Erosion Behavior of CA-15 Tempered Martensitic Stainless Steel

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Martensite stainless steel (MSS) possesses excellent strength and medium corrosion resistance, and is often used in industrial applications, such as for highly stressed parts like turbine blades and pipe materials. However parts are often damaged by flow field particles interact with the materials, in a solid particle erosion (SPE) phenomenon, which may even lead to injuries. In this paper we discuss the effects of the tempering treatment and the erosion incident angle on the CA-15 MSS erosion behavior. The results show that, in single particle erosion tests, the main mechanisms that cause problems are micro-cutting and deformation craters at low and high incident angles, respectively. In repetitive particle erosion tests, grain boundary cracking is one of the main fracture mechanisms. The platelet mechanism also obvious affected at high incident angle erosion. Materials tempered at 573–673 K, tempered martensitic embrittlement (TME) occurred, which caused serious boundary cracking and grain broken-down. The serious erosion damage showed at medium incident angle for this material that result in combine of cutting, deformation crater, and cracking mechanism. The maximum erosion rate of material occurred at an incident angle of $\pi/6$ and the deepest erosion penetration occurred at an incident angle of $\pi/4$.

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1. Introduction

CA-15 martensitic stainless steel (MSS) possesses excellent strength, corrosion resistance, and erosion resistance, which is the similar grade to wrought AISI 410 stainless steel. This material has good cast-ability and is widely used in highly stressed and complex shape parts, such as turbine blades, pipe or tube materials, valve body, and ship propellers. In general, this material is always heat treated by austenitizing and tempering processes for industrial application, which induce moderate mechanical properties.

The flowed carrier in transported pipe or turbine (such as powder, sand, or mineral, residue on sanitary sewer) or dust in environment impacted the turbine blade, that solid particles interactive with material cause the weight loss of material, thinner of pipe wall, crack of components, even damage of parts. Some researchers²–14) have discussed erosion mechanisms for some metallic materials. They utilized mechanics analysis to get results, which are summarized as follows: cutting erosion occurs at a low incident angle and deformation erosion occurs at a high incident angle.²–⁸) The erosion damage can be serious at low incident angles for ductile materials, and at high incident angles for brittle materials.²,⁴,⁵) In addition, the resolved shear stress of particle impact provides the force for cutting, boundary cracking of material, and the eroding away of pieces.²–⁶,⁸) The resolved normal stress provides the force for plastic deformation²–⁷) (which causes lipping,²,⁷,ⁱ⁰) ridging,⁹) and cratering²,⁹,¹⁰) , surface and sub-surface cracking,¹⁰) and platelet.²,⁹,¹⁰) The related erosion mechanisms are description as follow: material lipping was produced by oblique impact, and was finally detached along shear band. Ridge of material was formation by extruded at the back of the crater and the slip band always shown at the side of ridge. The erosion crater was produced by a deformation that produced by shear stress was smear crater and by normal stress was indentation-like crater. Material platelet mechanism was produced by extrusion and forging due to repeated impact¹⁰) and some discussion²–⁹) about platelet mechanism was assertion that surface temperature rise due to erosion leads to softening of the near-surface region so that a layer of work-hardened material beneath this acts as an anvil against which the softer material is deformed. In the multi-phase material, the erosion rate is decreased with hardness of matrix²,⁴,⁵,¹⁰,¹²) but the result opposite from Hung.¹³) The only few¹⁴) report discussed with solid particle erosion (SPE) behavior for MSS but no paper was about the erosion of CA-15 MSS. It is thus the purpose of our research to study the erosion mechanisms affecting CA-15 MSS specimens after different tempering treatments.

2. Experimental Procedures

2.1 Material and heat treatment

The material was cast into 240 mm × 80 mm × 18 mm Y-block molds using regular foundry practices. The chemical composition of the material was analyzed by a glow discharge spectrometer (GDS) using a chilled sample. The steel was then cut and machined in preparation for the heat treatment and specimen testing. Specimens were austenitized at 1283 K for 14.4 ks followed by air quenching, then double-tempered at 573, 673, 773, and 873 K, respectively. The heat treatment procedure is shown in Fig. 1.

