Erosion Resistance of Stellite Alloys under Solid-Particle Impact

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Abstract: Selected Stellite alloys, which are currently or potentially employed in an environment involving erosion, are studied under solid-particle erosion test. These alloys include high-carbon Co-Cr-W system and low-carbon Co-Cr-Mo system. Two particle impact velocities (84 m/s and 98 m/s) and two impingement angles (30° and 90°) are used in the test. It is shown that Stellite alloys are more resistant to erosion at 90° impingement angle than at 30° impingement angle and the weight losses of Stellite alloys increase with the particle impact velocity. The erosion resistance of Stellite alloys is controlled mainly by their carbon content, but tungsten and molybdenum contents also play an important role in the erosion resistance of these alloys, because these elements determine the volume fractions of carbides and intermetallic compounds in the alloys. The eroded surfaces are analyzed using SEM to further understand the erosion test results.

Key words: Solid-particle erosion, Stellite alloy, hardness, particle impingement angle, particle impact velocity.

1. Introduction

Stellite alloys are a family of cobalt-based alloys containing a large amount of chromium, Cr (20 ~ 30 wt.%), medium tungsten, W (4 ~ 18 wt.%) or molybdenum, Mo (up to 28 wt.%) and a small amount (< 3 wt.%) of carbon, C [1]. These alloys display excellent corrosion and oxidation resistance [2-5] due to the high Cr content and a unique combination of mechanical and tribological properties such as high hardness and strength, superior wear resistance and excellent solid particle and cavitation erosion resistance because of their chemical compositions and microstructural features [6-8]. Owing to the presence of carbon, stellite alloys are generally strengthened by the precipitation of carbides in the cobalt solid solution matrix [9], and the carbon content significantly affects the performance and properties of Stellite alloys such as wear resistance, ductility and fracture toughness, because it determines the volume fraction of carbides in the alloys. For example, high-carbon Stellite alloys are very hard (HRC50 ~ HRC60) and resistant to severe wear under poor or unlubricated conditions while low-carbon ones are relatively soft (~HRC30) and good for high temperature service and are excellent to combat corrosion or simultaneous corrosion and wear [1].

Erosion wear is one of the popular wear modes, which occurs in three categories: solid-particle erosion, slurry erosion or liquid-solid particle erosion, liquid-droplet erosion and cavitation erosion [10]. Solid-particle erosion, which is caused by the impingement of small solid particles against a surface, in some cases, is a useful phenomenon, as in sandblasting and high-speed abrasive water jet cutting.
but it is a serious problem in many engineering systems, including steam and jet turbines, pipelines and valves carrying particulate matter, and fluidized bed combustion systems [11], because it causes the loss of materials. With the complex mechanisms of the erosions, however, the general abrasion mechanism may not be warranted. For instance, in solid-particle erosion, ductility of Stellite alloys can also be a factor characterizing their erosion resistance, in addition to the carbide volume fraction thus bulk hardness [1].

There are several impact parameters that influence the erosion damage of any particular material. The extent to which each parameter contributes to the erosion damage would depend on the environmental conditions together with the type of material under investigation. However, the main impact parameters are generally known to be impact angle, particle velocity, particle size, shape and properties of both the abrasive particles and the target material under consideration [12-15].

Although Stellite alloys have largely served in the environments subjected to erosion, the research in erosion behavior, particularly, in solid-particle erosion behavior of these alloys has been rarely reported, due to the limitation of testing facilities/methodologies and the complexity of analytical methods. Relationships between erosion resistance, chemical composition and microstructure for Stellite alloys have never been studied systematically. Levin et al. [16] investigated the solid-particle erosion behaviour of several weld overlay coatings that included cobalt-based alloys, nickel-based alloys and iron-based alloys, but only one Stellite alloy: Stellite 6 from the cobalt-based alloy group was under the investigation. Thus it was impossible to find the correlations among these properties, based on the experimental data of only one alloy. Also, the impingement angle dependence erosion for Stellite alloys has not yet been investigated. However, these data will help in the understanding of the damage of these alloys under different erosion conditions. The lack of knowledge in these aspects is significantly limiting the proper use of Stellite alloys in erosive environments. It is more prevalent that applications in increased severe environments push engineered materials to their limits, therefore a better understanding of these relationships involving chemical composition, microstructure, hardness and erosion for Stellite alloys is crucially required, and hence it is the emphasis of this research.

