ULTRA HIGH FINISHING OF OVAL BORES USING ELASTIC ABRASIVE BALLS

V.S. Sooraj*, V. Radhakrishnan

Department of Aerospace Engineering
Indian Institute of Space Science and Technology
Valiamala, Kerala, India-695547

Abstract

Ultra fine finishing of engineering surfaces using elastic abrasive balls is a simple, flexible, multi application oriented-cost effective approach developed in the recent past. Considering the industrial relevance, the application of such balls for fine finishing of an intricate oval bore is presented in this paper. In this methodology, abrasive grains are flexibly bonded in the form of meso scale balls using an elastomeric medium which will facilitate the balls to deform in conformity to the work surface, thereby producing fine refinement of surface profile. Major process variables involved in the operation as well as the influence of these parameters in surface roughness of the bore are discussed in detail. Remarkable improvement in finish, almost 85 % reduction in average roughness (Ra) is noticed after the use of elastic abrasives for a processing time of 45 minutes, yielding a final Ra value of 25 to 30 nm, without altering the oval form.

Keywords: Elastic-abrasive balls, Fine finishing, roughness

1 Introduction

Ultra fine finishing of internal surfaces is one of the challenging requirements in many industrial applications. A series of fine finishing processes using abrasive grains in its loose and bonded form starting from precision honing to magneto-abrasive flow finishing is reported in literature. Abrasive Flow Finishing (AFF) and Magnetic Abrasive Finishing (MAF) are the most recent methodologies attempted in this series. Inner surface finishing of aluminium, brass and stainless steel tubes by magnetic abrasives is reported by Wang and Hu (2005). According to Jain (2013), the characteristics of magnetic abrasives and the control of magnetic field are critical requirements in this methodology. Magnetic abrasive jet machining, Magnetorheological abrasive flow finishing and Magnetorheological jet finishing are some of the advanced strategies reported in this category for nano scale finishing of internal surfaces, which use a field responsive smart fluid for carrying the abrasives. The concept of centrifugal force assisted abrasive flow finishing projected by Walia et.al. (2006), investigated a hybrid approach by introducing centrifugal force to the abrasive media by rotating a centrally placed rod inside the hollow workpiece. But special fixtures and tooling arrangements are the complex requirements in this technique. The fundamental mechanism of material removal in all of these methods mentioned is ‘abrasion and micro cutting’. As a different approach, Barletta et al. (2007) developed a Fluidized Bed Assisted Abrasive Jet Machining (FB-AJM) for precision internal polishing of tubular specimens. This technology uses the fluidized bed hydrodynamics to feed the abrasives uniformly inside the hollow workpiece. The experimental system in FB-AJM includes a compressor, two fluidized beds, venture pipes, three-way valves and a nozzle to allow the impingement of abrasive grits at moderate velocity, of the order 10-15 m/s.

The preparation of abrasive media, complexities in finishing setup, tooling and fixture requirements, limitation posed by the intricacies in internal surfaces are the major challenges associated with the aforementioned procedures. An internal circumferential groove, oval shaped bore, high aspect ratio hole etc. are typical examples of such challenging tasks. Achieving ultra fine finish, of the order of 10-50 nm, without altering the surface form is also critical, but not that easy in existing operations. Very recently, Sooraj and Radhakrishnan (2013, 2014) proposed and investigated a new methodology referred as ‘elastic abrasive finishing’ for fine finishing of internal surfaces such as tubes and internal circumferential grooves. The method is proven to be a versatile, multi-application oriented methodology capable of giving micro/nano finish, keeping the form unaltered. In this approach, specially prepared elastic abrasive balls of diameter 3 to 4 mm are used as the medium, which is cost effective, flexible and convenient to handle.
In this paper, an extension of the application of elastic abrasive balls for fine finishing of oval bores is addressed. The characteristic features of elastic abrasive balls and the major process variables involved are discussed in detail. The ease, flexibility and viability of the process are well exhibited by the simple and cost effective experimental setup and procedure used. The mechanism of material removal is explained with substantial theoretical justifications.