![Heat treatment conditions in this experiment.](image-url)
2.2 Erosion test

The dimensions of the experimental specimens for erosion tests were either $35 \text{ mm} \times 35 \text{ mm} \times 5 \text{ mm}$ or $35 \text{ mm} \times 60 \text{ mm} \times 5 \text{ mm}$. The former size was used for the high incident angle ($\pi/3, \pi/2$) tests and the latter for the low incident angle ($\pi/12, \pi/6, \pi/4$) tests. The erosion operating parameters were as follows: the erosion incident angles included $\pi/12, \pi/6, \pi/4, \pi/3$, and $\pi/2$; the amounts of erosion particles were 5 g and 6000 g, respectively; the erosion pressure was maintained at a constant value (3 kg/cm$^2$) by an air compressor; a $\phi5$ mm size nozzle was employed; and the erosion velocity at a distance from the nozzle tip of 30 mm (practical erosion distance) was 83.2 m/s. The eroding carriers were $\text{Al}_2\text{O}_3$ particles about 177 $\mu$m in size and irregular in shape.

2.3 Microstructural analysis

Scanning electron microscopy (SEM) and optical microscopy (OM) were utilized to examine the material’s microstructure. The specimens were polished and etched with Vilella’s reagent (5 ml HCl + 1 g Picric + 100 ml ethanol). SEM was also applied in order to observe the surface and subsurface of the eroded specimens for the evaluation of the fracturing mechanism. The penetrating depth of damaged samples after erosion testing was measured using a non-contact CNC laser measurement machine. For clear observe the erosion cavity contours, the measurement data were then transferred from concave to convex by a computer software package.

2.4 Hardness test

Hardness tests were performed at the different phases in the matrix and on the bulk sample using the Vickers (100 g) and Rockwell hardness testers, respectively. All the Rockwell hardness readings were converted to Vickers hardness numbers. Prior to hardness testing the specimens were polished and etched in the same way as for the metallographic examination. Five hardness readings were taken and averaged, to produce the heat-treatment data.

3. Result and Discussion

3.1 Chemical composition and microstructure

The chemical composition of the experimental material is given in Table 1. The as-cast microstructure, shown in Fig. 2(a), consisted of the mixed phases of ferrite and martensite.
and carbides that precipitated at the grain boundaries. These precipitates were evaluated and determined to be Cr$_2$C$_6$, similar to those observed in the AISI 403 stainless steel made by Miao. However, we were able to eliminate them by austenitization at 1283 K for 14.4 ks (Fig. 2(b)). After tempering at 673 K, the martensite had decomposed into tempered martensite and chromium-rich carbides, as shown in Fig. 2(c). Tempering at 773, 873 K, caused the carbides to disappear and ferrite islands to precipitate from the martensite positions (Fig. 2(d)).

### 3.2 Hardness analysis

The hardness variations for the different heat treatment specimens are shown in Fig. 3. Secondary hardening of the whole piece of material and the martensitic phase occurred at 623 K, while the ferritic phase was delayed until 773 K. The secondary hardening mechanism of the martensitic phase was due to the alloy precipitating in the martensitic area. For the ferritic phase it was due to spinodal decomposition.

### 3.3 Single particle erosion mechanism

Figure 4 shows a diagram of the single particle erosion mechanism along with the SEM micrographs. The surface of the low incident angle ($\pi/12$) specimen shows long, narrow grooves and lipping at the side of the softer ferrite phase (Fig. 4(a)). The surface of the medium incident angle ($\pi/6$) erosion specimens shows a mixture of cut grooves and smear craters (Fig. 4(b)). High incident angle (over $\pi/4$) erosion caused indentation-like craters, with a ridge being extruded at the back of the crater (Fig. 4(c)). The slip band goes along with the side of ridge is also shown in Fig. 4(c). Therefore, the erosion mechanism was followed from cutting, mixture of cutting and smear crater, to indentation-like craters with the resolved normal stress increased.

