Particle Erosion of SUS403 Tempered Martensitic Stainless Steel

Dong Cherng WEN

Department of Mechanical Engineering, China Institute of Technology, 245, Yen-Chiu-Yuan (ACADEMIA) Road, Section 3, Nankang, Taipei, Taiwan 11581, Republic of China. E-mail: dcwen@cc.chit.edu.tw

(Received on September 26, 2005; accepted on February 10, 2006)

The particle erosion behavior of SUS403 martensitic stainless steel tempered with five different temperatures range from 200 to 600°C were studied as a function of impact angle and hardness. The results indicate that the dominated mechanisms for material removal are cutting and extrusion at low and high impact angles, respectively. A transition of mechanism mixed by cutting and extrusion occurs at medium impact angle. Grain boundary cracking is often found for all impact angles that seem to be one of the major erosion mechanisms for two-phase materials mixed with martensite and ferrite. The erosion rate of all the experimental materials increases first, and then decreases with increase in impact angle. Thus, the maximum erosion rate occurs at the angle between 30° and 45°. At 15° and 30° of impingement, the erosion rate is virtually independent of hardness. While impact angles exceed than 30°, erosion rate increases with increasing hardness.

KEY WORDS: particle erosion; martensitic stainless steel; impact angle; hardness; tempering; secondary hardening.

1. Introduction

SUS403 martensitic stainless steel (MSS) with microstructure mixture of martensite and ferrite possesses excellent ductility, strength, heat resistance, and corrosion resistance. It is widely used in highly stressed and complex shape parts, such as valve or pump body, pipe material, and turbine blades.1) In general, this material is always heat treated by quenching and tempering processes for industrial application.

The flowed carrier, such as sand, powder, or residue on sanitary sewer, in transported processes impacted the pipe, valve and turbine blades, that solid particles interactive with MSS cause the weight loss of material, thinner of parts wall, crack even damage of components. Hence they have a problem of slurry erosion. Moreover, the sand or dust in environment may impact the outside wall of these parts, and thus particle erosion is also a topic. Two models have been employed to describe the erosion behavior for ductile materials and brittle materials respectively. Ductile materials during erosion are considered to lose material via a cutting mechanism at a low impact angle in the erosion rate as a function of the impact angle.2) On the other hand, the erosion damage of brittle materials is based on cracking and occurs at impact angle closed to normal.3) The resolved shear stress of particle impact provides the force for cutting, boundary cracking of materials, and eroding away of pieces.4,4) The resolved normal stress provides the force for lipping, ridging, cratering, surface and sub-surface cracking.4,5) However, the cutting mechanism is only valid at oblique impact angle. The erosion rate of material neither very soft nor very hard is generally regarded as the mixture of these two models. The angle of maximum erosion rate increases with increasing hardness of the materials.4,10) In the multi-phase material, the erosion rate is decreased with hardness of matrix4,11) but the results opposite from Hung.12) The influence of microstructure of two-phase alloys on erosion behavior has been the focus of many studies in ductile iron.13–15) However, few reports discussed the particle erosion for MSS.16) In order to understand the erosion wear mechanism and to build a base for slurry erosion test further, the particle erosion test was carried out first in this study. The SUS403 MSS was processed with tempering, those contain tempered martensite and ferrite with different in hardness, the aim is to investigate the erosion behavior in these two-phase materials, in which erosion rate as a function of impact angle and hardness will be discussed.

2. Experimental Procedures

2.1. Experimental Material and Heat Treatment

The raw materials with dimension 200 mm×150 mm×17 mm were first homogenized to eliminate the segregation by holding at 1000°C for 24 h, and then air cooling down to ambient temperature. The chemical compositions analyzed by wavelength dispersive spectrometer (WDS) are shown in Table 1.

After homogenization, the steels were cut into 50 mm×35 mm×6 mm shapes for erosion tests and dimension 20 mm×20 mm×6 mm for metallographic examination and hardness tests. These specimens were austenitized at 1010°C for 2 h, followed by air quenching, and then double-tempered at 200, 300, 400, 500, and 600°C, respectively. The heat treatment procedure is shown in Fig. 1.
2.2. Erosion Tests

The specimens for erosion tests, after the above heat treatments, were polished with 800-grit SiC paper to remove surface scales. These samples were then subjected to erosion wear test. The erosion tests were conducted in a typical sand-blast type of test rig with a 5 mm size nozzle. The Al₂O₃ particles about 177 μm in size and irregular in shape were used as the erodent. Erodent particles were fed to the test rig at a constant rate of 600 g/min by using a pressurized carrier gas of 0.3 MPa, whereas the erosion velocity at a distance from the nozzle tip of 30 mm was 83.2 m/s estimated by a single-shot high-speed photography. The erosion stream being directed to impinge in the sample surface at different angles of 15°, 30°, 45°, 60°, and 90°; while the amount of erosion particles was 6000 g for each experience run. Each erosion datum was the average of at least three test results. The samples were ultrasonically cleaned in acetone before weighting.

