Tribological behavior of HM1 steel fabricated by precision spray forming under high temperature

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Abstract. In this study, we investigated the tribological behavior of HM1 steel fabricated by precision spay forming (PSF). WE used block ring friction test for our investigation, at various temperature, which was compared with that of the as-cast specimen. The results indicate that the wear rate and the friction coefficient of the PSFed specimen are reduced compared to that of the as-cast specimen. Attribution to these results is the fine grain, the eliminated segregation of elements, and the uniformly distributed matrix material elements for the PSFed specimen. SEM morphology of wear scar shows that the mainly wear mechanism of the as-cast specimen is adhesive wear, while the wear mechanism of the PSFed specimen is mainly abrasive wear.

1. Introduction

The procedure of hot work dies created different types of damage such as wear, plastic deformation, thermal and mechanical cracking, gross cracking to occur during the process. More than 70% of the failure for the hot work die is caused by wear [1]. Therefore, it is important to reduce the wear and decrease the friction in order to retard the wear failure. It is usually better to have the wear resistance of hot work die fabricated by the material with more uniform microstructure and fine grain size [2, 3].

The materials processed by spray forming have many advantages. This includes, uniform microstructure and fine grain size and non-segregation, which has a better wear resistance than that of the same materials processed by other methods [4~8]. Xu et al [4] studied the microstructures and wear resistance of the Cr12MoV steel and the results indicated that the spray formed steel exhibited more homogenous distribution of alloy element and finer grains than that of the conventional cast steel. The wear resistance of the spray formed steel improved near 20% compared to that of the conventional specimen. Rodenburg et al [5] found that the wear rate of spray formed M3:2 high-speed steel was lower than the specimens produced by powder metallurgy, which potentially is attributed to the carbide size distribution.

Within the last few decades, PSF was developed as an effective way to process steel into near-net-shape mould & die and tooling [9~11], which could reduce the cost and time compared with the conventional machining. The service life of a PSFed forging die was improved over 25% than the conventional die [10, 11]. In addition, the dimension tolerances are usually within ±0.05mm in the length of 200 mm with a satisfactory surface roughness, which is used directly without machining [10, 11].Therefore, it is important to study the tribological behavior of PSFed steel in order to promote the

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application of the hot work dies fabricated by PSF. The influence of PSF on the tribological behavior of HM1 steel is investigated under high temperature using dry sliding in order to explore the method to improve the wear resistance of HM1 steel.

2. Experimental procedure

2.1. Materials

The materials used in this study were fabricated using the self-developed PSF device with the type of PSF-20KG. The scrapped HM1 steel forging die was used as the raw materials, which was induction melted in the medium frequency furnace under a nitrogen atmosphere with slag refining after eliminating the oil, oxide, etc. The chemical composition of the raw materials is listed on Table 1.

Table 1. The chemical composition of HM1 steel (wt. %)

Composite	C	Cr	Mo	W	V	Si	Mn
	0.41	3.05	2.8	1.28	1.02	0.72	0.28

During the procedure of PSF, the superheated temperature of the metallic solution is about 100℃. A ring-seam constraint straight spray nozzle was used with the atomization pressure of 0.6MPa under the industrial nitrogen. The spray deposition height was 140mm, and the ceramic plate was used as the receiver that was preheated to the temperature of about 600℃. The reference specimen was produced by the ceramic mold casting under the same melting conditions. For the PSF specimen, the average density was up to 99.5%, which we used the method of drainage to measure [10].

2.2. Wear and wear scar presentation and measurement

The circular specimens with a dimension of 60mm(Diameter)×10mm(Height) are electro-discharged machined from the precision spray deposited ingot and the casting ingot. Prior to testing, all specimens were polished using diamond pastes, alcohol cleaning, drying, and the ultrasonic cleaning was used for 15 min. The rotating dry sliding wear test in the nitrogen atmosphere was carried out on HT-1000 type friction, while the wear testing carried out at a linear speed of 0.4m/s for 40 minutes under the load of 200N in a nitrogen atmosphere at the high temperature of 420 ℃, 520 ℃,620 ℃, and 720℃, respectively. In addition, a C-Si ceramic ball with a diameter of 4mm was used as the counterpart. The wear rate was measured by multi-functional materials surface topography tester. All tests were repeated at least three times to calculate the average values. Worn surface morphology and energy spectrum analysis were carried on Hitachi S-3400II type scanning electron microscope.

3. Results and discussion

3.1. Friction behavior

Fig.1 shows a group of typical relationship between friction coefficient and the times of both types of specimens. It is observable that the friction behavior is similar with each other under different temperatures for all of the specimens. After the stabilizing of the wear test around 15min into the friction and wear procedure, the friction coefficient of both types of specimens has an obvious fluctuation.