### 3.4 Repetitive particle erosion

#### 3.4.1 Erosion damage

Table 2 and Fig. 5 show the erosion rate and the penetration depth of the 6000 g particle amounts used to test specimens after the different heat treatments and at different incident angles. The maximum erosion rate occurred at an incident angle of $\pi/6$, as shown in Fig. 5(a) and the deepest penetration depth occurred during an incident angle of $\pi/4$, as shown in Fig. 5(b). The erosion rate of the 573 and 673 K tempered specimens was higher than that of the 773 and 873 K tempered specimens. The grain boundary embrittlement of specimens tempered at 573 and 673 K was derived from the tempered martensitic embrittlement (TME) effect, which was the result to cause the erosion rate raised.

For the high incident angle erosion ($\pi/3$ and $\pi/2$), the resolved normal stress is higher, that provides bigger indented force but the eroding pieces can not been taken away at repetitive erosion. The eroding pieces, lips and ridges re-forged into base material that cause erosion rate and penetrant depth reduce. For low incident angle erosion ($\pi/12$), the resolved shear stress is higher, that provides a bigger force to take eroding pieces away but the cutting is shallow. For medium incident angle erosion ($\pi/6$ and $\pi/4$), the resolved shear stress and resolved normal stress was close to equal, the erosion mechanism combined with cutting, boundary cracking, grain pieces broken down, deformation craters, and appropriate taking away force, which in turn raised the erosion damage. The resolved normal stress is bigger at the incident angle is $\pi/4$ that causes the deeper penetrant. Another reason of the maximum erosion rate and deepest erosion penetration depth occurred at different erosion incident angle is illustrated in Fig. 6. The erosion rate is defined as weight loss of material divided by total weight of erosion particle. Consideration the erosion action area is the intersectional plane between an inclined plane and a cone. The action area decreased followed with the incident angle increased. There are the similar erosion mechanism at medium incident angle furthermore the action area was bigger at incident angle was $\pi/6$. Therefore, at the same erosion amount, the heavier weight loss and erosion rate while bigger action area (incident angle is $\pi/6$) and the deeper penetrant depth while smaller action area (incident angle is $\pi/4$).

#### 3.4.2 Surface appearance

Figure 7 show the diagrams of the mechanism of repetitious particle erosion, and SEM micrographs of the surface appearance of specimens tempered at 873 K, that were erosion tested by 6000 g of particles. The results were similar to the single particle erosion tests, low incident angles...
Fig. 4 Schematic mechanism diagram of single particle erosion and SEM micrographs of samples tempered at 873 K at variant incident angle (a) low incident angle, (b) medium incident angle, (c) high incident angle.

Table 2 Erosion rate and erosion penetrant depth for the resulting materials.

<table>
<thead>
<tr>
<th>Erosion Angle</th>
<th>As-cast</th>
<th>Austenitized</th>
<th>Tempered at 573 K</th>
<th>Tempered at 673 K</th>
<th>Tempered at 773 K</th>
<th>Tempered at 873 K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate, g/kg</td>
<td>Depth, mm</td>
<td>Rate, g/kg</td>
<td>Depth, mm</td>
<td>Rate, g/kg</td>
<td>Depth, mm</td>
</tr>
<tr>
<td>$\pi/2$</td>
<td>0.140</td>
<td>1.40</td>
<td>0.159</td>
<td>1.80</td>
<td>0.125</td>
<td>1.45</td>
</tr>
<tr>
<td>$\pi/3$</td>
<td>0.206</td>
<td>2.62</td>
<td>0.219</td>
<td>3.12</td>
<td>0.199</td>
<td>2.44</td>
</tr>
<tr>
<td>$\pi/4$</td>
<td>0.222</td>
<td>3.96</td>
<td>0.269</td>
<td>3.57</td>
<td>0.285</td>
<td>3.85</td>
</tr>
<tr>
<td>$\pi/6$</td>
<td>0.255</td>
<td>2.20</td>
<td>0.301</td>
<td>2.42</td>
<td>0.335</td>
<td>2.31</td>
</tr>
<tr>
<td>$\pi/12$</td>
<td>0.249</td>
<td>1.06</td>
<td>0.298</td>
<td>1.43</td>
<td>0.315</td>
<td>1.11</td>
</tr>
</tbody>
</table>

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erosion produced long, narrow cutting grooves and high incident angle erosion produced indentation-like craters. In addition, the lips and ridges that formed during cutting or plastic deformation that provided important platelet mechanism sources.