2 Characteristic features of elastic abrasive balls

Elastic (or elasto) abrasive balls referred in this paper are abrasive embedded elastomeric spheres of diameter 3 to 4 mm, prepared using a specially developed chemical method. It combines the characteristics of a hard abrasive as well as an elastomeric material. The action of such an elasto-abrasive ball during abrasion, in comparison with a standard abrasive grit, is shown in Figure 1.

As shown in the figure, the elasto-abrasive balls are capable of deforming in conformity to work surface due to its elastomeric effect and thereby reduces the depth of penetration. This is slightly different from the action of a standard abrasive grit of same size and shape, which in effect will act like a hard indenter penetrating into the work surface. More precisely, the presence of elastomeric medium with low elastic modulus in the proposed balls will reduce the equivalent elastic modulus at the contact interface. This in turn will allow the balls to absorb some of the energy by deforming it in conformity to work surface and thereby reduces the depth of penetration. A detailed description on this deformation behaviour is discussed in detail by Sooraj and Radhakrishnan (2014).

The elastic-abrasive balls used in this paper are prepared using special grade elastomeric polymers and silicon carbide grains. The special features of these balls are listed below:

- Type and size of embedded abrasive grains can be varied according to the functional requirements.
- When the elastic abrasive ball is in contact with the work surface, a number of embedded grains engage in the finishing action. Therefore, the number of active abrasive grains per contact area tends to be relatively high.
- Overall size and elastic characteristics of the elastic abrasive balls are easily controllable
- Elastic abrasives in the form of small balls are convenient to handle, transport and allows easy cleaning of the part after finishing. These balls can be applied without any slurry medium, making them environment friendly.

The geometry and characteristics of elasto-abrasive balls used in this paper are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Characteristics of elasto-abrasive balls</th>
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<tbody>
<tr>
<td>Overall diameter (x 10^{-3} m)</td>
</tr>
<tr>
<td>Mass (x 10^{-3} Kg)</td>
</tr>
<tr>
<td>Density (x 10^{3} Kg/m^{3})</td>
</tr>
<tr>
<td>Volume fraction (elastomer: abrasive)</td>
</tr>
<tr>
<td>Size of embedded abrasive grain (µm)</td>
</tr>
</tbody>
</table>

3 Experimental setup and procedure

The oval shaped internal surface to be finished is shown in Figure 2. The oval bore is cut on a cylindrical hardened steel specimen with diameter 40 mm and length 25 mm, using wire EDM operation.
Figure 3 Experimental setup used for oval bore finishing

The through oval bore is having major axis 18 mm and minor axis 8 mm, with internal surface of initial average roughness (Ra) 0.2316 ± 0.02 µm, peak to valley roughness (Rt) 2.2164 ± 0.28 µm and peak height (Rp) 0.6161 ± 0.05 µm.

The experimental setup used for finishing the oval bore is shown in Figure 3. It mainly consists of a double acting piston-cylinder arrangement with an extension rod attached to each piston located on either side of the setup. The work specimen is located inside a simple fixture integrated with guide bush developed using rapid prototyping machine. After filling the oval bore with elastic abrasive balls, both the pistons will be moved to its extreme position squeezing the balls. The pneumatic circuit is designed to reciprocate the pistons in the same direction, for a fixed processing time, using a dedicatedly developed micro-controller based machine control box.

