Euro PM2004
Full Density and Alternative Consolidation

# Powder Metallurgy and Spray Formed 10% V Cold Work Tool Steels, A Comparison

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*Abstract:*
*Vanadium rich carbides are typically desired in cold work tool steels, to increase wear resistance and tool life. However, the coarsen as-cast microstructure limits vanadium content in conventionally cast steels. Powder metallurgy (PM) and the emerging spray forming (SF) process are useful alternative processes to refine as-cast microstructure and enable high V tool steel production. Therefore, the present work aims to compare PM and SF 10%V cold work tool steels, as regards to wear resistance and toughness. Microstructural results has shown that both steels have homogeneous carbide distribution, but V rich carbides are finer in the PM than in the SF steels. Such microstructure leads to better abrasive wear resistance but lower toughness for the SF material.*

Key words: 10%V Cold Work Tool Steel, Spray Forming, Powder Metallurgy, Wear Resistance, Toughness.

## 1. Introduction

Cold work tools are commonly employed in several industrial applications, for forming or shaping metallic or ceramic materials [1]. Some typical applications are tools and dies for metal cold drawing, coining, piercing or sheet cutting, as well as dies for thread-rolling and punches. Such steels are also employed in ceramic shaping, for example in pressing bricks moulds or in abrasive cutting processes. In all these application wear is the dominant failure mechanism, in abrasive or adhesive conditions[1].

Abrasive wear is the most well known wear type. It is described by material removal form a surface caused by the action of hard abrasive particles [2], which slices or roll under pressure across it. The force component that is normal to the surface acts on the hard particles, causing their penetration on the metal surface and surface material loss. This action causes grooves across the surface much like those produced by a cutting tool [2]. The abrasive wear is typically present in ceramic shaping applications, but can also be present associated to other wear types. In metal forming applications, however, adhesive wear is also an important factor. In the metal-to-metal contact, the surface roughness lead to very high local pressure in some micro-areas, and may even cause microscopic bond. In the subsequent sliding operation, tearing of one surface occur and mass is transferred to the other – which, in turn, can lead to further wear [2]. The process may also result in the formation of loose wear particles, which may contribute to abrasive wear[2]. Such particles, or other particles present in the forming

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[1] Actually, other wear mechanisms can be present, depending on the tooling situation, such as erosive, corrosive or surface fatigue. However, the most common are really the abrasive and adhesive types.
[2] The metal particles generated can actually oxidize, acting as abrasive hard particles.

process, can thus result in a combined wear mechanism, where either adhesive or abrasive wear are present.

Wear resistance in cold work tool steels is promoted by a well dispersed carbide distribution in a high hardness martensitic matrix. The basic role of microstructural matrix is to support the dispersed carbides, which are the really important microstructural phases for avoiding tool wear. This carbides are normally primaries, and their hardness is in the range from 800 HV to 3000 HV [1], i.e. in the same range or even harder than the abrasive particles. The highest hardness is attained in the V-rich and MC type carbides, which are commonly present in high speed steels [3]. In usual cold work tool steels, as in AISI D series, the chromium rich $M_7C_3$ type carbides are predominant in the microstructure, in large size and massive distributions. However, these carbides attain for approximately 1000 HV lower hardness than the MC type. Some steels have high V content to promote MC carbides formation, like AISI D7 with 4%V. However, the as cast microstructure is normally too coarse, which impairs the material hot ductility and toughness.

Alternative solidification routes are therefore desired for the production of high V tool steels. Powder metallurgy is today the main process employed in high V tool steel production, and the V content is virtually unlimited. The high cooling rate during solidification leads to very refined initial (as-cast) microstructure, and thus improves material toughness, isotropy [4] and strongly increases the hot workability. Therefore, for highly stressed tools, 10% V PM steels are frequently applied, due good combination of wear resistance and toughness. Another process, known as spray forming (SF) process or Osprey process, has recently been employed for industrial tool steel production [5]. The microstructure and mechanical properties of this process present intermediate behaviour, when compared to conventionally cast and PM tool steels. In previous studies [6-7], it was determined that SF improves toughness and enhance mechanical properties isotropy of high speed steels, compared to the same grade conventionally cast and wrought deformed. However, the toughness properties are inferior to the PM steel, due to the larger primary carbides of SF high speed steel [7].

