On surface integrity of Al 2014 alloy finished by Ultrasonic Assisted Abrasive Flow Machining

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Abstract. Ultrasonic Assisted Abrasive Flow Machining (UAAFM) is a finishing process for both external and internal surfaces such as holes that are not necessarily straight and of long length. The latter type prohibits the use of a simple honing tool. In UAAFM hard abrasive particles are mixed in a carrier fluid and flown past. The hole surfaces at fairly high speeds back and forth using hydraulic circuits. It has been observed that providing ultrasonic harmonic motions to the work-piece or the fluid or both can improve the material removal rate and surface finish. The present paper discusses an experimental study on finishing internal primitives of Al alloy 2014 series with effect of ultrasonic assistance work-piece on process performance in axial vibrations.

Keywords: Surface finish, UAAFM, ultrasonic assistance

1. Introduction

Honing becomes inapplicable for complex geometries such as intricate holes, curved tubing etc. There are ways to improve finish on the cylindrical outer diameter (OD) via center less grinding, polishing, chemical, electro-polishing and other methods or some combination thereof. Whereas internal diameter (ID) finish improvement options for tubing are more limited and preferably rely upon multiple mandrels or plug passes to achieve better finish. Mechanical options to improve tube ID finish are limited to larger diameters. Typically, as a stainless or alloy tube is drawn down, its finish gets worse once the plug or mandrels removed (a process limitation). Finishing of internal geometries of alloys tubes or tubular components are in high demand in industries like medical, aerospace, electronics or micro mechanics.

In the basic Abrasive flow machining (AFM) process, however a considerable number of abrasives remain idle and flow part of the workpiece without coming into contact with the candidate surface, a few of them roll over the surface without causing any material removal. Thus a considerable fraction of the total cutting edges (abrasives – the tiny tools) is ineffective during the process. Many attempts have been made to make them effective, that is to make them take part in the material removal action through some mechanism [1-2]. In the UAAAFM process, the abrasives are made agitated relative to the workpiece through
additional mechanical vibration so that the mechanism of asperity abrasion gets boosted. The application of additional vibration can be effected in two modes –

(a) Radial mode in which the workpiece is vibrated orthogonal to the direction of medium flow, that is radial to the medium cylinders [3-4]
(b) Axial mode in which the workpiece is vibrated along the axis of the medium cylinder, that is in the direction of medium flow.

In the present work axial mode of vibration is used to conduct the experiments on finishing of Al-2014 alloys.

2. Ultrasonic assisted abrasive flow machining
In axial mode UAAFM process, the piezo actuator is mounted axially or parallel to the medium flow direction with a flexible fixture. This is implemented by using support of a specially designed collect and ultrasonic horn. Fig. 1 shows the schematic and photographic view of the actuator shaft connected directly to the work piece.

In this mode of vibration, the relative velocity of the system is used to determine the interaction of an abrasive particle in the proximity which can be observed from the illustrations of different events shown in Fig. 2 (a-d). The rolling and sliding inactive abrasive particles will likely become active with the additional ultrasonic assistance to the work-piece [2]. However, as the vibration is assisted parallel to the medium flow direction, the asperities advance in axial direction during rising half of the sinusoidal wave as shown in Fig. 2 (b), whereas the asperities advance in another direction opposite to medium flow direction during the receding half of the cycle as shown in another event in Fig. 2 (c). It is noted that the medium is pushed to and fro in both the directions.
3. Experimental procedure

3.1 Work material preparations

Fig. 3 shows Al 2014 alloy hollow cylindrical workpieces prior to finishing which were prepared to conduct trials on axial mode UAAFM such that the positioning of the ultrasonic actuator will become axial to these workpieces and the medium flow direction (see Fig. 1 - inset). The Al 2014 alloy chemical composition is shown in Table 1.

![Al 2014 alloy workpieces](image)

**Table 1 Chemical composition of the Al 2014 alloy.**

| Element | Al   | Si   | Mn   | Cu   | S    | Cr   | Zn   |
|---------|------|------|------|------|------|------|------|
| Weight (%) | 91.98| 1.25 | 0.85 | 4.75 | 0.02 | 0.01 | 0.23 |

![Chemical composition table](image)


3.2 Design of experiments

A response to the surface methodology approach is used to explore the responses of surface finish improvement. Accordingly, a set of twenty experiments were conducted based on central composite rotatable design (CCRD) [5]. The process parameters & their levels selected for the trials are given in Table 2 and the experimental results are shown in Table 3. In the present set of trials, abrasive mesh size, media flow rate, media viscosity, and abrasive concentration are maintained constant based on the pilot study and previous investigation. Based on the setup constraints and processing quality requirements, the key input parameters applied frequency (A), extrusion pressure (B), and processing time (C) are varied at three levels.

