Surface roughness investigation of ultrafine-grained aluminum alloy subjected to high speed erosion

N. Kazarinov\textsuperscript{a,b,*}, A. Esvyifeev\textsuperscript{a}, Y. Petrov\textsuperscript{a,c}, V. Lashkov\textsuperscript{a}, S. Atroshenko\textsuperscript{c}, R. Valiev\textsuperscript{a}

\textsuperscript{a}Saint Petersburg State University, Saint Petersburg 199034
\textsuperscript{b}Lavrentyev Institute of Hydrodynamics, Siberian Branch of the RAS, Novosibirsk 630090, Russia
\textsuperscript{c}Institute of Problems of Mechanical Engineering RAS, Saint Petersburg 199178, Russia

Abstract

This work presents first attempts to study influence of severe plastic deformation (SPD) procedure on material surface performance in high speed erosion conditions. Ultrafine-grained Aluminum alloy samples (after high pressure torsion) and were subjected to intensive erosion by corundum particles together with their coarse-grained counterparts. Particles were 100 $\mu$m in diameter and were accelerated via air flow up to 40-200 m/s velocities in a special experimental setup. Surface roughness measurements were performed to compare surface properties of SPD-processed and original samples. Additionally, SPD processing appeared to increase noticeably threshold velocity of the surface fracture process. A structural analysis of fracture surfaces was carried out on the samples in initial state and after erosion with different intensities.

Copyright © 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the Scientific Committee of ECF21.

Keywords: erosion; SPD; fracture analysis, surface roughness

1. Introduction

Performance of machines and constructions operating in highly aggressive erosive conditions is often defined by characteristics of surface of metals and alloys. Some parts of jet engines, steam turbines and boilers, nuclear reactors...
are particularly subjected to intensive erosion. In such conditions surface damage is induced by flow of rigid, liquid or gas abrasive particles or electrical discharges. Rigid particles deform and fracture surface layer colliding with the studied object. One should treat erosive fracture as an explicitly dynamic process as characteristic time of particle-surface interaction is proportional to time an elastic wave needs to travel across the particle which is often hundreds of microseconds. Investigation of such fast processes requires application of methods and approaches from dynamic elasticity theory and dynamic fracture mechanics (see Petrov and Smirnov (2010), Ravi-Chandar (2004)). In addition to this threshold, parameters of erosion process (such as critical particle velocity and dimensions, experiment duration, etc.) are of high interest and provide possibility to study transient processes and corresponding effects (Berezhkin et al. (2000), Bratov et al. (2004)).

In order to make surface of parts and units more resistant to erosion their construction and manufacturing process are optimized, however proper material choice, enhancement of material properties under high rate loading, surface coating play important role in reduction of erosion damaging effect. Application of new materials (e.g. ultrafine-grained metals and alloys) requires theoretical and experimental investigation of their dynamic strength. In this work first experimental results on ultrafine-rained (UFG) aluminum alloy behavior in intense erosion conditions are presented.

Bulk ultrafine-grained materials produced with use of severe plastic deformation method have been attracting attention of researchers for the last several decades due to their enhanced material properties comparing to their coarse-grained (CG) counterparts and relative simplicity of their manufacturing process (see Valiev (2004) for details). Multiple studies of properties of UFG materials including static and dynamic strength (Wei et al. (2006), Mishra et al. (2008)), fatigue (Witney (1995)), wear and coating adhesion (Wang et al. (2013)), and electricity conduction (Murashkin et al. (2013)) have been recently carried out by various research groups all around the world.

Various techniques of severe plastic deformation processing including ECAP (equal-channel angular pressing) (Valiev and Langdon (2006)), High pressure torsion (Hebesberger et al. (2005)), multidirectional forging (Belyakov et al. (2001)) and accumulative roll bonding (Saito et al. (1999)) have been developed and studied. All these methods have their advances and limitations and should be applied according to practical needs and scientific interests.

This study considers erosion of aluminum alloy 1235 (99.3 Al) samples by corundum particles accelerated in an air flow up to 40 – 200 m/s velocities under room temperature. Surface characteristics were assessed through surface roughness (Ra) measurements which provided information on roughness increase due to high speed erosion for the material in both states – coarse-grained and ultrafine-grained.

