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Evaluation of optimized surface properties and residual stress in ultrasonic assisted ball burnishing of AA6061-T6

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ABSTRACT

Ultrasonic assisted ball burnishing process is a newly developed alternative of conventional ball burnishing process that enhances the surface properties of engineering materials through imposing both the static and dynamic loadings. The process needs careful selection of design parameters to improve the performance measures such as surface roughness and hardness. In the present study an experimental investigation was carried out to analyze effect of ultrasonic vibration amplitude, feed rate and static force on surface roughness and hardness of aluminum 6061-T6 alloy. Here, number of 20 experiments was carried out through face centered central composite design and values of surface roughness and hardness after each experiment were measured. Hereafter, response surface methodology (RSM) was utilized to correlate empirical relationship between process parameters and responses. Further, numerical simulation of process using ABAQUS software has been carried out to study states of residual stress and plastic equivalent strain under different processing condition. Results indicated that in order to achieve maximum hardness and minimum surface roughness simultaneously, ultrasonic vibration amplitude of 8 µm, feed rate of 1000 mm/min and static force of 38 N, should be selected. The obtained optimal results were then experimentally verified and the prediction errors for both the responses were lower than 10%, implying rigidity of proposed methodology in finding the optimum results. The results obtained by FE simulation showed that the maximum value and effective depth of compressive residual stress in ultrasonic assisted process is significantly higher than that of conventional burnishing.

1. Introduction

Aluminum 6061-T6 alloy has wide application in manufacturing of aerospace and automotive component due to its desired strength to weight ratio. However, poor surface properties such as surface hardness, wear resistance and fatigues strength is main disadvantages associated with this type o aluminum alloy. Hence, surface treatment process is a key operation that should be induced on this alloy to enhance the surface properties.

Burnishing is a surface modification technique that finds its application in various industries as s final finishing process. The process exerts sever plastic deformation on the samples which produced by machining, coating casting etc. By exerting plastic deformation to surface irregularities the distance between peak and valley of decreases and the surface quality enhances. On the other hand, the surface of the material is work-hardened and microstructure of the work surface is refined [1]. Furthermore, during burnishing compressive residual stress is induced at the work surface and causes enhancement of fatigue strength of engineering component [2].

The burnishing process can be used for both the cylindrical and flat surfaces whit different burnishing tool such as ball or roller. In this case, various works have been carried out. Rodriguez et al. [3] applied ball burnishing process to enhance microstructure, hardness and residual stress distribution of as turned rods. In further work, Rodriguez et al. [4] used ball burnishing to improve surface properties of concave and convex surfaces made of aluminum alloy. The results revealed that, higher radius of curvature for concave surface and lower radius of curvature for convex surface cause desired surface quality. El-Taweel and El-Axir [5] analyzed influence of ball burnishing process parameters namely burnishing speed, feed rate, contact force and pass number on surface hardness and roughness through design of experiment approach. Analysis of variances of experimental data showed that contact force is the most influential parameters affecting both the hardness and surface roughness. El-Axir et al. [6,7] developed a ball burnishing tool for inner surface finishing of cylindrical rods. They found that the process yields desired dimensional accuracy and high surface properties for inner surface of AA2014 cylinders. In a separate study, El-Axir et al. [8] used ball burnishing process to enhance the

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state of residual stress and fatigue strength of aluminum 6061 alloy. They revealed that by a careful control on burnishing force and burnishing feed the compressive residual stress is exerted to machined surface that causes a delay in initiation of crack propagation during fatigue testing. Gharbi et al. [9] used ball burnishing process for improvement of surface quality of AISI 1010 as-milled surface. They designed series of experiments based on L_{25} Taguchi design to find effect of spindle speed, contact force, feed rate and pass number on hardness and surface roughness. They found that the contact force has the greatest impact on surface properties. Revankar et al. [10,11] analyzed effect of ball burnishing factors on Ti-6Al-4V. They have found that burnishing with optimal parameter setting significantly improve surface quality and wear resistance. Also, it was shown that as the burnishing force and burnishing feed increases, the values of compressive residual stress exerted to turned surface significantly enhances. Sequera et al. [12] utilized ball burnishing process to study surface quality and integrity Nickel based super alloy Inconel 718 milled flat surface. They have found that increase in ball diameter and burnishing pressure causes a significant reduction of surface roughness.