3.4.3 Sub-surface appearance
The SEM micrographs of the subsurface of the 573 K tempered specimens, that were erosion tested using 6000 g of particles at different incident angles, are respectively shown in Figs. 8(a)–(f). Obvious cracks occurred at the martensitic grain boundary during low incident angle erosion, resulting in the production of tempered boundary embrittlement, which affected by the resolved shear stress of the erosion force. In the medium incident angle erosion, the SEM micrographs of the subsurface also showed this cracking mechanism. Some of the cracks extended from the surface to the subsurface, while others originated from the subsurface. These cracks became connected which caused the material to break down further. Fine surface and subsurface cracks occurred at the martensitic grains during high incident angle erosion, induced by the resolved normal stress. Cracking therefore was one of the major mechanisms involved in repetitious erosion fracturing for all tempering treatments. For the two-phase material, the grain boundary provides the cracking site during erosion impact. Figures 8(e,f) shows an approximately 10 μm thick plastic deformation layer that was a result of the high incident angle erosion platelet mechanism.

3.4.4 Erosion cavity contours
The erosion cavity contours of samples tempered at 673 K after being subjected to different erosion incident angles are shown in Fig. 9. Long and narrow but symmetrical erosion cavities can be found on the low erosion incident angle samples, while the cavity contours tended toward a Gaussian distribution as the incident angle increased. The base plane of cavity contours compare to the Fig. 6 also shows approximately.

4. Conclusion

The erosion behavior of CA-15 MSS, after different tempering treatments was studied in this paper. The following conclusions were drawn.

(1) The as-cast microstructure of CA-15 MSS consists of martensitic and ferritic phases in the matrix, and carbides that precipitate around the martensitic grain boundaries. These precipitates could be eliminated by a 1283 K 14.4 ks austenitizing treatment. In addition, secondary hardening of the material occurred after a 673 K tempering.

(2) After the single and repetitive particle erosion, respectively, the morphology of the surface damage was found to include: long and shallow cutting from low erosion incident angle erosion; short, deep cutting and smear craters from medium incident angle erosion; and indentation craters and platelet formation from high incident angle erosion.

(3) From the subsurface examination of fractured specimens it was determined that cracking at the grain boundary and in the martensitic matrix were the main
Fig. 7 Schematic mechanism diagram and surface SEM micrographs of samples tempered at 873 K, while tested by 6000 g repetitious erosion at variant incident angle (a) low incident angle, (b) medium incident angle, (c) high incident angle.
Fig. 8 Subsurface SEM micrographs after 6000 g erosion tested (a) 573 K tempered-π/12 erosion, (b) 873 K tempered-π/12 erosion, (c) 573 K tempered-π/4 erosion, (d) 873 K tempered-π/4 erosion, (e) 573 K tempered-π/2 erosion, (f) 873 K tempered-π/2 erosion.
erosion mechanisms. These cracks became connected, causing the material to break down further during later erosion.

(4) The maximum erosion rate occurred at an erosion incident angle of $\pi/6$, and the deepest erosion penetration occurred at an erosion incident angle of $\pi/4$.

(5) For materials tempered at 673 K, secondary hardening and TME occurred, which intensified cracking at the grain boundary and in the martensite grains, which caused the erosion damage to increase.

(6) The eroded cavities had long and narrow ridges that were symmetrical on both sides for low incident angle erosion, but tended towards a Gaussian distribution for high incident angle erosion.

Acknowledgments

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REFERENCES


Fig. 9  Erosion cavity contours of the samples tempered at 673 K and erosive tested on variant incident angle (a) $\pi/12$, (b) $\pi/6$, (c) $\pi/4$, (d) $\pi/3$, (e) $\pi/2$. 