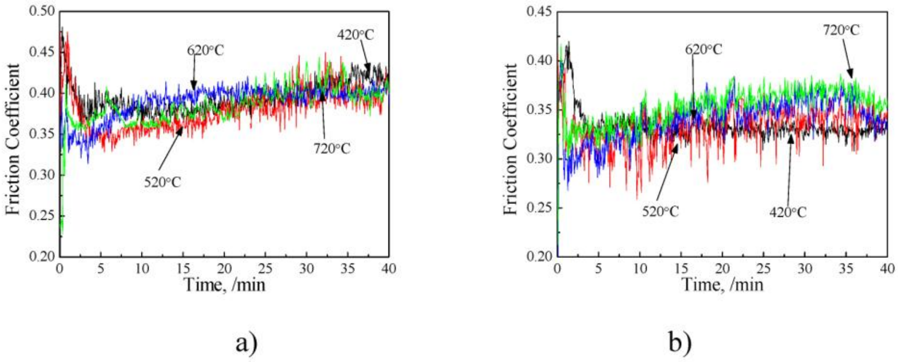


Figure 1. The friction coefficient curves of a) As-cast; b) PSFed HM1 steel under different temperature.

3.2. Wear behavior

Fig.2 illustrates the wear rate and the friction coefficient of HM1 steel for the as-cast specimen and PSFed specimen. It is observable that the wear rate of the PSFed specimens are lower than that of the as-cast specimens under various temperatures, which indicates that the wear resistance of HM1 steel could be enhanced by PSF. The friction coefficient of the PSFed specimens is also lower than the as-cast specimens. The results show that the wear of materials failure could be reduced by PSF. In addition, the wear rate for both types of specimen increases slightly when the temperature is lower than 620℃, whereas it rises at the temperature of 720℃. This implies that the wear mechanism was potentially changed at 620 ℃. These also indicate that the working temperature for HM1 steel should be not above of 620℃ in order to decrease the wear loss.

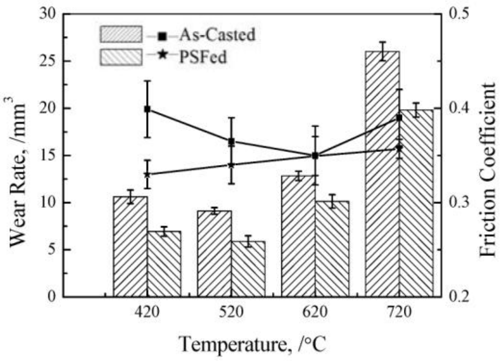


Figure 2. The wear rate and the friction coefficient of HM1 steel under different temperatures.

For the PSFed specimens, the friction coefficient changes slightly, which indicates that the temperature has little effect on the friction coefficient for both types of specimens under the experimental conditions.

3.3. Wear mechanisms

Fig.3 shows the typical SEM morphology of the wear scar of both types of specimens at the temperature of 620℃. In addition, the wear scar of the as-cast specimen exhibits a large number of adhesive material morphology (Fig.3 a), which indicates that the adhesion wear occurs under the experimental condition. While for the PSFed specimen, the wear scar surface morphology is observably different from the as-cast specimen and the amount of white hard particles presents on the wear scar surface. This illustrated that the abrasive wear occurred.

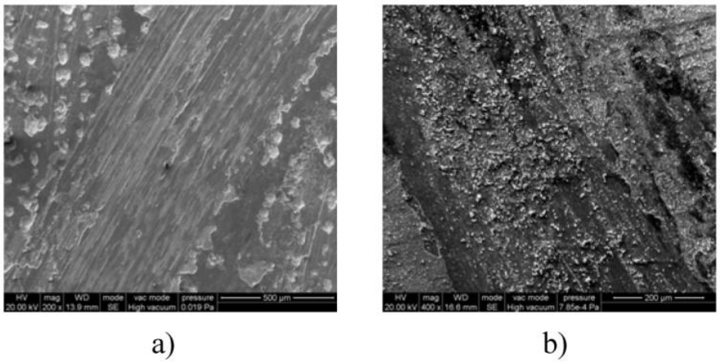


Figure 3. SEM morphology of the wear scar of both types of specimens under the temperature of 620℃. a) As-cast; b) PSFed

Fig.4 shows the EDS linear scan spectrums of the worn scar at the testing temperature of 620℃. It is observable that the Fe and O contents for both types of specimens on the wear surface fluctuate greatly and the content of O element increases at the adhesion complexes. While the content of O and Fe elements tends to stabilize in the original region. All of these observations indicate that the oxidation wear occurred during the friction procedure. Furthermore, a lot of heat will generate under the testing condition with a sliding dry friction, especially at an elevated temperature. Therefore, the surface oxidation phenomenon of the specimens occurs although the testing was carried out in a nitrogen atmosphere. In addition, the content of O element on the worn surface for the as-cast specimen is higher than the PSFed specimen. According to the results of EDS quantitative analysis, it indicates that the oxidation wear could be reduced for the specimen produced by PSF.