Nevertheless, wear resistance in cold tooling is influenced by both factors: toughness and carbide size. In predominantly adhesive conditions, as in metal forming, toughness plays a very important role, as it inhibits the metal tearing after adhesion or also micro-cracking in the sharp regions. On the contrary, large and well distributed carbides are desired in for abrasive wear applications, since they avoid abrasive penetration and material chipping. In the technical literature, no criterions comparisons has been made on the same grade of high V tool steels produced through PM and SF processes. Thus, the present wok aimed to compare both processes regarding the properties of a 10%V tool steels produced, with absolutely the same chemical composition. The materials were industrially produced, being the PM steel in the as-HIPed (Hot Isostatic Pressed) condition and the SF steel forged to a large section bar.

## 2. Experimental

The chemical composition of PM and SF 10%V steels is shown in Table 1, and one can notice they are very close. The PM material was analysed in the as-HIPed condition, as in the PM process employed lead to fully dense and segregation free bars, with no necessity of hot working reduction. This fact is important for providing full isotropy in mechanical properties, as shown in previous work [4]. The SF as-cast billet normally presents some remaining porosity, around 2%, and the billet was forged with two times area total reduction. The initial billet size was ∅ 500 mm and the final size 250 x 400 mm. The forging was successful due to the good hot workability, as shown by the hot workability test, Figure 1, where more than 50% area reduction is attained above 1000ºC.

Abrasive wear resistance were determined by pin on grinding paper test. The test specimens had 25 mm round section size, and the test conditions were: applied force 44.5 N, mean sliding speed 1.72 m/s, disc as #80 and #120 mesh sanding paper (with $Al_2O_3$) and total test time equal to 60s. The test specimen holder has a turning movement independent on the disc, and the grinding path constantly changed during the test, avoiding abrasive paper grindability change during the test.

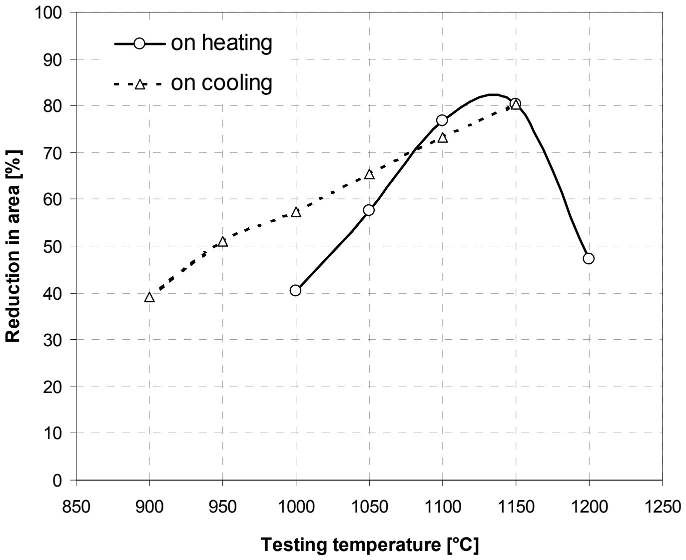


**Figure 1:** Hot ductility results for SF 10V tool steel, indicating material hot workability. The test was performed in high strain rate, around 5 $s^{-1}$. Specimens in the as-cast SF condition.

The microstructures were analysed in optical and SEM microscopy, and EDS microanalysis were employed for carbide characterisation. Worn specimens were also evaluated. In order to quantitatively compare the MC carbides in both steels, the carbides were evaluated by an automatic image analyser, model Feature Sizing/Voyager. All samples were metallographically prepared and electroetched in 4% chromic acid (5V and 5s). As a result, accurate images were converted, from secondary electron grey images to binary mode. 12 fields at 1000x magnification for PM and 200x for SF steels were evaluated for each sample. Carbides with an area lower than 1 $\mu m^2$ and size smaller than 1 $\mu$m were filtered, to reduce errors and processing time.

**Table 1:** Chemical composition of SF and conventionally cast 10%V cold work tool steels. Weight percent and iron balance.