Table 2 Process parameters & their levels used in an axial mode UAAFM.

| CCRD coded values | Applied frequency (A), kHz | Extrusion pressure (B), bar. | Processing time (C), min. | Response parameters |
|-------------------|----------------------------|----------------------------|---------------------------|---------------------|
| Low (-1)          | 5                          | 10                         | 4                         | Surface finish improvements (%) |
| Middle (0)        | 10                         | 15                         | 6                         | |
| High (1)          | 15                         | 20                         | 8                         | Material removed (mg) |

Constant parameters:
- Abrasive size, mesh: 200
- Abrasive concentration, %: 60:40
- Media flow Rate, m3/s: 560
- Temperature of media, °C: 32 ±2
- Initial surface roughness, µm: 0.9 to 1.0

Table 3 Experimental results

| Run | Type | A (kHz) | B (×10^5 Pa) | C (min) | ΔRa (%) | MR (mg) |
|-----|------|---------|--------------|---------|---------|---------|
| 1   | Fact | 15      | 10           | 4       | 64.31   | 13.072  |
| 2   | Axial| 10      | 20           | 6       | 82.61   | 21.934  |
| 3   | Fact | 5       | 10           | 8       | 67.14   | 8.453   |
| 4   | Axial| 10      | 15           | 8       | 77.12   | 15.293  |
| 5   | Axial| 15      | 15           | 6       | 76.12   | 14.52   |
| 6   | Center| 10     | 15           | 6       | 76.15   | 14.924  |
| 7   | Center| 10     | 15           | 6       | 77.19   | 15.991  |
| 8   | Center| 10     | 15           | 6       | 80.443  | 14.121  |
| 9   | Fact | 15      | 20           | 4       | 80.12   | 15.302  |
| 10  | Axial| 10      | 10           | 6       | 72.12   | 17.32   |
| 11  | Axial| 5       | 15           | 6       | 64.12   | 9.912   |
4. Result and discussion

The improvement (percentage) in material removal and surface finish are computed by measuring the weight of samples and final surface roughness before and after machining using Eqns. (1) & (2). A Taylor-Hobson precision perthometer with gauge range of 300μm and resolution 0.01μm is used for monitoring the surface roughness of the finished surface while the material removal measurements are performed using Shimadzu digital weighing machine (model: AUW220D) with an accuracy of 0.01 mg.

\[
\Delta R_a = \frac{\text{Initial wt} - \text{final wt}}{\text{initial wt}} \times 100 \quad \text{(\%)} \quad \text{Eq. (1)}
\]

\[
\text{MR} = [\text{Initial weight} - \text{final weight}] \quad \text{(mg)} \quad \text{Eq. (2)}
\]

The Analysis of Variance (ANOVA) were carried out at 95% confidence level for surface finish improvement and material removed in axial mode UAAFM process. The quadratic models of respective response characteristics as a function of both the responses for \( \% \Delta R_a \) and \( \text{MR} \) in terms of coded values are presented in Table 4

Figure 4 shows the plot between predicted and actual responses. It is observed that the results between the predicted and actual were very close for both surface finish and material removed (Fig. 4 (a-b)). This confirms that the model is acceptable; further prediction helps in parameter setting directly in a shop floor and provides enough research scope. Furthermore, the experimentally obtained values of the surface roughness corresponding to the initial and final machining conditions are depicted in Fig. 4(c).
Figure 4 Average arithmetic mean (Ra) values corresponding to the initial and final machining conditions.

Table 4 Regression relations for surface finish improvement and material removed.

| Responses                        | R-square (%) | Adjusted R-square (%) | Regression model                                                                 |
|----------------------------------|--------------|-----------------------|----------------------------------------------------------------------------------|
| Surface finish improvement (ΔRa) | 0.9784       | 0.9590                | Surface finish = -32.49042 + 6.42436A - 0.1551B + 18.7766A^2 + 0.046122B^2 + 1.02299C^2 + 0.068400AB - 0.21800AC - 0.1242BC |
| Material removed (MR)            | 0.9831       | 0.9678                | Material removed = +11.83769 + 3.13398A - 4.75976B + 4.98120C - 0.12946A^2 + 0.1669B^2 - 0.50602C^2 - 0.027840AB + 0.053275AC + 0.08962BC |

where A: Applied frequency, kHz, B: extrusion pressure, bar and C: Processing time, min.

The proposed work-piece and abrasive interaction in axial mode were further validated using scanning electron microscopy (SEM). Figure 5 shows a typical surface of Al
2014 alloy work-piece before and after UAAFM. The feed marks were clearly observed on the pre-finished work surface. After finishing with the UAAFM process, the abrasive impacts on the work surface of different irregularities, consequently fine and deep abrasive scratches towards the medium flow direction one clearly visible; a glazed look on the surface was observed (Fig. 5 b)). It is clear from the SEM images that during UAAFM, the asperity peaks of the work surface advance due to the ultrasonically assisted provision and leads to trimmed surface and becomes significantly finer. The surface roughness of the finish machined (AFMed) surface got improved by approximately 50% as compared to the un-finished work surface (Fig. 5(b)). The improvement in surface topography can be further enhanced with optimized setting of the parameters like high frequency, pressure and machining time [4]

Fig. 5(a) Micrograph of Pre-AFMed surface, (b) Micrograph of the axial mode UAAFMed surface at 5 kHz, applied frequency; 10 bar, extrusion pressure; 4 min, processing time.

5. Conclusion

The following are the conclusions that were drawn from the study

- The most significant factor in UAAFM (axially mode) is the applied frequency and extrusion pressure which helps in attaining an improvement in surface finish for upto 85.120% at 10kHz applied frequency, 15 × 10⁵ Pa, extrusion pressure. The maximum value of material removed (MR) obtained in UAAFM is 21.93 mg.
- The prediction capability of the model is evaluated and compared vis-à-vis the predicted values using the regression model.

6. References

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