2. Experiments

2.1 Stellite Alloy Specimens

Five Stellite alloys, which are currently or potentially used in industrial erosive environments, were selected in this study. Their chemical compositions are given in Table 1. The specimens of alloy A and alloy B were fabricated by a forging process and those of the others by a centrifugal casting process. These alloys have a carbon content in the range between 0.25 ~ 1.6 wt.%, chromium content between 22 ~ 30 wt.%, tungsten content between 4 ~ 32 wt.% except alloy D and alloy E which do not contain tungsten. These two alloys contain the least carbon contents of 0.35 wt.% and 0.25 wt.% but high molybdenum contents of 11.8% and 11%, respectively. Alloy A, alloy B and alloy C belong to medium-carbon Stellite alloys while alloy D and alloy E fall into low-carbon Stellite alloys. Alloy D further contains an additional 2.07 wt.% niobium, Nb, which is added to improve the high temperature performance [17].

The microstructure analysis of these alloy specimens was performed on a Scanning Electron Microscope (SEM) with an EDAX energy dispersive X-ray (EDX) spectroscopy system; the obtained images are shown in Fig. 1. Stellite alloys have a microstructure typically

<table>
<thead>
<tr>
<th>Element</th>
<th>Alloy</th>
<th>Cr</th>
<th>W</th>
<th>Mo</th>
<th>C</th>
<th>Fe</th>
<th>Ni</th>
<th>Si</th>
<th>Mn</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy A</td>
<td>30</td>
<td>4.5</td>
<td>1.5</td>
<td>1.6</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alloy B</td>
<td>30</td>
<td>4</td>
<td>1.5</td>
<td>1</td>
<td>3</td>
<td>2.5</td>
<td>0.7</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alloy C</td>
<td>22</td>
<td>32</td>
<td>0</td>
<td>1.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alloy D</td>
<td>24.2</td>
<td>0</td>
<td>11.8</td>
<td>0.35</td>
<td>1</td>
<td>3.8</td>
<td>0.45</td>
<td>0.52</td>
<td>2.07</td>
<td>Nb</td>
</tr>
<tr>
<td>Alloy E</td>
<td>27</td>
<td>0</td>
<td>11</td>
<td>0.25</td>
<td>3</td>
<td>2.75</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. 1  SEM microstructures: (a) alloy A; (b) alloy B; (c) alloy C; (d) alloy D; (e) alloy E.
Some arrows in Fig. 1 do not point to correct phases. The annotations in this figure are not well located.

consisting of complex hard carbides (mostly Cr-rich carbides) dispersed in a tough cobalt solid solution matrix mainly containing Cr and W or Cr and Mo. Alloy A and alloy B have a similar microstructure consisting of two phases, as shown in Figs. 1a and 1b; primary Co solid solution and eutectic carbide Cr7C3. However, because of the higher carbon content, alloy A has a larger volume fraction of carbides but the sizes of the carbides are relatively small compared to those of alloy B. Alloy C has a microstructure containing three
phases, as shown in Fig. 1c. Due to the high W content, this alloy has primary (W, Co)₂C carbide and eutectic mixture consisting of Co solid solution and carbide Cr₂C₃. Alloy D and alloy E all contain very low carbon content so that they have a small volume fraction of carbides. However, owing to the high Mo content, these alloys contain the intermetallic compounds of Co₃Mo and CoMo₆. As shown in Fig. 1d, the microstructure of alloy D consists of primary Co solid solution and the eutectic containing Cr₂C₃ carbide and the intermetallic compounds of Co₃Mo and CoMo₆. Moreover, secondary carbide precipitates of Cr₂C₆ are found in this alloy. Alloy E has a microstructure consisting of primary Co solid solution and the eutectic including Cr₂C₃ carbide and the intermetallic compounds of Co₃Mo and CoMo₆, as seen in Fig. 1e.