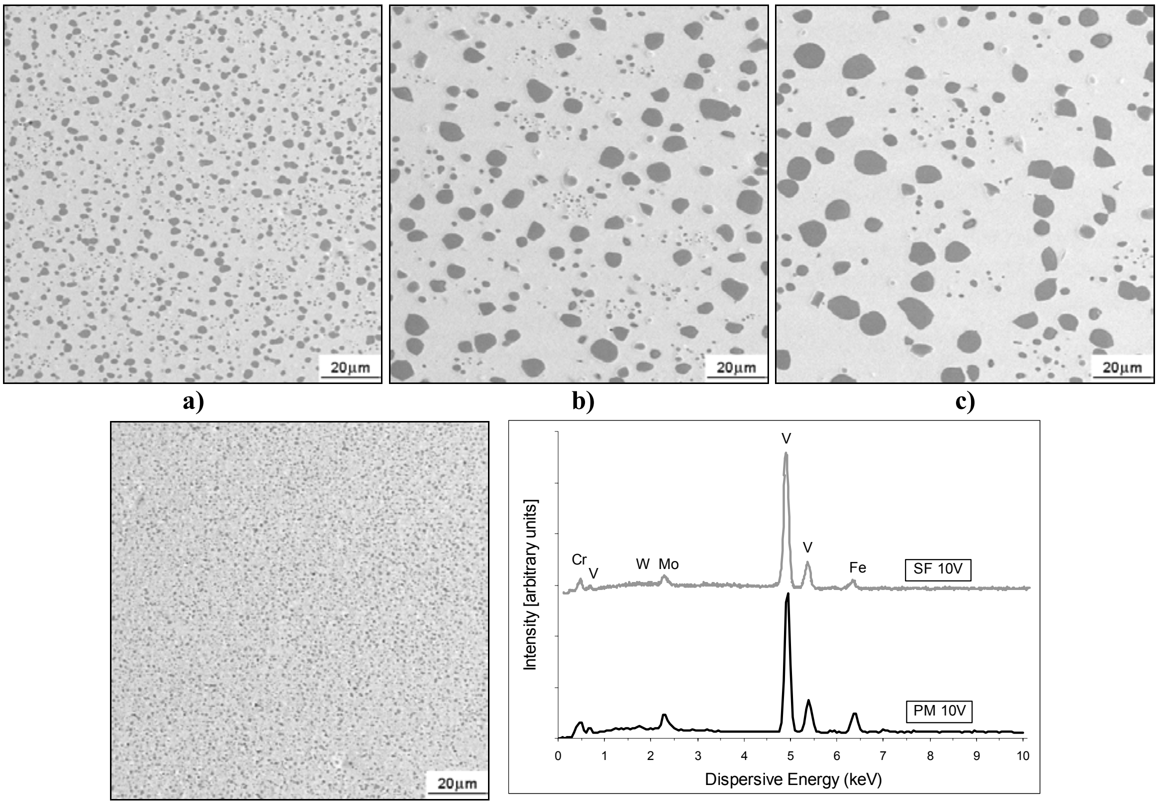
| | C | Si | Mn | Cr | Mo | W | V | N | S | P |
|---|---|---|---|---|---|---|---|---|---|---|
| PM 10V | 2.58 | 0,82 | 0,47 | 5,28 | 1,36 | 0,05 | 9,92 | 0,053 | 0,069 | 0,020 |
| SF 10V | 2,63 | 0,81 | 0,49 | 5,16 | 1,34 | 0,08 | 9,84 | 0,072 | 0,018 | 0,030 |

Heat treating response were evaluated after hardening from 1050 or 1170 ºC, and tempering between 450 and 600 ºC. Hardening time was fixed on 15 min for PM and 30 min for SF steel, and double tempering treatments were employed for 2h each. Strength was determined by 4 point bend test; the results can be considered a proper indicative of material toughness, in hardened tool steels [8-10].

## 3. Results and Discussion

The carbide images for both steels and EDS analysis are presented in Figure 2, identifying the V-rich carbides, which are the main responsible for the high wear resistance. Regular high speed steels also have primary MC carbides, but such carbides have large amounts of Mo or W in solid solution [3,11], due to the high amounts of both elements in the total steel composition. In the PM and SF 10%V steels, MC are more concentrated in V, with low concentration of other alloy elements.

V-rich carbides in SF steel has strong size variation through section position. A rapid size increase is identified from surface to mid-radius regions, followed a slight increase from mid-radius to core (see Fig. 2a, 2b and 2c). These results are related to the cooling rate in spray formed billet solidification [12-13]. Cui et. al [13] show that for a 200 mm round SF billet, local solidification time increase approximately 5 times from near surface regions to mid-radius and only 1,7 times from mid radius to core. The Figure 2 microstructures show that the same effect is present in the analysed SF material, produced from a larger billet (∅ 500 mm), which can even increase the heat concentration in core regions.