4 Mechanism of material removal

An individual elastic abrasive ball squeezed inside the bore will deflect in the radial direction as shown in Figure 4. As the deflection of elastic ball gets constrained by the work surface, it will deform in conformity to the surface and all the active embedded grains in this contact zone get penetrated into the work surface. The produced penetration depth is analogous to the depth of cut. The linear reciprocating velocity of the piston will act as the cutting velocity and the material will be removed by micro-cutting action. Because of the elastomeric effect, the depth of cut will be very low and thus the embedded grains will get interacted with the irregular surface peaks. As the piston reciprocates for a certain processing time, the surface peaks get gradually demolished and will yield a smoothened profile with lower peak heights. Based on the detailed theoretical analysis performed by Sooraj and Radhakrishnan (2014), it can be concluded that the depth of penetration of a single abrasive grain 'Δ' can be written as,

\[ \Delta = \frac{F_r}{\pi \cdot d_g \cdot K \cdot H_w} \]  

Here, \( F_r \) denotes the radial force acting on an embedded abrasive grain calculated using the relation

\[ F_r = P_r \cdot \pi \cdot \frac{d_g^2 \cdot s}{4} \]

Where \( P_r \) is the radial pressure, which is a function of axial pressure maintained in the pneumatic circuit, and \( d_g \) is the diameter of embedded abrasive grain assuming it as spherical in shape.

Based on this, the volume corresponding to the penetration of a single embedded grain can be written as
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\[ V_g = \frac{1}{2\pi} \left( \frac{1}{d_g} \right) \left( \frac{F_t}{\sigma_w} \right)^2 \]

In this equation, \( \sigma_w \) is the flow strength of work material which is a function of work material hardness (Jain et al. (2009)).

4.1 Total volume of material removal per stroke

In actual situation, individual elastic abrasive balls get squeezed within the bulk filling inside the bore due to the pneumatic pressure. Assuming that the abrasive grains are embedded uniformly over the ball surface, and the total internal surface area of the bore is in contact with these embedded grains due to the deformation of elastomeric balls filled inside the bore (as given in Figure 5), the total volume of material removal per stroke can be derived as follows;

\[
V_t = V_g \times N_g \quad (4)
\]

\[
V_t = V_g \times \frac{A_{in}}{A_g} \quad (5)
\]

Where, \( N_g \) is the active number of embedded grains per stroke, approximately evaluated by dividing the total internal surface area of embedded abrasive grain (\( A_{in} \)) with the cross sectional area of embedded abrasive grain.

![Figure 5 The mode of material removal](image)

But in actual situation, only the irregular surface peaks are cut down during the stroke. As the number of strokes increases, gradual refinement of surface profile occurs as indicated in Figure 6.

4.2 Correlation of material removal with roughness parameter

The above discussions clearly indicate that the final finish achievable highly depends on the initial profile of the surface. Thus, it is important to mention that the actual material removal is still lower than what is predicted using the above equation. The analysis presented here is an attempt to correlate the material removal with the material ratio curve (Abbott-Firestone curve) of the surface. Due to the action of elastomeric abrasive balls, the peak area (\( A_1 \)) associated with material ratio curve is expected to reduce. The measurement of roughness is done in the present case using a diamond stylus traversing linearly inside the bore over its entire length.

![Figure 6 The refinement of surface profile](image)

Assuming identical surface profile along all the evaluation lengths within the inner surface, the volume of material removed can be correlated approximately to peak area reduction as follows.

\[
V_t \propto [A_1(\text{after}) - A_1(\text{before})] \times C \times \frac{L_w}{l_n} \quad (6)
\]

Where, the ‘\( L_w \)’ is the bore depth (length of specimen) and ‘\( l_n \)’ is the evaluation length of roughness measurement which is considered as 5 times the sampling length. In the equation, ‘\( C \)’ is denoting the circumference of the oval bore. Since the material removal is addressed only through the reduction in peak area, the above equation provides only an approximate prediction. It is also worth mentioning that the above theory shows a clear indication of reduction in maximum peak height (Rpk), which is a closely related to peak area (\( A_1 \)), after finishing.