2.2 Solid-Particle Erosion Test

The specimens for erosion test were rectangular blocks of 3 × 1 × 0.125 inch. The specimen surfaces for test were polished with silicon carbide (SiC) abrasive paper having a 320# grit size. The erosion test was conducted in ambient temperature environment according to the ASTM G76-02 standard test method for conducting erosion tests by solid particle impingement using gas jets [18]. The distance between the nozzle head and specimen surface was set based on the hardness of the tested Stellite alloys such that reasonable damage could be identified on the specimen surfaces with the set test duration of time. According to the hardness of Stellite alloys (HRC38 ~ HRC57), the distance was set to be 5 mm. The specimen holder contains a screw that allows for the specimen to be adjusted and rotated at various angles so as to correspond to different impingement angles in the test. Two typical impingement angles, α = 30° and 90°, as illustrated in Fig. 2, were used for each alloy at each particle impact velocity, in order to investigate the change of erosion behavior of these alloys at different particle impingement angles. The duration time of each test was set to be 10 min, which was measured via a stopwatch. The voltage controller was adjusted to a values between 4 ~ 6 V, which could achieve a particle flow rate in the range of 0.70 ~ 1.28 g/min at two particle impact velocities of 84 m/s and 98 m/s. The erosion test unit containing erodent particles (sand) was placed on a scale throughout the test process; the mass of this unit was recorded before and after running each test. Thus the amount of sand used in each test could be quantified by taking the difference between these two values. The sand (erodent particles) used for this test was aluminum oxide and angular in shape, as shown by the SEM image in Fig. 3, with the hardness of ~HRC70.

One location was selected on each specimen and tested four times at a same particle impact velocity and impingement angle. The duration of time for each test

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**Fig. 2** Schematic diagram depicting the impingement/impact angle.

**Fig. 3** SEM morphology of erodent particles - angular alumina powder.
was 10 min. Before the test each specimen was weighed and after each test the specimen was cleaned and weighed again, thus the weight loss (erosion loss) of the specimen material due to the erosion could be obtained. The purpose of selecting a same location on each specimen for repeated tests was to simulate the real service scenario of Stellite alloys under solid-particle erosion, for example, in the case of gas turbine the blades are impacted by dust particles ceaselessly once the engine is turned on. Three specimens were tested for each alloy in each test condition (impingement angle and impact velocity). The final results of erosion loss for each alloy under each test condition are the averages of twelve test results.

3. Results

3.1 Erosion Loss

The averages of mass loss for each specimen were calculated from the differences of specimen weight before and after testing. It was found that for each test condition there was no significant difference in erosion loss between the first test and repeated tests on the specimen. This implies that the top surface layers of the specimens were removed quickly once the particles impacted the surfaces so that the surface conditions of the four tests on a specimen can be considered the same. Once the amount of sand used (g) in each test was computed from the mass difference of the test unit containing aluminum oxide particles (sand) before and after testing, this value was used together with the erosion time recorded (10 min) to calculate the sand (erodent particle) flow rate in g/min. The amount of sand used (g) per test was taken together with the specimen mass loss (µg) to calculate the material erosion loss per gram of sand or impact particles used (µg/g). To predict the errors of the test results, the statistics analysis tool of the standard deviation, σ, was computed for the erosion loss results of each test condition using the equations below:

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \quad \text{and} \quad \sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}
\]

where \(x_i\) = erosion loss of test \(i\), and \(n\) = number of test; in this analysis, \(n = 12\). Assuming a normal distribution of the erosion loss results for each test condition, the average erosion loss results are plotted in Fig. 4, accompanied with 3σ, that is, within 99.73% confidence range (mean value \(\mu \pm 3\sigma\)). Erosion loss can also be expressed in volume loss. Using the alloy density data in Table 2, the erosion volume losses of the tested alloys were obtained and the values are illustrated in Fig. 5.

