Surface Integrity in Abrasive Flow Machining of Hardened Tool Steel AISI D2

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Abstract

The abrasive flow machining (AFM) is a recent manufacturing technique that uses the flow of a pressurized abrasive media for removing workpiece material. In comparison with hand polishing, AFM is very efficient process, suitable for finishing of complex surfaces. In this paper, the influence of the process parameters on surface integrity, i.e. surface roughness and induced residual stresses, is investigated. The electrical discharge pre-machined hardened tool steel AISI D2 samples have been used to be processed with AFM. Results of the work show that AFM is capable to remove EDM damaged surface and significantly improve surface roughness. Moreover, it is capable of inducing high compressive residual stresses to the machined surface, in a very thin sublayer of ~10 µm, and so prove that AFM offers an alternative finishing process, beneficial from the surface integrity and productivity point of view.

1. Introduction

Nowadays, a lot of various parts demand a high level surface finish. Classical hand polishing procedure, which is the most frequently used for this purpose, represents time-consuming and expensive solution. However, the finishing time and costs can be reduced more than ten times with the application of an alternative AFM process [1]. AFM is suitable for finishing external as well as internal workpiece surfaces that are often complex and out of reach. However, the efficiency of the AFM process depends on number of process parameters, which can be classified in three groups, namely, the polishing media.
parameters (viscosity, abrasive material, abrasive mesh, abrasive concentration and temperature), the
AFM process (Fig. 1) parameters (pressure, volume flow, number of cycles and machining time) and the
workpiece parameters (material, hardness, roughness, pre-machining process, texture orientation and
workpiece shape).

One of the major problem in the AFM process is to determine the relationship between process
parameters and the process results, i.e. the workpiece surface roughness, residual stresses, defects,
changes in geometry, etc. In the past ten years, some theoretical models, deriving the finite element
calculations or experimental plans, have been proposed. Some of them are dedicated to the optimization
of the material removal rate and surface roughness as a function of the grain concentration in the AFM
polishing media [2, 3]. Some other investigate the density of active grains, which are in contact with the
workpiece surface [4]. According to several authors [5-7], the rheological properties of the AFM media
play an important role on the material removal rate. Additionally, Williams and Rajurkar [8] have shown
that the medium viscosity significantly affects surface roughness in AFM. Most of these investigations
deal with the optimization of the surface roughness. Based on those results, it is now known that super-
finishing processes may also improve the surface integrity of engineering surfaces. One can notice works
of Matsumoto et al. [9], Coulon [10], Axinte et al. [11] and Rech et al. [12, 13], which have shown that
honning processes, belt finishing processes and polishing can induce compressive residual stresses in the
external layer of workpieces and lead to a significant improvement of final product fatigue life.
Particularly, Matsumoto et al. [9] have shown that honing of bearing steels shifts the residual stresses
toward compression in a very thin layer smaller than 10 microns beneath the surface, whereas the bulk of
the material is not affected. Rech and Moisan [12] and Rech et al. [13] have recently shown that also the
belt finishing process used after a hard turning induces compressive residual stresses on and beneath the
machined surface (down to ~10 microns). According to those investigations and work from Uhlman et al.
[14], it is believed that the AFM process should also influence the residual stress on and beneath the
machined surface. Therefore, the AFM influence on surface integrity is the focus of this paper.

The research presented in this paper was carried out on steel grade material that is used in injection
molds and is coated with TiN, TiCN, TiAlN, CrN, etc. coatings to enable longer injection mold life. The
purpose of the research is to investigate the influence of AFM process parameters on surface integrity.
Measured and analyzed are surface roughness in two directions, along (in direction of AFM flow – $\sigma_{11}$)
and transverse (perpendicular to AFM flow – $\sigma_{22}$) to the workpiece surface, as is shown in Fig. 2.
Besides roughness also 3D roughness, defects of machined surface and residual stresses on and beneath
the surface have been analyzed.
2. Experimental work

2.1. Workpiece material

The workpieces are made of the heat treated tool steel AISI D2. Hardness of pre-machined workpiece is 59 HRc, roughness is $R_a = 1.69 \mu m$ and $R_z = 10.66 \mu m$. Workpiece that is used as a tool for rotary swaging process, is 35 mm long, 14 mm width and 10 mm high, as it is shown in Fig. 2. The workpiece has been pre-machined by electrical discharge machining (EDM).