After SPD treatment both CG and UFG disks were polished in equal conditions in order to obtain equal sample thickness (1 mm) and equal initial surface roughness (0.95 μm). Afterwards 8.1 mm diameter semicircles were cut from both CG and UFG disks (6 pieces from each).

Average grain size measurement was performed using the electron backscatter diffraction (EBSD) method on Zeiss Merlin SEM equipped with Oxford Instruments HKL EBSD Detector. The mapping area was 28.5x21.4 μm and the step size was 0.1 μm. The obtained orientation map includes 1348 grains, measured average grain size is 650 ± 180 nm. Energy-dispersive X-ray spectroscopy analysis (EDS) was used to determine segregations.

2. Materials

Aluminum alloy 1235 (99.3 Al) was investigated in this study. This is a widespread material (and similar aluminum alloys) has a broad range of practical applications including those requiring operation in erosive conditions (e.g. pipes for pneumatic transport). Material composition is aluminum with addition of Fe, Si, Mn, Ti, Cu, Mg, Zn in the quantity no more, then 0.3%. Disks 20 mm in diameter were cut from the alloy sheet to fit into anvils of the HPT press. Half of the prepared disks went through HPT processing in the following regime: 6 GPa pressure, 10 revolutions with 1 revolution/minute rotational speed at room temperature. The measurements using Shimadzu HMV-G machine and ISO 6507-1:2005 standard showed 87% (on average) increase in Vickers microhardness for the HPT processed samples (from around 28.6 HV to 53.7 HV). The applied load was equal to 50 g and a dwell time was chosen to be 15 s. The samples (both CG and UFG) appeared to be uniform along their radii in terms of HV: multiple measurements with 1 mm interval between them demonstrated that HV dispersion from the average value is around 0.9%.
After SPD treatment both CG and UFG disks were polished in equal conditions in order to obtain equal sample thickness (1 mm) and equal initial surface roughness (0.95 μm). Afterwards 8.1 mm diameter semicircles were cut from both CG and UFG disks (6 pieces from each).

Average grain size measurement was performed using the electron backscatter diffraction (EBSD) method on Zeiss Merlin SEM equipped with Oxford Instruments HKL EBSD Detector. The mapping area was 28.5x21.4 μm and the step size was 0.1 μm. The obtained orientation map includes 1348 grains, measured average grain size is 650 ± 180 nm. Energy-dispersive X-ray spectroscopy analysis (EDS) was used to determine segregations.

3. High speed erosion tests

3.1. Experimental setup

There are two approaches to erosion testing: in first case a fixed object is put into two-phase flow (gas mixed with abrasive particles) or flow of liquid droplets (e.g. Kamkar et al (2013) and Kamkar et al. (2015)) while the second variant assumes movement of the sample in the abrasive medium (Goodwin et al. (1969), Tilly and Sage (19)). In the presented study the first variant was utilized. The sand particles were accelerated by an air flow in a small-scale wind tunnel (see Lashkov (1991) for details). Figure 1 schematically shows the experimental setup including: 1 – compressor room, 2 – air flow acceleration pipe, 3 – solid particles feeder device, 4 – sample inlet device, 5 – holder with mounted samples, 6 – working chamber.

![Fig.1. Utilized experimental setup – small scale wind tunnel with abrasive particle feeding devise and sample inlet device.](image)

The two-phase flow is controlled by air pressure in the system. Special reservoirs connected to the setup are filled with air under high pressure before each series of tests. Relation between air pressure and flow velocity is known due to calibration procedures. Solid particles are mixed into the air flow using feeder device which is also controlled by an operator who sets particle concentration and abrasive material consumption rate. One may control duration of the
experiment using remotely controlled sample inlet device. Thus, basic parameters of the erosion experiment – particle velocity, abrasive material consumption rate and experiment duration – were controlled and therefore various conditions were obtained. All the tests were performed at room temperature and the samples were hit at an angle of 90 degrees.

Corundum particles with 100 μm average diameter of the main fraction (40-45% of all particles) were used as an abrasive material. Experimental data obtained with such hard abrasive particles may be used for calculations of dynamic strength properties using Herz theory and incubation time approach developed in Petrov and Smirnov (2010). This particular particle size was chosen to perform calibration of the experimental setup using previous experimental data. The fixed value of particle consumption (3.5 g/s) was applied for the presented study.