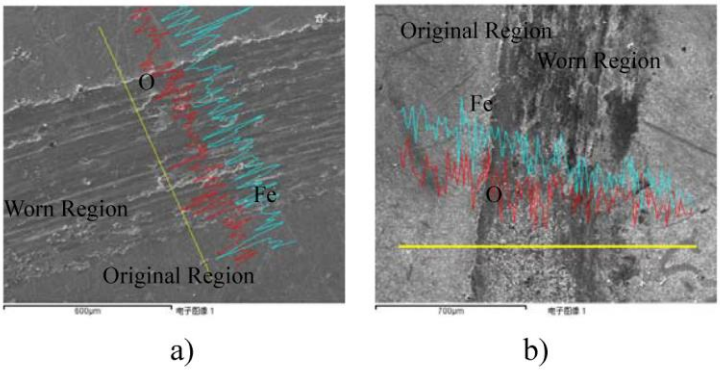
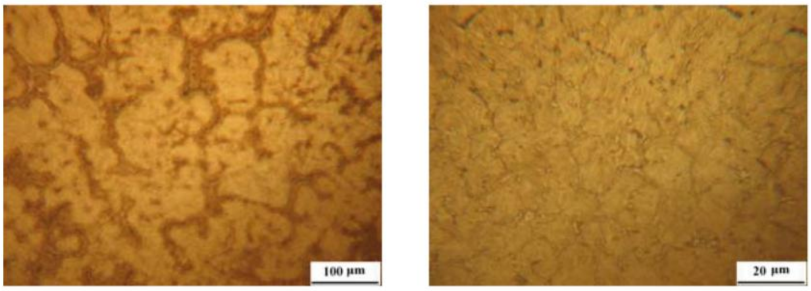


Figure 4. EDS linear image of the worn surface for both types of specimens at 620℃. a) As-cast; b) PSFed

3.4. Discussion

We concluded from the experimental results that the wear resistance of PSFed specimens can be reduced compared with that of the as-cast specimens. Fig.5 shows the microstructure of as-cast HM1 steel and PSFed specimen. In Fig.5 a, the grain of as-cast specimen is coarse with the average grain size of approximately 100μm. In addition, the coarse intergranular connected net carbide is observable. The microstructure of PSFed specimen is more uniform with fine grains and fine carbide dispersed. The average grain size was approximately 15μm. . Therefore, compared with the as-cast specimen, the improved wear resistance of the PSFed specimen can be attributed to the uniform microstructure and fine grains.



a) b)

Figure 5. Microstructure of HM1 steel a) As-cast; b) PSFed.

Fig.6 shows the X-ray diffraction patterns of both the as-cast HM1 steel and the PSFed. As observed from the diffraction pattern, the martensite and Cr_7C_3 type carbide and residual austenite are found in both types of specimens. The relative content of the austenite for the as-cast samples and the PSFed samples are solved by X-Ray diffraction quantitative analysis method. The arithmetic mean of the relative volume fraction for the austenite is 14% for the as-cast samples and 8% for the PSFed samples, which solves for six sets of data. It might be attributed to the relatively high amounts of Cr, Mo, W, V and other alloy elements for the PSFed specimen are solid solution during rapid solidification, which should improve the wear resistance of the PSFed specimen.

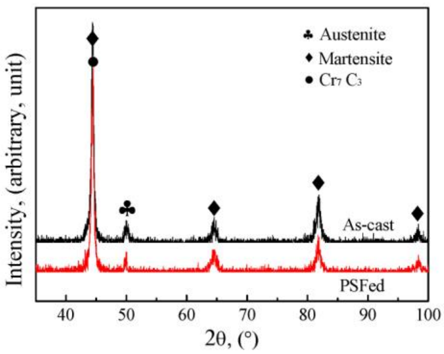


Figure 6. X-ray diffraction pattern of as-cast and PSFed HM1 steel.

Therefore, in order to improve the wear resistance of HM1 steel, the material preparation process should focus on the content of MC type high hardness carbide with the fine grain and non-segregation. This was optimized around the PSF and the subsequent heat treatment process of steel [12].

4. Conclusions

The wear resistance and wear mechanism of HM1 steel fabricated by casting and PSF at high temperature are investigated in order to explore the influential factors to improve their working performance. The following conclusions can be drawn from this study:

- The wear rate of PSFed HM1 steel is lower than the as-cast specimen under the experimental conditions with different high temperatures, which indicates that the wear resistance can be enhanced by PSF.
- Observably, the wear rate of as-cast HM1 steel and PSFed specimen are increased at the temperature of 620ºC, which implies that the wear mechanism may change at 620 ºC.
- At the temperature of 620ºC, the adhesion wear for the as-cast specimen occurs, and this is

also where the abrasive wear for the PSFed specimen is exhibited. The attributions to the changes are to the fine grain, eliminated segregation of elements, and uniformly distributed matrix material elements for the PSFed specimens.

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