:2 do not form coarse morphologies. The majority of primary carbides are individualized and are finer. Besides, Osprey M3:2 HSS shows less variation in microstructure between core and surface (compare Fig.5b, 5d and 5f). This fact is strictly related to spray forming process. As considerable amounts of particles solidifies during the "flight" period, final microstructure is less dependent of the section position than that of conventional HSS. Because of the coarseless microstructure and small variation throughout section, Osprey material is considered to be close to PM HSS. However, some differences still remain.

In Fig.6, scanning electron microscopy of carbides are presented. By EDS, all carbides may be divided in two types: V rich and W-Mo rich carbides. According to literature [1, 2], the stoichiometry of these carbides are MC and M₆C respectively. Thus, after annealing and hardening, all materials are shown to present the same carbide types, regardles the casting process. This fact agrees with other reports [4, 5], showing that the increase in cooling rates only cause the variation of carbide sizes, without changing the stoichiometry types.

Comparing Fig.6b and Fig.3b and 3c, one can see a sensible variation in carbide size for Osprey M3:2. In Fig.3, carbide sizes of Osprey material, especially in the porous regions, are comparable to that of PM. On the other hand, the same carbide comparison in Fig.6 shows relatively high difference between them. As the PM material was not hot worked, its microstructure is
the same. The microstructural variation of Osprey HSS shows the occurrence of carbide coarsening after hot working, possibly during the heating previous to forging and rolling. Therefore, Osprey HSS is shown to be able to present more refined microstructures if lower temperatures were employed to its conformation, which indicates the possibility of process optimisation.

Hardness after tempering is shown in Fig.7, in relation to austenitizing temperature. For all materials, increase in austenitizing temperature leads to increased hardness. PM material leads to higher hardness levels, even in low austenitizing temperatures. In the same way, the Osprey material present the same hardness levels as conventional HSS, in spite of having considerably smaller equivalent carbon content. All these phenomena are related 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. The results of Fig.7 are relevant, showing the first relation regarding casting process, finer structure and mechanical properties.

Figure 8 presents bend test results for all materials, heat treated for hardness between 64.0 and 65.3 HRC.

In Fig.8, two points may be attained: 1) the general toughness levels and 2) the degree of isotropy for all material. Concerning the first point, it is clear that PM Sinter 23 is tougher than the others, attaining 40% higher longitudinal bend strength values.
Figure 7. Hardness after tempering as a function of austenitizing temperature for PM Sinter 23, conventional VWM3 and Osprey M3:2.

Figure 8. Bend strength results for PM Sinter 23, conventional VWM3 and Osprey M3. The relative difference on longitudinal and transverse directions results indicates isotropy degree. Considering the experimental, for Sinter 23 isotropy is calculated as 100%, for Osprey M3 88% and for VWM3C 53%.
In HSS, toughness depends on two basic factors: matrix fracture toughness and carbides morphology and distribution. It is considered [20] that fracture occurs after cracking of carbides, which forms subcritical cracks; with increase loading, crack grows and failure of the specimen occurs when the crack exceeds the critical length. Based on this, it is possible to affirm that improved toughness of Sinter 23 results directly from its microstructure: smaller grain sizes and more uniform and finer distribution of primary carbides.

It is well known that, under working condition, tools are stressed in complex arrange of forces and they must resist, regardless of the direction of application. A high degree of isotropy in mechanical properties is thus desirable. Comparing longitudinal and transverse bend strength, it is shown that PM Sinter 23 is fully isotropic, while Osprey M3:2 presents 88% of isotropy and conventional VWM3C have only 53% of isotropy. These results lead to important conclusions, with relation to microstructure.

The full isotropy of Sinter 23 results from its fine microstructure and as-HIPed condition, as shown in previous work [7]. The higher isotropic properties thus improve tool life (retarding failures by cracking), in cutting or cold work tooling.

In conventional VWM3C, the reduced isotropy is related to the coarsen carbide network in the microstructure (see Fig. 5). For longitudinal stressing, the crack propagates throughout the material crossing the carbide cells. Based on some reports [7, 20], longitudinal toughness may be attributed to general carbide sizes, being less sensible to the coarse morphology. As Osprey and conventional M3:2 do not have strong variation in this aspect, the comparable toughness attained may be understood. In transverse stressing, however, cracking occurs when cracks propagate in the same direction of cells orientation. In this situation, coarsen carbide networks of conventional material are thus preferential weaker ways for cracking propagation, decreasing toughness. For the Osprey M3:2, carbide arrangements are less oriented (see Fig.5), being close the values for longitudinal and transverse direction strength. Therefore, the Osprey M3:2 present important benefits, regarding real tooling conditions. In a complex arrange of stresses, better isotropy of Osprey HSS can conduct to substantial improvements in tool performance.

Coarse carbide arrangements also have consequences for heat treatment. Such regions presents different behaviour regarding thermal expansion and, as a consequence, may cause distortion. Therefore, PM Sinter 23 and Osprey
M3:2 are also interesting materials considering this aspect. Their non-oriented carbide microstructures lead to more isotropic expansion, as well as occurred for toughness values. It is thus expected that these materials present less distortion and less problems in relation to heat treatment, which are common in conventional HSS.

It is important to note that the present work is the first evaluation of Osprey process on HSS production in large billets. Optimisation of spray deposition and, as already discussed, billet hot working conditions can produce results even better than that showed here.

Although it was not the aim of the present work, microstructure comparison of conventional and Osprey material in small sizes (round 11.11 mm bars) are also presented in Fig. 9. One can see that carbide distribution of Osprey material is absolutely uniform. It was not verified any indications of carbide stringers and the regions related to base and middle of the billet have the same aspect. As usual in conventional wrought HSS, all regions of VWM3C presented carbide stringers, which are thicker for regions re-

![Figure 9. Microstructures of VWM3C and Osprey M3:2, for 11.11 mm round bars. The regions relative to base and middle Osprey billet or bottom and top ingot are indicated.](image-url)
lated to hot top ingot positions. The absence of carbide stringers is another advantage of Osprey process for HSS production.

CONCLUSIONS

The characterization of VWM3C production through conventional casting, Osprey process and powder metallurgy may be summarized in the following points:

- Sinter 23 presents fine carbides, which are totally dispersed in non coarsen morphologies and without orientation throughout longitudinal direction. This microstructure leads to improved properties and full isotropy.

- Carbide distribution of Osprey material is more disperse than conventional HSS, without coarsen arranges. In small diameter bars, Osprey material has no carbide stringers.

- As a consequence of its microstructure, Osprey material presents higher transverse direction toughness, in relation to conventional VWM3C, and 88% of Isotropy.

- Sinter 23 is shown as an important option to tool producer considering reproductively, security in heat treatment and performance aspects.

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

REFERENCES