To ensure equal testing conditions for both types of samples (CG and UFG) a special holder was manufactured which provided possibility to mount two samples side by side and therefore test them simultaneously.

3.2. Surface roughness assessment

To measure surface characteristics of both types of samples roughness of their contact surfaces was investigated. Surface roughness was assessed using Mahr M1 perthometer. In this method roughness is measured through vibrations of the needle which slides over the investigated surface and contacts with obstacles – surface irregularities. Quantitatively roughness is described by parameter $R_a$ which has dimension of length and is calculated as an average distortion of the surface profile from the mean line measured at $n$ equally spaced points located along a line.

To be more precise, increase of surface roughness $\Delta R_a$ was investigated for each particle velocity value. $\Delta R_a$ is calculated as difference between initial surface roughness of samples (equal 0.95 μm) and increased $R_a$ due to erosion. One should note here that traditional methods of erosion investigation include mass loss and thickness reduction measurements (see Grant and Tabakoff (1975)). In our case these methods appeared to be insufficiently accurate to correctly capture difference between CG and UFG materials. However, future research plans include preparation of larger samples with larger effective contact area and therefore potentially more considerable advantage of UFG alloy over CG one in terms of erosion resistance.

3.3. Shear fracture quantity assessment

The quantity of shear fracture (Shear, %) was determined by the formula Shear = $100 \times X$ (GOST30456-97 standard similar ASTM E436-91 standard) wherein $X$ - fragile component area was determined by measuring the area of brittle fracture on the photograph. The measurements were made at the optical microscope Axio-Observer-Z1-M in a dark field.

4. Results and discussion

The difference between two materials is visible to naked eye especially for high particle velocities (see figures 2). The surface of CG sample is covered with deep and large craters while UFG samples exhibit more smooth surface with smaller craters.
Figure 4 depicts dependence of surface roughness $R_a$ on experiment duration time with fixed 100 m/s particle velocity. One may see that $R_a$ does not change significantly if test duration is longer than 5 minutes and that difference between CG and UFG materials remains almost constant. To ensure that $R_a$ reaches its final value in the end of experiment and erosion process enters its final steady stage, 10-minute experiment duration was chosen for main tests.

The investigation of erosion of two materials was carried out for several values of particle velocities – 40, 80, 160 and 200 m/s. Figure 5 shows dependence of $\Delta R_a$ on particle velocity. The larger particle velocity is, the larger is roughness change. Additionally, particle velocity increase leads to greater difference in roughness change between CG and UFG alloys. Points for both materials may be well fitted with a straight line. Extrapolation provides possibility approximately to calculate particle velocity corresponding to zero roughness change ($\Delta R_a = 0$). This velocity is regarded an estimate for a threshold particle velocity value for the surface damage. Particles with lower velocities are supposed not to change roughness of sample’s surface. The estimated threshold velocity for CG alloy is 6.44 m/s, while UFG alloy demonstrates 14.72 m/s value. Such property of the SPD processed material may be explained either by improvement of static strength properties or by changes in dynamic mechanical characteristics of the material (see Smirnov (2007) for details) – this is matter for further research and investigation.
er corundum particles were used as an abrasive material. Surface roughness change of these materials. From this it can be concluded that the surface roughness for the CG and UFG materials appears to be approximately equal to the ratio of surface roughness values for damaged layer after erosion for all particle velocities is shown in Figure 6. The ratio of the thicknesses of destroyed layer due to erosion of the aluminum alloy 1235 in the initial state (Table 1) and after HPT (Table 2). The greater the percentage of fiber in the fracture surface, the more viscous material is, and reduction of this index indicates an increase in the fragility of the material. As can be seen from the data, after erosion brittleness of the material is increased comparing to the initial state. With the increase in erosion rate the brittleness of the CG material increases (Table 1). The UFG samples appeared to exhibit maximal brittleness at a speed 40 m/s particle velocity. The material behaves like a steel pipe in which a failure of viscosity occurs in the 8,12 - 10,33 m/s range of particle velocities (Atroshenko and Smirnov (2010)). With further increase of the erosion rate an increase in the fragility occurs for the UFG samples, which might be associated with grain refinement and an increase in grain boundaries, where the failure begins.