**a)** **b)** **c)**

**d)** **e)**

**Figure 2:** Scanning electron microscopy images for MC carbides in SF 10%V 250 x 400 mm$^2$ forged bar for: **a)** 10 mm from the surface, **b)** mid-radius and **c)** core regions. **d)** carbides in the PM 10%V steel. All images are SEM backscattered electrons. **e)** EDS patterns for the carbides in both steels.

Heat treating response of SF and PM 10%V steels is compared in Figure 3, and approximately 2 HRC higher hardness pick is identified in the PM steel. This result is related to the material finer microstructure, which lead to better V dissolution during austenitizing and more intense secondary carbide precipitation response. Analogous results were found by comparing SF and PM high speed steels; for the same hardness, lower austenitizing temperatures are shown to be required for the PM steel [6].

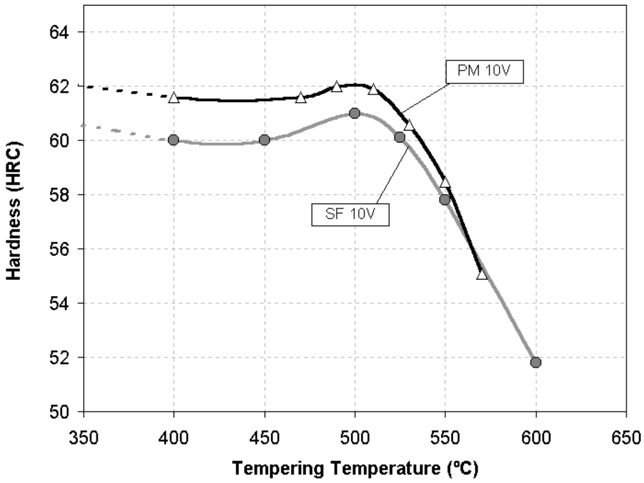
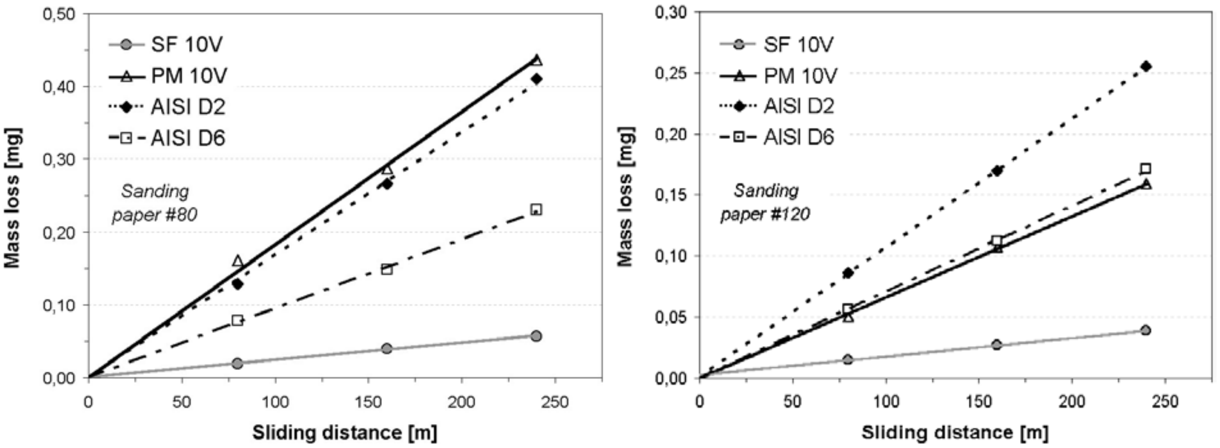


**Figure 3:** SF and PM material tempering curves. The hardening treatment was fixed at 1050 ºC for 30 min for both steels, and all samples were oil quenched. SF results refer to mid-radius samples.