![Workpiece dimensional properties](image)

2.2. Presentation of experiments

The initial state of the workpieces has been obtained by a pre-machining operation and a heat treatment, in order to reach a martensitic structure with hardness 59 HRc. After this step, all workpieces have been finished with the following two manufacturing procedures:

- Electrical discharge machining + AFM with polishing media under the pressure of 3.5 MPa
- Electrical discharge machining + AFM with polishing media under the pressure of 6.0 MPa

Workpieces are fixed in fixture as is shown on Fig. 3. Before AFM, polishing media is heated to the working temperature, which is approximately 40°C and remains constant during the experiments.

![Fixture with workpieces](image)

The problem of EDM is that the machined surfaces are after the process full of micro cracks and craters due to the high heat erosion (Fig. 3). These defects result in poor quality and short fatigue life of the mold, as a product. Therefore, the finishing processes have to be applied, after EDM, to improve surface integrity. The surface roughness characteristics, dealing with the EDM, can be classified as VDI 24. This corresponds to the workpiece surface roughness of $R_a = 1.69 \mu m$ and $R_z = 10.66 \mu m$.

2.3. Abrasive flow machining

AFM machine tool – Profile 80, manufactured by Kennametal Extrude Hone, has been used in this work. The machine consists of three parts, namely the machine frame, computer control system and the
The hydraulic unit ensures adequate movement and polishing media pressure that can be manually configured. The computer control system is designed to control the volume of extruded polishing media and the number of extrusion cycles. Used process parameters in this work are presented in Tab. 1. For all the experiments, polishing media with silicon carbide abrasive and mesh size 80 is used. Polishing time for each workpiece is approximately 1800 s.

Table 1. Used AFM process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polishing media parameters</td>
<td></td>
</tr>
<tr>
<td>viscosity</td>
<td>2650 Pas</td>
</tr>
<tr>
<td>abrasive mesh</td>
<td>Mesh 80</td>
</tr>
<tr>
<td>abrasive concentration</td>
<td>57 %</td>
</tr>
<tr>
<td>AFM machine parameters</td>
<td></td>
</tr>
<tr>
<td>pressure</td>
<td>3.5 MPa, 6.0 MPa</td>
</tr>
<tr>
<td>volume flow</td>
<td>0.00000109247 m³/s, 0.00000355053 m³/s</td>
</tr>
<tr>
<td>machining time</td>
<td>1800 s</td>
</tr>
<tr>
<td>Workpiece parameters</td>
<td></td>
</tr>
<tr>
<td>Roughness before AFM</td>
<td>$R_a=1.67 \mu m$, $R_z=10.66 \mu m$</td>
</tr>
</tbody>
</table>

3. Experimental measures

3.1. Measurements of surface roughness

Firstly, surface roughness is measured by profilometer MAHR MarSurf XR 20. Cut-off length is set to 0.8 mm, the evaluation length is equal to $l_n = 2.4$ mm and selected heights ($R_a$, $R_z$, $R_t$) were measured. After, the roughness measures, 3D roughness measurements are carried out with a SURFASCAN profilometer. Accordingly, SURFASCAN software procedure is applied to analyze 3D surface texture. Area of measurements is set to 1 mm², distance between points in $X$ (parallel with AFM flow) and $Y$ (perpendicular to AFM flow) direction is 5 µm. Measured are $S_a$, $S_z$, and $S_t$ characteristics. Results of 3D roughness measurements are also analyzed with SPIP 5.1.5 surface texture software, to achieve more representative 3D plots on the same scale: from 6 µm to -12 µm. All the results are presented in Fig. 4.

3.2. Measurements of residual stresses

In this study residual stress with two components, along ($\sigma_{11}$) and transverse to the workpiece ($\sigma_{22}$) (Fig. 5), are measured using the X-ray diffraction method (XRD). The measurements are performed at 20 kV tension, 4 mA current (0.08 kW) using CrKα tube and angle of Bragg 156.1°. Residual stresses are measured at the surface and at different depths beneath the surface, by successive etching off ultra-thin stressed layers.