Short-term erosion tests were also conducted on alternative erosion specimens with each impact angle to characterize the erosion wear mechanism. These samples were pre-polished and pre-etched in Fry reagent, then eroded by a total of 5 g Al₂O₃ particles after the compressed air flow reaching steady state.

2.3. Metallography

After polishing and etching with Fry reagent, the metallography specimens were used to examine the microstructure by utilizing scanning electron microscopy (SEM) and optical microscopy. SEM was also applied to observe the surface and subsurface of the eroded specimens for the evaluation of the fracturing mechanism. The electron probe microanalyzer (EPMA) and WDS were used to estimate the chemical composition distribution and content at individual phase in matrix of metallography specimens.

2.4. Hardness Tests

Microhardness tests were performed at phase of martensite and ferrite in the matrix of hardness samples using standard Vickers diamond pyramid hardness testing machine with 100 g indentation load. Before testing, the specimens were polished and etched in the same way as for the metallographic examination. Bulk hardness was also measured by Rockwell hardness tester. All the Rockwell hardness readings were converted to Vickers hardness numbers. At least five hardness reading were taken, and then averaged.

3. Results and Discussion

3.1. Microstructure and Chemical Composition

A typical microstructure of the raw material is shown in Fig. 2(a), which shows a banded microstructure consisted of martensite and connecting ferrite. The characteristic of banding is no more obvious after homogenizing at 1000°C for 24 h, as shown in Fig. 2(b). At this condition, the ferrite is dispersed over the matrix fragmentally. After tempering at 200°C, some ferrite islands are found in martensite plate, as shown in Fig. 2(c). The forming of low carbon ferrite
means that the martensite had decomposed into tempered martensite and chromium-rich carbide. The result of line scan by EPMA also suggests the distribution of C and Cr both being more turbulent than that of Fe, providing the evidence for precipitation of carbides. These carbides were identified as Cr$_2$C$_6$ by Miao. Similar phenomenon is also observed in other specimens tempered within 300–500°C, whereas the precipitation of alloyed carbide increases with increasing tempering temperature up to 500°C; while tempered at 600°C, the carbide decreases and the ferrite island increases (Fig. 2(d)), and this leads to the decreasing in hardness.

The content of C and Cr variations in individual phase of martensite and ferrite for the different heat treatment specimens and raw material are shown in Fig. 3. The content of element C in martensite is higher while the element Cr is enriched in ferrite after homogenizing. During tempering, both content of C and Cr are larger than those in the samples treated by homogenizing. This supports reasonably that the precipitation of chromium-rich carbide described in Fig. 2(c). These carbides precipitate both in the phase of martensite and ferrite since the contents of C and Cr over there in each case are higher than the average content in the bulk material as list in Table 1. The higher content of C and Cr with the higher tempering temperature in the range of 200 to 500°C implies that larger amount of carbides are precipitated. This situation also can be seen from the careful metallography observation.

### 3.2. Hardness Analysis

Figure 4 shows the hardness variations for the different heat treatment samples. When the hardness data of tempering specimens is compared with that of specimen after homogenizing, the harden effect of martensite is more obvious than that of the ferrite. Both bulk material and individual phase of martensite and ferrite exhibit similar tendencies, which indicates that the hardness first increases with increasing tempering temperature up to 500°C and then decreases, a typical secondary hardening behavior. The secondary hardening mechanism is due to alloy carbides precipitating in the phase of martensite and ferrite. The increase in hardness is agreement with the increase in amount of carbides after tempering between 200°C and 500°C.

### 3.3. Short-term Erosion Tests

The scanning electron micrographs of short term erosion tests are shown to assist better understanding the erosion wear mechanism as in Fig. 5. The surface of low impact angle (15°) sample shows long and narrow groove, in
which cutting chips can be found at the side of the groove along the blast stream direction (Fig. 5(a)). The wider cutting groove is formed while the impact angle is at 30° (Fig. 5(b)). The surface of the specimen at the impact angle of 45° shows a mixture of cutting groove and extrusion crater (Fig. 5(c)). Erosion tests at 60° and 90° reveal extrusion of lips and cracks, where the deformation band goes along with the side of lips also presented (Fig. 5(d)). It is therefore reasonable to summarize that the wear mechanism for lower than 30° is dominated by cutting; for the angle higher than 45° is based on extrusion and cracking; and a transition of mechanism mixed by cutting and extrusion occurs between 30° and 45°.

3.4. Erosion Data

The results of erosion test of SUS403 with the different heat treatment are shown in Fig. 6. All five heat treatment specimens exhibit similar erosion rate at the impact angle less than 30°. Because cutting is effective in both phases of martensite and ferrite, this dominating mechanism is revealed as shown in Figs. 5(a) and 5(b), in which the eroding pieces are taken away by cutting. Another reason is that the matrix of experimental materials consists of martensite and fragmented ferrite. When they are mixed, the erosion rate difference between martensite and ferrite of the mixed phase due to the effect of hardness difference is less than that between the single phase matrix martensite and the single phase matrix ferrite. Therefore, all five specimens get the similar erosion rate even their bulk hardness are different. As the impact angle exceed 30°, the erosion rates of 400°C and 500°C tempered specimens are higher than that of the others. The grain boundary embrittlement of samples tempered at 400°C and 500°C is derived from the tempered martensite embrittlement effect, which leads to the erosion rate increasing. The maximum erosion rate occurs at the angle between 30° and 45°, which implies that the two-phase material mixed with martensite and soft ferrite causes the angle of maximum erosion rate being neither close to 15–30° observed in ductile materials\textsuperscript{14,10,18} nor at normal angle reported in brittle materials\textsuperscript{19,20}.