Fig.5. Dependence of surface roughness change on particle velocity. Arrows show threshold velocities for both materials obtained via data extrapolation.

Tables 1 and 2 show the results of measurement of the percentage of fiber on the fracture surface and the thickness of destroyed layer due to erosion of the aluminum alloy 1235 in the initial state (Table 1) and after HPT (Table 2). The greater the percentage of fiber in the fracture surface, the more viscous material is, and reduction of this index indicates an increase in the fragility of the material. As can be seen from the data, after erosion brittleness of the material is increased comparing to the initial state. With the increase in erosion rate the brittleness of the CG material increases (Table 1). The UFG samples appeared to exhibit maximal brittleness at a speed 40 m/s particle velocity. The material behaves like a steel pipe in which a failure of viscosity occurs in the 8,12 - 10,33 m/s range of particle velocities (Atroshenko and Smirnov (2010)). With further increase of the erosion rate an increase in the fragility occurs for the UFG samples, which might be associated with grain refinement and an increase in grain boundaries, where the failure begins.

Table 1. Degradation of the sample surface after erosion (CG sample).

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Shear, %</th>
<th>Damaged layer, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>92.4±0.2</td>
<td>27.8±0.1</td>
</tr>
<tr>
<td>80</td>
<td>91.3±0.2</td>
<td>28.4±0.1</td>
</tr>
<tr>
<td>160</td>
<td>90.7±0.2</td>
<td>28.9±0.1</td>
</tr>
<tr>
<td>200</td>
<td>74.2±0.2</td>
<td>29.6±0.1</td>
</tr>
</tbody>
</table>

Table 2. Degradation of the sample surface after erosion (UFG sample).

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Shear, %</th>
<th>Damaged layer, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>88.4±0.2</td>
<td>16.1±0.1</td>
</tr>
<tr>
<td>80</td>
<td>97±0.2</td>
<td>17.7±0.1</td>
</tr>
<tr>
<td>160</td>
<td>91.6±0.2</td>
<td>19.2±0.1</td>
</tr>
<tr>
<td>200</td>
<td>89.5±0.2</td>
<td>26.7±0.1</td>
</tr>
</tbody>
</table>

Thickness of the destroyed layer for the material without HPT processing is larger than for the UFG material. Damaged layer after erosion for all particle velocities is shown in Figure 6. The ratio of the thicknesses of destroyed layer for the CG and UFG materials appears to be approximately equal to the ratio of surface roughness values for these materials. From this it can be concluded that the surface roughness $R_a$ value may characterize damage of the material.
5. Summary and conclusion

In this study influence of severe plastic deformation treatment on material’s surface behavior in intense erosion conditions was studied. Aluminum alloy 1235 (99.3 Al) was subjected to high pressure torsion procedure and then tested together with its coarse-grained counterpart in a special small scale wind tunnel which provided controllable air-particle flow. 100 μm diameter corundum particles were used as an abrasive material. Surface roughness change (∆Ra) was measured afterwards to assess surface changes on both specimens. Investigation of the damaged layer proved surface roughness to characterize material damage. The series of experiments with varying velocity of the two-phase flow revealed growing difference in surface roughness between CG and UFG alloys with increasing particle velocity. Data fitting and extrapolation provided possibility to calculate threshold particle velocities for both materials. Threshold velocity for the UFG alloy appeared to be more than two times higher than for CG material. This effect might be attributed to changes in both static and dynamic strength properties of the material due to severe plastic deformation processing. In addition to this ratio of brittle and viscous fracture due to erosion was determined.

Acknowledgements

The work has been done under financial support from the Russian Federal Ministry for Education and Science (Grant 14.B25.31.0017). Additionally, the authors received support from RFBR (16-31-60003 mol_a_dk, 16-31-60047 mol_a_dk, 14-01-00814, 16-51-53077) and Russian Science Foundation (15-11-10000). Additionally, authors...
were supported by the Presidium of the RAS, by the Marie Curie Foundation (TAMER no. 610547) and by Saint Petersburg State University (grant 6.38.243.2014).

References