4. Results and analysis

4.1. Surface roughness analysis

The changes of the selected roughness parameters $R_a$, $R_z$, $R_t$, resulting from different machining processes, are presented in Tab. 2. The values are the average values of several measures. The corresponding 3D surface textures are shown in Fig. 4. It can be seen that surface obtained by EDM exhibit texture with no significant orientation or trend. In contrast, the AFM modified surfaces contain scratches in direction of finishing, with significant lower amplitudes.
Table 2. Roughness measurements

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>Direction</th>
<th>$R_a$ [µm]</th>
<th>$R_z$ [µm]</th>
<th>$R_t$ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM</td>
<td>along</td>
<td>1.67</td>
<td>10.66</td>
<td>15.54</td>
</tr>
<tr>
<td></td>
<td>transverse</td>
<td>1.69</td>
<td>10.59</td>
<td>13.80</td>
</tr>
<tr>
<td>AFM – 3.5 MPa</td>
<td>along</td>
<td>0.470</td>
<td>1.97</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>transverse</td>
<td>0.94</td>
<td>5.16</td>
<td>6.40</td>
</tr>
<tr>
<td>AFM – 6.0 MPa</td>
<td>along</td>
<td>0.23</td>
<td>1.02</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>transverse</td>
<td>0.55</td>
<td>3.15</td>
<td>3.88</td>
</tr>
</tbody>
</table>

From a quantitative point of view, it appears that EDM generates surface with average value of $R_a$ parameter of approximately 1.68 µm. On the other hand, AFM reduces it to the value between 0.94 and 0.23 µm. The $R_z$ and $R_t$ depict the same trend.

From the measurements of surface roughness, it can be seen that AFM modified surface has not the same roughness in both directions ($\sigma_{11}$ and $\sigma_{22}$). Roughness along the workpiece is lower than the transverse one that corresponds to the flow direction of polishing media. Along the media, $R_a$ reaches values between 0.47 and 0.23 µm, while in transverse direction, values are higher ($R_a$ is between 0.94 and 0.55 µm).

4.2. Residual stresses

Distribution profiles of residual stress components along ($\sigma_{11}$) and transverse to the workpiece ($\sigma_{22}$), measured by XRD after EDM, are shown in Fig. 5. It is necessary to keep in mind that the precision of the measurements has been quantified with an accuracy of ±26 MPa. Fig. 5a shows that EDM induces tensile stresses to the machined surface. Obtained tensile stress amplitudes reach approximately 550 MPa. The thickness of the affected layer is about 10 µm for EDM, where achieved surface is classified as VDI 24. Observing the influence of the AFM, the tensile stresses from EDM is removed. Even more, high compressive stresses are induced in a machined surface (Fig. 5b and 5c). The thickness of the affected layer stays unchanged (approximately 10 µm). Fig. 5b and 5c show that the obtained compressive stresses are more dominant after AFM with applied higher pressure of polishing media (6.0 MPa) and are -350 MPa in contrast to lower pressure (3.5 MPa), where stresses are about -200 MPa.

5. Conclusions

In this paper, the surface integrity induced by the AFM process on hardened tool steel AISI D2 has been investigated. The samples that were treated with AFM have been premachined using EDM. It has been shown that the EDM induces undesired high tensile stresses in and beneath the machined surface.
This poor surface integrity seems to be correlated to the presence of a white layer, micro-cracks and craters on the surface, negatively affecting the fatigue life of the final product. The application of AFM offers possibility to remove this damaged surface. With application of AFM, a high compressive stresses are observed in a very thin sub-layer, down to approximately 10 µm. This compressive stress can be explained by the mechanical phenomenon of scratching according to the previous studies ([13], [15]) on belt finishing. It has been shown also that an increase in the AFM media pressure leads to an increase in compressive stresses. Consequently, it can be claimed that with the application of finishing process like AFM, the surface integrity induced by EDM can be significantly improved.

In short, the paper highlights the interest of using AFM process for improved machined surface integrity.

References