Effect of fabrication process on wear and impact toughness of high speed steel

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Abstract: Three kinds of high speed steels with similar composition were selected, which were produced by powder metallurgy (named PM20), spray forming (named SF20) and electroslag remelting (named ESR20) respectively. Their microstructure and mechanical properties were studied. The results indicated that the carbides in PM20 are fine and evenly distributed carbides, but there is carbide segregation in SF20, the carbides in ESR20 are banded distribution, carbide aggregation is much more serious than SF20. The segregation of carbides is beneficial to the wear property, but it will reduce the impact toughness. Consequently, PM20 has the worst wear properties but the best impact toughness, ESR20 is the opposite. The mechanical properties of SF20 are in between of them.

1. Introduction

High-speed steel (HSS) is widely used in manufacturing cutting and fine blanking tools due to its excellent hardness, strength and wear resistance [1-2]. Generally, the fabrication process of high speed steel mainly includes conventional casting, powder metallurgy (PM), spray forming (SF) and electroslag remelting (ESR). The HSS produced by conventional casting usually contains coarse eutectic carbides at the grain boundary of matrix, which will contribute to wear resistance but severely deteriorate the toughness of the steel [3-5]. In comparison, PM, SF and ESR can effectively avoid the formation of coarse eutectic carbides, and improve the shape, size, distribution of carbides.

It reported that the carbide phases play an important role in mechanical properties of high speed steel [6]. Niederkofler and Peng et al. [7,8] studied the PM HSS S390, the experimental results indicated that the spherical carbides are uniformly distributed in the matrix, the size and distribution of carbide affect the compressive strength and fracture strain of the steel. Spiegelhauer et al. [1,9,10] studied the SF tool steel, the results showed that coarse carbides in conventional castings are eliminated, carbides are uniform distributed. Yin and Luo et al. [4,11] reported that microalloying during ESR process and heat treatment after ESR can refine the carbide and make the distribution more uniform, the formation of finer carbides improve both the wear resistance and impact toughness.

In this work, three kinds of high speed steels with similar composition were selected, which were produced by PM, SF and ESR respectively. After the same heat treatment, the carbides distribution, wear properties and impact toughness were studied, the influence of carbide on mechanical properties were analyzed.
2. Materials and Methods

For the investigation, three kinds of HSS were prepared by PM, SF and ESR, named by PM20, SF20 and ESR20. The chemical compositions used in this study were tested using spark discharge atomic emission spectroscopy, as shown in Tab. 1. The samples were austenitized at 1125 °C for 2h, followed by quenching in a vacuum furnace, and then tempering at 560 °C three times for 2h.

|        | C   | W   | Mo  | Cr  | V   | Fe  |
|--------|-----|-----|-----|-----|-----|-----|
| PM20   | 0.83| 5.0 | 4.9 | 4.0 | 1.8 | bal.|
| SF20   | 0.93| 5.0 | 5.3 | 4.5 | 2.1 | bal.|
| ESR20  | 0.86| 5.0 | 4.9 | 4.1 | 1.9 | bal.|

The X’tpert3 powder X-ray diffractometer with Cu Kα radiation was used to measure the phase composition, the angle is 30 °- 90 ° and the step is 0.02 °. To study the microstructure, Zeiss Gemini SEM 300 field emission scanning electron microscope was used to observe the polished samples. The Rockwell-C hardness (HRC) was measured by 600MRD Rockwell hardness tester at room temperature. The hardness of each sample was obtained by averaging at least seven points. Instron-5500 testing system was used to test the compressive strength at room temperature. Nanoindentation tests were carried out by In-Situ Nanomechanical Test Instrument (T1705) with a standard Berkovich indenter. The wear test was carried out on the UMT-Tribolab high speed and high temperature friction and wear tester. The sample size was 15mm×10mm×5mm. The depth of scratches was characterized by surface profilometer. Charpy impact tests were performed on Pendulum Impact Testing Machine (JB/300) with dimensions of 10mm×10mm×55mm.