At lower impact angle (15° and 30°), the resolved shear stress is higher, that provides a cutting force to take material pieces away. In this case, the cutting groove is shallow and the material loss and erosion rate are lower. For higher impact angle (60° and 90°), the resolved normal stress is higher, that provides bigger indented force but the material pieces can not be taken away, and as a consequence, the formation of extrusion lip causes erosion rate less than that of the medium impact angle (30–45°). For medium impact angle, the resolved shear stress and resolved normal stress is close to equal, those appropriate taking away force to remove the cutting chips and extrusion lips, which in turn raised the erosion rate.

The relationship between the erosion rate of the experimental materials and their hardness is shown in Fig. 7. At 15° and 30° of impingement, the erosion rate is virtually independent of hardness, which causes the effect of hardness on erosion rate leveling off. While impact angles exceed than 30°, increasing hardness leads the increasing erosion rate. Figure 7 reveals that the wear mechanism at impact angle of 15° and 30° is dominated by cutting; for the angle higher than 45°, the wear mechanism is based on extrusion or cracking; and at the angle 30–45°, a gradual shift in the slope of the curves presents a transition in the dominated mechanism for erosion.

3.5. Examination of Eroded Samples

The worn surfaces of the specimen tempered at 500°C are shown in Fig. 8, and those were erosion tested by 6000 g of particle. The cross-sectional views of these samples reveal more information about the wear mechanism, as shown in Fig. 9. The results are similar to the short-term erosion tests. Low impact angle erosion causes long and narrow cutting grooves with no surface crack, as shown in Fig. 8(a). However, some boundary cracks due to the effect of tempered boundary embrittlement are close to the worn surface in Fig. 9(a), which affected by the resolved shear stress. For the medium impact angle, the equal of resolved shear stress and resolved normal stress produces cutting grooves and extrusion lips, where the craters and surface cracks are found (Fig. 8(b)). Figure 9(b) shows that the sample undergoes plastic deformation nearby the surface, and both surface cracks and boundary cracks are observed. The boundary cracks formed at the site far away from the worn surface, which are resulted by interaction of resolved shear stress and resolved normal stress on martensitic grain boundary. When these cracks become connected, that causes the material to remove further, therefore the erosion rate raise. In high impact angle, resulting in normal stress, fine surface cracks occur at the martensite grains, and extrusion lips form by indentation, as shown in Fig. 8(c). The severe plastic deformation and boundary crack also appear as in Fig. 9(c), as a consequence, these eroded pieces remove difficult than that impinged at medium angle due to the lower shear stress, thus, the erosion rate reduces. Further, the
cracks are observed in other samples with different tempered treatments. For two-phase material, the grain boundary provides the initiation and propagation sites of cracks. Therefore, cracking is one of the major wear mechanisms in erosion tests.

4. Conclusions

The particle erosion of SUS403 MSS, processed with different tempering treatment was studied in this paper. The following conclusions are drawn.

1. After homogenizing, the microstructure of SUS403 consisting of martensite and fragmental ferrite phases are presented. Meanwhile, the content of element C in martensite is higher and the element Cr is enriched in ferrite. When those materials treated with tempering, both increase of C and Cr with increasing in the tempering temperature range of 200 to 500°C implies that larger amount of alloyed carbides are precipitated. Finally, secondary hardening of the material occurs at 500°C.

2. For all the experimental materials, cutting is the dominated mechanism for material removal at oblique impact angle. In this case, the morphology of the surface damage is long and shallow cutting grooves. At the higher impact angle, the mechanism is based on extrusion and cracking. However, at the medium impact angle, the wear is dominated by transition of mechanism mixed with cutting and extrusion. Both features of grooves and indentation craters associated with cracking are observed.

3. The erosion rate of all the experimental materials is increased first and then decreased with increasing in impact angle. The maximum erosion rate occurs at the angle between 30° and 45°. At the impact angle less than 30°, all five heat treatment materials exhibit similar erosion rate due to the cutting is the dominating mechanism in both phase of martensite and ferrite.

4. At 15° and 30° of impingement, the erosion rate is virtually independent of hardness. While impact angles exceed than 30°, erosion rate increases with increasing hardness. The effect of hardness on erosion rate exhibits a sudden change at the angle 30–45°, that corresponds to a transition in the dominated mechanism for erosion.

5. For two-phase material consisting of tempered martensite and ferrite, cracking at the grain boundary and in the martensitic matrix is the general erosion mechanism. The connection of these cracks causes the material to remove further. These two phases mixed in the matrix produces that the effect of hardness of individual phase on erosion rate decreases.

Acknowledgements

The author thanks the National Science Council (Taiwan,

REFERENCES