In various researches, it is reported that static loading caused by conventional burnishing process is not effective enough to change the surface properties of various engineering materials. Hence, recently the process is modified by association of vibratory impacts to conventional burnishing process to provide both the static and dynamic loads form enhancing the materials' surface properties. Rodriguez et al. [13] integrated longitudinal low-frequency vibration with burnishing tool to improve surface characteristics of steel G10380. They analyzed surface roughness, hardness and residual stress of burnished parts. Research finding showed that applying vibration to burnishing tool significantly improves the surface roughness of the burnished sample. Karimi and Amini [14] studied effect of impact number on producing of steel 7225 ultrafine structure. They have found that by increase of impact number through decreasing of feed rate, the surface roughness is significantly reduced and hardness and fatigue life are impressively enhanced. In another attempt, Amini et al. [15] applied ultrasonic peening to enhance the corrosion properties of AA7075 alloy. They showed that by use of tungsten carbide ball and increase in impact number the corrosion properties enhances about 20 times compared to as-received material. Minglang et al. [16] used ultrasonic surface rolling to enhance the fatigue resistance in the root face of the treads made of high alloy steel. They showed that exerting of burnishing process without ultrasonic vibration causes increase of surface roughness from 0.106 μm to 0.194 μm. However, when the ultrasonic vibration is applied on roller burnishing process, it is seen that the surface roughness values decreases to 0.053 μm.

The ultrasonic assisted surface treatment process utilizes the ultrasonic energy and impacts to induce sever plastic deformation on the work surface. However, in majority of the previous works, the pin shape of the tool tip causes sliding friction between tool and surface of the work. This condition causes slight material removal from work surface and destroys the surface quality. For this purpose, during ultrasonic assisted ball burnishing, the rolling friction between tool and work eliminates the material removal and enhances the surface quality.

The burnishing process can be compared with other surface modification techniques such as laser shock peening and shot peening. In some aspects, the burnishing process has superiority compared to the aforementioned processes. In laser shock peening and shot peening the equipment for providing high power laser for former and a gun for former are expensive and the process needs careful control and skilled operator; while the burnishing process can be implemented on a simple lathe or milling machine and requires less skill that is cost effective compared to laser shock peening. On the other hand, the laser shock peening is suitable for only sheet metals while the burnishing can be applied on both the sheet and bulk materials. Also, it is worth mentioning that during shot peening process, only dynamic load (due to impact of ball) affect the surface of component, while for burnishing process both the static load (due to indentation force) and dynamic load (due to feed motion and burnishing speed) are applied on the surface specimen. Therefore, in ball burnishing process the work hardening affected by both the strain and strain rate action that significantly improve the surface properties.

According to what surveyed above, it is found that using response surface methodology incorporating multiple factor and multiple responses for modeling and optimization of ultrasonic assisted burnishing of aluminum 6061 sheet material has hardly been reported in the literatures on the basis of authors' knowledge. Hence, this article deals with the RSM in finding of optimal parameter setting of ultrasonic amplitude, feed rate and static force regarding maximum hardness and minimum surface roughness. Further, this article presents how the response surface obtained by developed RSM models can be used to show interaction and complexity between process factors. It should be stated that in the current work, the optimal parameter setting and corresponding physical meaning refer specifically to work hardening, temperature rising, strain and strain rate effects.

2. Experiments

2.1. Material

The material used in the present work is heat treatable aluminum 6061-T6. Table 1 presents mechanical properties of as received metals. The 2 mm thickness of aluminum sheet were cut into size of 100 mm in length and 50 mm in width and subjected to 3 pass burnishing process. Tables 1 and 2 presents chemical composition and properties of aluminum 6061-T6 alloy.

2.2. Equipment

The burnishing process is carried out on DECKLE CNC milling machine modified with ultrasonic apparatus on machine head. In order to perform ultrasonic assisted burnishing process, an ultrasonic package including power supply, transducer, and horn were designed and associated with CNC machine. A high frequency vibration is provided by a 1000 W SIGMASONIC power supply manufactured in Iran. It transfers the ultrasonic vibration to a transducer comprised by piezoelectric rings, backing and matching. The system causes a ultrasonic frequency vibration in the tip of the horn with 8 μm amplitude. Fig. 1a presents the experimental setup including milling machine and ultrasonic apparatus. To effectively transfer the vibration from the transducer to the ball, a horn should be designed and analyzed to obtain its resonance frequency within the range of 17–23 kHz that is available for this package. In order to attain desired frequency for effective vibration of the tool, the tool was numerically modeled in ABAQUS software and its resonance frequency was determined through modal analysis. Fig. 1b depicts the analyzed vibratory burnishing tool in ABAQUS software along with fabricated one which utilized for experiments. It is seen from the figure that resonance frequency for the vibratory tool is 20,400 Hz that is within the available range.

2.3. Measurement

The ultrasonic apparatus is equipped with a power control system that can regulate the amplitude and frequency of vibration. The system can regulate the efficiency of vibration and show the value as percentage of maximum nominal power that can be generated by power

Table 1
Chemical compositions of Al 6061 alloy.

Components	Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
Percents (%)	0.9	0.62	0.33	0.28	0.17	0.06	0.02	0.02	Bal