From the erosion loss results, firstly, all the alloys exhibited higher erosion resistance at 90° angle impact than at 30° angle impact regardless of particle impact velocity. Secondly, at 30° angle impact, in general, the alloy that had higher content of carbon was more resistant to erosion. For example, among the alloys being studied, alloy A contained the highest amount of carbon so that it displayed the best erosion resistance, followed by alloy C that had the highest content of carbon among the rest. On the contrary, alloy E that had the lowest carbon content showed the worst erosion resistance in the test condition of 30° angle impact and 84 m/s impact velocity, but at 98 m/s impact velocity this alloy exhibited better erosion resistance than alloy D which contained higher level of carbon. Thirdly, at 90° angle impact, it seemed no direct relationship between chemical composition and erosion resistance for these alloys. Finally, the erosion losses of the alloys increased with particle impact velocity. This can be explained as when the particle

| Table 2  Density data of Stellite alloys.          |
|-------------------|-------------------|
| Alloy Material density (kg/m³) |
|-------------------|-------------------|
| Alloy A           | 8,387             |
| Alloy B           | 8,346             |
| Alloy C           | 9,720             |
| Alloy D           | 8,400             |
| Alloy E           | 8,420             |
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impact velocity was increased, the number of particle impact on the surface within unit of time became larger. As a result, the damage and erosion loss of the surface would be aggravated.

3.2 Eroded Surface Analysis

To further understand the erosion test results and investigate the erosion damage mechanisms of these alloys, the eroded surfaces of each specimen were analyzed using SEM. It was found that the eroded surfaces of alloy A and alloy B had a similar morphology while alloy D and alloy E similar. This was due to the similar chemical compositions of the alloys, respectively. Thus the SEM morphologies of eroded surfaces of alloy A, alloy C and alloy E at 98 m/s particle impact are shown in Fig. 6 to Fig. 11. From the images at low magnification, the craters resulted from repeated sand impact show an approximately elliptical shape for 30° angle impact because of the inclined angle to the target surface and circular shape for 90° angle impact as the sand impact was normal to the target surface.

In the images at high magnification, a considerable amount of overhanging lip was formed in the surfaces due to repeated cutting by the sand particles. In the meanwhile, obvious plastic flow that squeezed the lips can be observed. This plastic deformation feature is also characterized by the layered rings as observed in the eroded surfaces at low magnification, which were formed from accumulated plastic deformation due to repeated sand impact.

Two main material damage/removal mechanisms...
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Fig. 6  SEM morphology of eroded surface of alloy A tested at 98 m/s sand velocity and 30° impingement angle: (a) at low magnification; (b) at high magnification.

Fig. 7  SEM morphology of eroded surface of alloy C tested at 98 m/s sand velocity and 30° impingement angle: (a) at low magnification; (b) at high magnification.

Fig. 8  SEM morphology of eroded surface of alloy E tested at 98 m/s sand velocity and 30° impingement angle: (a) at low magnification; (b) at high magnification.
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Fig. 9  SEM morphology of eroded surface of alloy A tested at 98 m/s sand velocity and 90° impingement angle: (a) at low magnification; (b) at high magnification.

Fig. 10  SEM morphology of eroded surface of alloy C tested at 98 m/s sand velocity and 90° impingement angle: (a) at low magnification; (b) at high magnification.

Fig. 11  SEM morphology of eroded surface of alloy E tested at 98 m/s sand velocity and 90° impingement angle: (a) at low magnification; (b) at high magnification.
involved in solid-particle erosion wear have been suggested [19, 20], which are the cutting and extensive/repeated deformation of the target material. The phenomena resulted from these mechanisms have been observed in the eroded surfaces of the Stellite alloys studied in this research, as discussed above. However, it was also observed that the effects of these mechanisms on the erosion behavior of a material eroded at 30° and 90° angle particle impact were different. At the inclined angle (30°) impact, the cutting of the target surface by particles was accompanied with shearing of the sub-surface layer; therefore both hardness and ductility of the surface material were the key factors characterizing the erosion behavior of the surface. Hardness dominated the resistance of the surface to cutting, while ductility controlled the plastic deformation of the sub-surface. On the contrary, at the normal angle (90°) impact, the particles exerted compressive loads on the target surface; therefore, the overall surface was subjected to compressive stresses, but local areas of the surface could be under tension due to the non-uniform particle impact on the surface, leading to local plastic deformation of the surface. However, comparing the morphologies of eroded surfaces at these two impact angles, plastic deformation in the surfaces eroded at 30° angle impact is obviously larger, see the images at high magnification. Moreover, the size of overhanging lips in the surfaces eroded at the inclined angle impact is apparently larger than that at the normal angle impact. This is because particles easier cut into the target surface to cause the laminates (lips) at the inclined angle. Since the overhanging lips were thin and brittle, they were vulnerable under continuous particle impact; therefore, some of them were broken during the erosion process. Again, due to the normal impact of particles and smaller size of overhanging lips, smashed lips were more in the surfaces eroded at 90° angle impact, in particular, in the surface of alloy C shown in Fig. 10b. This alloy contains the largest amount of carbides among the alloys being studied and the most brittle, which implies that the overhanging lips formed in its surface might be the smallest in size and easiest broken.