Based on the above discussion, the volume of material removal for an elliptical cross-section of bore can be evaluated by calculating ‘\( C \)’ as shown in the following equations.

\[
C = \pi (a + b) \left[ 1 + \frac{3h}{10 + \sqrt{4 - 3h}} \right] \quad (7)
\]
Where,

$$h = \frac{(a - b)^2}{(a + b)^2}$$ (8)

### Table 2 Observed roughness parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before Finishing</th>
<th>After elasto-abrasive finishing (45 minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reading 1</td>
<td>Reading 2</td>
</tr>
<tr>
<td>Ra</td>
<td>0.2202</td>
<td>0.2501</td>
</tr>
<tr>
<td>Rt</td>
<td>2.4979</td>
<td>2.4027</td>
</tr>
<tr>
<td>Rp</td>
<td>0.5876</td>
<td>0.6667</td>
</tr>
<tr>
<td>Rz</td>
<td>1.3228</td>
<td>1.3576</td>
</tr>
<tr>
<td>Rpk</td>
<td>0.172</td>
<td>0.168</td>
</tr>
</tbody>
</table>

In equation 8, ‘a’ and ‘b’ are respectively the semi-major axis and semi-minor axis of the ellipse.

### 5 Results and discussions

From the discussions so far, it is clear that the major process variables that may affect the final finish are the configuration and elastic characteristics of balls, hardness and initial roughness of work surface, size of embedded grains, axial pressure as well as the reciprocating velocity of the piston.

The effect of the two operating variables, axial pressure and reciprocating velocity is shown in Figure 7. This is reported based on the experimental analysis performed on oval bores using the proposed setup, following the procedures reported by Sooraj and Radhakrishnan (2014) for plain tubular specimens.

#### 5.1 Effect of process variables

Better finish (lower values of roughness) is observed with elastomeric balls embedded with finer abrasive grains. It is because of the increase in number of active grains comes in contact with the surface during the deformation of elastomeric ball. The depth of cut also gets reduced, producing finer refinement in surface texture.

The roughness parameters were showing an optimum value at medium range of axial pressure, of the order 0.3 to 0.4 MPa. When the axial pressure is low, the radial force developed may not be sufficient to get an effective depth of penetration, which may result in rubbing and ploughing action rather than cutting of surface peaks. On the other hand, excess pressure in the axial direction will also increase the roughness values. At higher pressure, effective radial force (Fr) on the grain will increase and thus the penetration will be deeper which leads to high shear resistance and breakage of embedded grains.

Relatively lower values of roughness parameters were observed at high reciprocating velocity, as indicated by Figure 7. As shown in Figure 7, the
optimum axial pressure and reciprocating velocities in
the present case is observed to be 0.36 MPa and 12
m/min. The variation of 2D roughness parameters at
this operating condition, using elastomeric balls
embedded with 10 µm grains for a processing time of
45 minutes is shown in Table 2.

The geometric form of the oval bore before and
after processing is shown in Figure 8. It is very
significant to note that the form is unaltered, retained
without any change in the dimensions.

![geometric form of oval bore](image)

**Figure 8** The form of oval surface before and after
finishing, captured using profile projector

Typical surface profile before and after finishing
is indicated in Figure 9.

![roughness profile](image)

**Figure 9** Roughness profile before and after
finishing

6 Conclusions

The simplicity in usage and the order of finish
achieved was clearly indicating the capability and
industrial relevance of this new approach. At an
optimum axial pressure of 0.35 MPa and cutting
speed of 12 m/min, the average roughness of a
hardened steel specimen is reduced from 0.2 µm to
0.03 µm with substantial reduction in peak height and
peak to valley roughness. Elastic abrasive balls
embedded with 10 µm abrasive grains were showing a
better result, indicating the possibility of improving
the result by the usage of still finer grains. The
processing time is of the order of 40 to 45 minutes,
after which the roughness tends to have a steady
value. Here again, further reduction may be possible
with progressive finishing strategy, by step by step
usage of finer abrasive grains.

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