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An investigation of ultrasonic nanocrystal surface modification machining process by numerical simulation

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ABSTRACT

As a method for surface severe plastic deformation (S^2PD), ultrasonic nanocrystal surface modification (UNSM) enhances metal surface properties through striker peening, a metal dimpling process driven by ultrasonic vibration energy. UNSM treatment introduces residual stress, surface hardening, and nano-crystalline structures into metal surfaces which are beneficial for reducing wear, fatigue, and corrosion properties. In this paper, the process of UNSM is described and a simplified physical model created using the equivalent static loading method is presented. Along with the simplified physical model, a finite elements simulation model was developed. Effective plastic strain was considered as a parameter for evaluating the level of work hardening produced in the simulation. The dynamic processes and energy dissipation were also examined, and it was found that different kinds of energy dissipation occur during UNSM treatment. Comparisons between the processing parameters (processing velocity, static load, and feed rate) were performed using a simulated example of UNSM linear processing. The results show that the linear processing produces a uniform region containing identical distributions of residual stress and effective plastic strain. The effects of the parameters on the processing results (residual stress, plastic deformation and work hardening) were likewise studied using UNSM linear processing. Compared to processing velocity, a high static load produced more work hardening and higher compressive residual stress. Surface deformation and residual stress results were also more sensitive to static load than processing velocity. Feed rate was found to be an important parameter as well, greatly influencing both surface deformation and work hardening.

1. Introduction

Surface deterioration is one of the most common causes of metal failure, which includes loosening of metal parts due to wear, surface breakage induced by corrosion, and fatigue fractures. Because the occurrence of all of these faults is closely connected to metal surface properties, surface enhancement is often performed to improve the surface properties of metal products. Increasing surface roughness, strength [1,2], abrasion resistance, corrosion resistance [3–5], residual stress [6–12], and fatigue properties [8,9,13] are all types of surface enhancement that can be achieved using various technological means. Compared to other methods for improving the longevity of metal materials, surface treatment is a promisingly low-cost and particularly effective process that enhances the overall quality of metal materials. New surface treatment techniques continue to be developed in order to save energy and shorten processing time, and the discovery of highly efficient and quick techniques will remain an important area for future study.

The S^2PD process was initially proposed by Lu [14] as an effective surface treatment for generating nano-crystalline structures on a material's surface using the method of surface mechanical attrition treatment (SMAT). In Lu's study, spherical balls composed of different materials (such as steel, glass, or ceramic) were vibrated over the surface of a target material using a vibration generator, forcing the balls to impact the target material. A subsequent method for S^2PD was carried out where a large number of balls were fired at the specimen surface from random directions and at high strain rates, introducing severe plastic deformation and grain refinement to the surface layer [15]. In both cases, enhancement of surface layer was produced without a chemical reaction on the material's surface or changing the material's chemical structure.

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A great number of alternative S^2PD methods have been invented and implemented to improve the surface properties of bulk materials: ultrasonic peening (UP) [4], laser shock peening (LSP) [16,17], improved methods of SMAT [18,19], ultrasonic shot peening (USSP) [20], ultrasonic surface rolling processing (USRP) [6], surface mechanical grinding treatment (SMGT) [21], and ultrasonic nanocrystal surface modification (UNSM) [22,23]. With work process principles varying, different levels grain refinement, depth of the processing layer, and size of refined grains differ across methods.

One method of S^2PD, UNSM [8,24–28], has been used to enhance surface properties by producing gradient changes in the grain refinement of a material's surface. In terms of equipment, UNSM requires an ultrasonic generator, an air compressor, a control card, and a guide unit (Fig. 1). UNSM is powered by the ultrasound transducer, which produces tens of thousands, even up to millions, of mechanical ultrasonic waves per second. However, because the ultrasound transducer can generate only a few micrometers of amplitude directly, an acoustic horn is frequently employed to magnify the amplitude. The amplified mechanical ultrasonic wave then used to drive a tip ball so that it strikes the surface of a target material, inducing severe surface plastic deformation on the specimen. Compared to the ultrasonic impact treatment (UIT), UNSM has several advantages. One is its low energy consumption; UNSM has an output power of approximately 1 kW. However, the most notable advantage of UNSM is that the use of static loading during surface treatment ensures uniformity of processing. These advantages have led to the increasingly wide application of UNSM and, for this reason, the processing characteristics of UNSM and the working process employed by UNSM to machine materials must be presented.