3. Results & Discussion

3.1 Microstructure

Fig.1 shows the XRD patterns of three kinds HSS. The XRD peaks of the three materials are almost the same. All the samples consist of α-Fe, M₆C and MC. Moreover, almost no peak of γ-Fe was detected in all three materials.

![Fig. 1 The XRD patterns of specimens](image)

Fig.2 presents the microstructure of three samples. They all contain two kinds of carbides, which are consistent with the XRD results. According to our previous study [12], the white carbides are (W, Mo)-rich M₆C and the dark carbides are V-rich VC. Fig.2a and d are PM20, carbides are uniformly distributed in the matrix. Fig.2b and e are SF20, the distribution of carbides is uniform, but there is still a small range of carbides segregation, and the size of the carbides is larger than PM20. Fig.2c and f are ESR20, carbides are distributed in bands with obvious carbide accumulation, and the size of the carbide is similar to that of SF20.
3.2 Mechanical properties

The mechanical properties are shown in Fig.3. The compressive strength, hardness and Nano-hardness have the same trend. PM20 shows the worst strength and hardness, while the strength and hardness of ESR20 are the highest (Fig.3a). Fig.3b is the depth and width of the scratch, the scratch of PM20 is the deepest, while ESR20 is the shallowest. The shallower the scratch depth, the better the wear resistance. Although the strength and wear resistance of PM20 is the worst, its impact toughness is the best (Fig.3c).

3.3 Wear performance

Worn surfaces are presented in Fig.4. It is apparent that characteristic wear grooves were formed along the sliding directions. This is a typical feature of abrasive wear. PM20 has some large damage regions (Fig.4a,d), which is consistent with its lowest nano-hardness (Fig.3a). The matrix of SF20 has some plastic deformation and a small amount of damage (Fig.4b, e). But the worn surface of ESR20 is smooth and almost without damage (Fig.4c, f).

The carbides sizes of SF20 and ESR20 is bigger than that of PM20. At the same time, the carbides in PM20 are uniformly distributed, but there is an obvious phenomenon of carbide segregation in SF20 and ESR20. Therefore, the distance between carbides is less than that of PM20. It is reported that the hardness of carbide is higher than that of matrix [13], the reduction of the distance between carbides is beneficial to the improvement on the wear performance of the material [14,15]. As a result, the wear performance of SF20 and ESR20 is better than that of PM20. ESR20 has the best wear performance because it has more carbide segregation than SF20.
3.4 Impact fracture surfaces

Fig. 5 is the SEM images of impact fracture surfaces and crack propagation of samples. The fracture surface of PM20 appears much rugged (Fig. 5a), which corresponds to its highest impact toughness (Fig. 3a). In addition to carbides broken and decohesion, the matrix of PM20 is quasi-cleavage fracture and plastic deformation. The plastic deformation of SF20 matrix is obviously lower than that of PM20 (Fig. 5b). The matrix of ESR20 has little plastic deformation, quasi-cleavage fracture of matrix is dominant (Fig. 5c).

The crack propagation of ESR20 is shown in Fig. 5d. The carbide segregation leads to the generation and expansion of cracks, thus accelerating the fracture of the material and reducing the impact toughness. In addition, the crack initiate along the coarse carbides, smaller and uniform carbides are beneficial to impact toughness [4]. As a result, PM20 shows the best impact toughness, while ESR20 with the most severe carbide segregation shows the worst impact toughness.
4. Conclusions
In this study, three kinds of high speed steels produced by PM, SF and ESR were selected. The microstructure and mechanical properties were investigated, following conclusions could be drawn:

1. The phases of HSS produced by the three fabrication processes are the same, they all contain two kinds of carbides, (W, Mo)-rich M$_6$C and V-rich VC. The carbides in PM20 are fine and evenly distributed, SF20 has a small part of carbide segregation, while the carbides in ESR20 are banded distribution, the segregation is the most serious.

2. The impact toughness of PM20 is the best, but the compressive strength, hardness and wear properties is worse than SF20 and ESR20. ESR20 has the best wear properties but worst impact toughness.

3. The segregation of carbides reduces the distance between carbides, so it is beneficial to the wear property, but it is easy to lead to the initiation and propagation of cracks, so it will reduce the impact toughness.

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