Finally, comparing the eroded surfaces of the specimens having low carbon content to those with high carbon content, it is evident that plastic deformation in the former is larger than that in the latter. This is because the proportion of Co solid solution in the low-carbon alloys is larger than that in the high-carbon alloys and plastic deformation can only take place in the Co solid solution but not in carbides and intermetallic compounds due to their brittleness.

4. Discussion

4.1 Microstructure Effects

Chemical composition, fabrication process, heat treatment, cold and hot work, altogether determine the microstructure of a material, and hence control its physical/mechanical properties. Carbon is a very important element, making the carbide volume fraction in Stellite alloys a critical parameter [1]. The volume fractions of carbides in each of the alloys being study were estimated using the image analysis software, Clemex Vision Lite™. Among the five alloys studied in this research, alloy D and alloy E contain considerably less carbon so that they are solution-strengthened alloys. In their microstructures, as shown in Fig. 1d and Fig. 1e, there are very small amounts of carbides, alloy D has about 7.22 vol.%
carbides and alloy E approximately 4.08 vol.%, but there is a certain amount of intermetallic compounds of Co₃Mo and CoMo₆ due to the high Mo content. These hard intermetallic compounds have a similar effect to carbides on strengthening the alloys, thus benefiting the erosion resistance of the alloys. On the contrary, alloy A contains a very high content of carbon, thus a large volume fraction of carbides (~24.42 vol.%), in the form of primary Cr₇C₃, as shown in its microstructure in Fig. 1a. In addition to carbon, other alloying elements such as Cr, W and Mo also play an important role in the microstructures and performance of Stellite alloys. For example, tungsten mostly exists in the Co solid solution enhancing the strength of Stellite alloys, but when it is present in large amounts, it contributes to (W,Co)₆C carbide formation [1], as demonstrated in the microstructure of alloy C in Fig. 1c. This carbide phase can improve the erosion resistance of the alloy. Chromium is the indispensable element in Stellite alloys and it provides corrosion and oxidation resistance and also forms chromium carbides beneficial for erosion resistance. These five alloys all contain a large amount of Cr (22 ~ 30 wt.%) for achieving these features.

4.2 Hardness Effects

Hardness is used quite often in the field of wear resistance as a qualitative indicator for judging alloys, coatings, hardfacings and overlays. It is generally accepted that the harder a material, the greater its wear resistance is, for most materials [21]. The cutting mechanism in erosion wear implies the significant effect of material hardness on its erosion resistance. It can be assumed that the harder the target surface, the more resistant to cutting the surface is. To verify this hypothesis, the hardness of the Stellite alloys being studied was measured and the results are reported in Fig. 12. It is shown that carbon content in Stellite alloys determines the volume fraction of carbides in these alloys thus the alloy hardness. Alloy A contains the highest carbon content among the alloys and has higher hardness, but not the highest. Alloy C contains lower carbon than alloy A, but it has much higher hardness. This is due to the very high W content, which induces a large amount of (W,Co)₆C carbide, as shown in Fig. 1c. In addition to carbides, intermetallic compounds also contribute to hardness. As demonstrated by alloy D and alloy E, although they contain very low carbon, they have compatible hardness to alloy B that has 1 wt.% C.