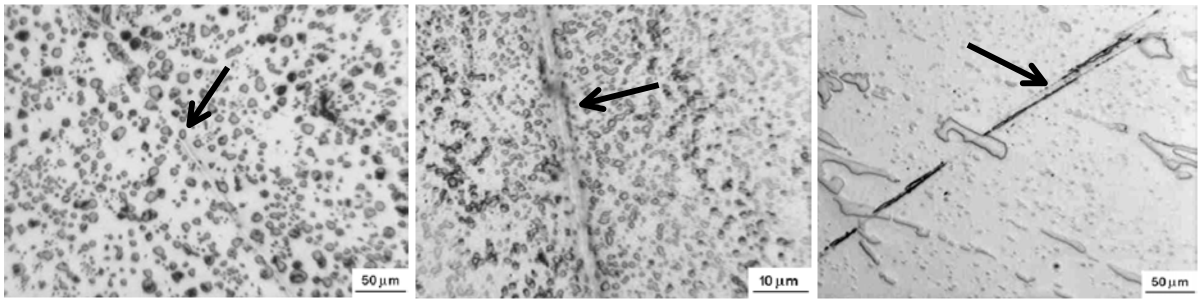
Abrasive wear resistance, determined by pin on grinding disk test, for both materials is compared in Figure 4; for comparison, the AISI D2 and D6 tool steels were also tested. Based on the wear rate results, which measure the actual wear, the SF 10V wear resistance is calculated as almost 8 times higher than PM 10V in the #80 mesh condition and 4,5 times higher in the #120 mesh condition. Comparing to D2, the SF 10V is again better wear resistance, and PM 10V has approximately the same resistance in the first condition, but higher in the second.

The wear test results are closely related to the materials microstructure. Comparing the worn specimens microstructures, Figure 5, it is shown the effect of larger carbides in avoiding grooves across the microstructure. Therefore, the larger carbides of SF 10V tool steel is more effective in conferring abrasive wear resistance, as shown in Figure 5a and 5b. However, the carbide distribution is also important. As shown in Figure 5c, AISI D6 tool steel also has large carbides, but these are not well distributed, leading to localised wear in the microstructural matrix. Therefore, the high abrasive wear resistance of SF 10%V steel is promoted by a combination of large carbides and adequate carbide distribution.



| *Wear rate* | *#80 mesh* $(x10^{11})$ | *#120 mesh* $(x10^{11})$ |
|---|---|---|
| ***SF 10V*** | 6,6 | 4,4 |
| ***PM 10V*** | 49,4 | 18,4 |
| ***AISI D2*** | 45,2 | 28,1 |
| ***AISI D6*** | 25,1 | 18,8 |

**Figure 4:** Abrasive wear test results for SF and PM 10%V and also for two AISI D steels. The test conditions were applied force 44.5 N, mean sliding speed 1.72 m/s, #80 or #120 mesh $Al_2O_3$ sanding paper and total test time equal to 60s. The wear rate (W) is non dimensional parameter calculated as W= $\Delta m/(\rho.A.L)$, being $\Delta m$ the mass loss, $\rho$ the density, and L the total sliding length.



**a)** **b)** **c)**

**Figure 5:** Worn samples microstructures for **a)** SF 10V, **b)** PM 10V and **c)** AISI D6 tool steels. SEM secondary electron images. The carbides in D6 tool steel are Cr-rich $M_7C_3$ type and they are quite large because the size bar from which the specimens were taken is relatively large (around 200 mm).

In the PM 10%V carbide distribution is also very homogeneous, but the small carbide sizes make them to be wear extracted in conjunction with the matrix (Fig. 5b). The end result for the PM steel is thus similar to AISI D steels. On one hand, it has better carbide distribution and more quantity of high hardness MC carbides; on the other hand the carbides are not large enough to avoid abrasive wear. This also explains the reason for the better relative results of PM 10V steel in the #120 mesh test than in the #80 mesh, as grinding particles are smaller in the first.

In tooling conditions, adhesive wear is also important and the material properties such as toughness and compressive strength should also be considered. Regarding this properties, the refined microstructure of PM material is interesting, leading to higher toughness and mechanical isotropy [6] than spray formed steel. The performance effect regarding wear resistance will thus depend on the combination of abrasive and adhesive components in each application. In metal forming process, adhesive is normally the predominant factor and the PM material can lead to good results. However, a totally adhesive condition is rare [2]. On the other hand, some applications are practically only abrasive, such as ceramic shaping and paper or wood cutting. In such applications, the high abrasive wear resistance of SF steel is of interest.

## 4. Conclusions

- 10%V tool steel have predominantly V-rich carbides in the hardened microstructure, and these carbides are considerably larger in the spray formed (SF) steel compared to the powder metallurgy (PM).
- Abrasive wear resistance of SF 10%V steel is substantially higher than the same steel produced by PM. The difference is higher when coarser abrasive media are employed.
- In pure adhesive wear conditions, PM steel should have better wear resistance due to the higher toughness and strength.
- Wear in tooling conditions is normally produced by a combination of abrasive and abrasive mechanism, and PM or SF can present distinct results depending upon the predominant factor.

## 5. References

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