From the erosion test results, at 30° angle impact, the erosion resistance of Stellite alloys is closely related to their carbon content and hardness. This is because harder surface is more resistant to cutting. However, it can also been seen that although alloy C is much harder than alloy A, it exhibited lower erosion resistance. To explain this observation, one may review the microstructure of this alloy in Fig. 1c. It contains a large amount of (W,Co)₆C carbide that has larger size than Cr₇C₃ carbide. Although carbides are hard, they are brittle. Under repeated attack of hard particles (about more than twice harder than the Stellite alloys) in the erosion process, the carbides were likely to break. Since the size of the (W,Co)₆C carbides in alloy C was larger, the resulted material loss of the specimen would be more when the (W,Co)₆C carbides were broken.

Expedited particle impact increased the erosion losses of the specimens, as shown by the histograms in Figs. 4 and 5. Alloy D and alloy E all contain a large volume fraction of intermetallic compounds of Co₃Mo and CoMo₆, which are mixed with Cr₇C₃ carbide in the eutectic. These intermetallic compounds, on one hand, enhanced the hardness of the alloys; on the other hand, were brittle and vulnerable under repeated particle impact. Since alloy D has slightly higher carbon content than alloy E, it is more brittle. When the velocity of the hard particles was increased, the impact of the particles on the target surface became more severe, which would cause more spallation of the intermetallic compounds from the target surface. This may explain why the erosion loss of alloy D was higher than that of alloy E at 98 m/s particle impact velocity.
At 90° angle impact, the erosion resistance of materials is mostly dependent on their compressive strength. Since metallic materials generally have higher resistance to compression than to tension, the erosion damage/wear of Stellite alloys at 90° angle impact is less than that at 30° angle impact, as demonstrated by the erosion test results in Fig. 4 and Fig. 5. In addition, because of the normal impact at 90° angle, the real contact area of particles with the target surface was smaller than that at 30° angle impact where the particles slid over the target surface thus caused more material removal. This can also be confirmed by the erosion crater shapes in Figs. 6-11. Brittleness of materials influences significantly their compressive strength. Under normal impact, the more brittle the surface material, the more the cracking/fracture generated in the surface layer and thus the more the material loss. As shown in Figs. 4 and 5, at 90° angle impingement, alloy C and alloy D exhibited higher erosion loss than the others. This was attributed to the larger amount of (W,Co)₆C carbide in the former and the large amount of eutectic mixture of intermetallic compounds (Co₂Mo and CoMo₆) and Cr₇C₃ carbide in the latter, which rendered these alloys relatively brittle compared to the other alloys. Alloy A, although, has the highest carbon content and a larger volume fraction of Cr₇C₃ carbide, the carbide size of this alloy was small. These small-size carbides not only benefited the strengthening effect to the solid solution matrix but also reduced the overall material loss of the target surface, because the amount of carbide debris would be less due to the smaller size even if the carbides were broken and splattered from the solid solution matrix.

5. Conclusions

Carbon content in Stellite alloys is one of the main factors governing their erosion resistance, because it determines the carbide volume fraction in these alloys. Tungsten and molybdenum also have significant effects on the erosion resistance of these alloys. They can enhance the strength of Stellite alloys and can also participate in the formation of carbides and intermetallics when present in large quantities. Increase of tungsten and molybdenum contents can enhance the performance of Stellite alloys in erosive environments.

Under 30° impingement angle erosion, the material damage is mainly controlled by the tensile plastic deformation of the sub-surface layer due to the shearing effect, while at 90° impingement angle impact, the material damage is mostly caused by compressive stresses induced in the surface layer due to the normal impact load.

The erosion losses of Stellite alloys at the impingement angle of 30° are higher than those at the impingement angle of 90°, because Stellite alloys have higher compressive strength than tensile strength. Also, the erosion losses of Stellite alloys increases with the particle impact velocity.

The hardness of Stellite alloys plays an important role in affecting their erosion resistance. In general, the alloy that is harder would be more resistant to erosion. On the other hand, harder Stellite alloys normally contain a larger volume fraction of carbides or/and intermetallics, which make them more brittle. Under continuous particle impact in the erosion process, in particular, at 90° impingement angle and at higher particle impact velocity, the surface was likely to crack and fracture.

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