In recent years, many numerical studies [10–12,29–50] of S^2PD have been published on simulations designed to examine the process parameters of a developed S^2PD model. Dai and Shaw [51] studied effect of ball diameter and velocity on impact peening and explained how process results varied using different levels of kinetic energy. Achintha [30,46] developed a hybrid explicit finite element-eigenstrain model to investigate the parameters of LSP and found that the study's simulated results corresponded well with its experimental results. Other process parameters and results such as shot peening coverage [42], surface roughness [37], residual stress [30,34,38,39,52], and process angle [49] have been successfully simulated and studied. The simulation of S^2PD to produce surface nano-crystallization was investigated by Bagherifard et al. [53], while other studies found that element size is sensitive parameter in the simulation results [35]. Liu et al. [39] developed a dynamic finite element model for the simulation of USRP using the governing equations ABAQUS/Explicit. USRPed parameters were evaluated according to the study conditions, which stipulated that an effective plastic strain equal or greater than 8 had to be used to form a nanostructured layer. Liu found the parameters required producing a nanostructured surface layer, and also that effective plastic strain is a reliable means of predicting the generation of nano-sized grains.

Taking into account the unique features of UNSM and its similarities with SP and SMAT, in this study, a simplified physical model of the UNSM process was created using the equivalent static loading method. A finite elements simulation model was then developed to investigate the dynamic processes of and energy dissipation during the processing process. Comparisons of different processing parameters—namely, processing velocity, static load and feed rate—were performed using the simulated results of UNSM linear processing. The effects of different parameters on the processing results (residual stress, plastic deformation and work hardening) were then studied using the UNSM linear processing model.

2. Mechanics and model of the UNSM process

2.1. UNSM process

The process UNSM is driven by an ultrasound transducer that produces tens of thousands mechanical ultrasonic waves per second. However, because only a few micrometers of amplitude can be generated by the ultrasound transducer directly, an acoustic horn is frequently is used to magnify the amplitude by dozens, or even several hundred, microns. The amplified mechanical ultrasonic wave is then used to propel a strike pin, so that it strikes the surface thousands of times per second with constant pressure, inducing severe surface plastic deformation. In this study the tungsten carbide (TC) was chosen as the strike pin as the properties of high hardness and high friction resisting. Small mechanical wear can ensure the working accuracy and system stability. A static load produced by air pressure is used to control the level of pressure with which the tip ball contacts the specimen surface. After UNSM treatment, the original grains of the specimen's surface layer have been refined into nanometer-sized grains by severe plastic deformation (SPD). In our study, this entire process was carried out using an ultrasonic generator (30 μm amplitude and 20 kHz), and air compressor devices producing the static force and amplitude of the dynamic load. The TC ball strikes the material surface of a rotating specimen traveling across its length, *s*, in a horizontal direction (Fig. 2).

Using the linear velocity of the rotating specimen and the feed rate of the strike device shaft, the number of strikes to the specimen surface per mm^2 can be calculated with Eq. (1):

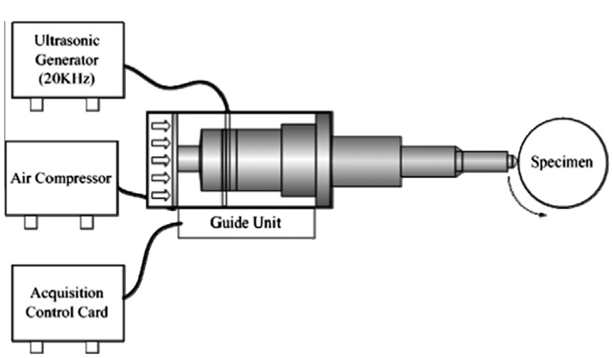

Fig. 1. Schematic diagram for UNSM.

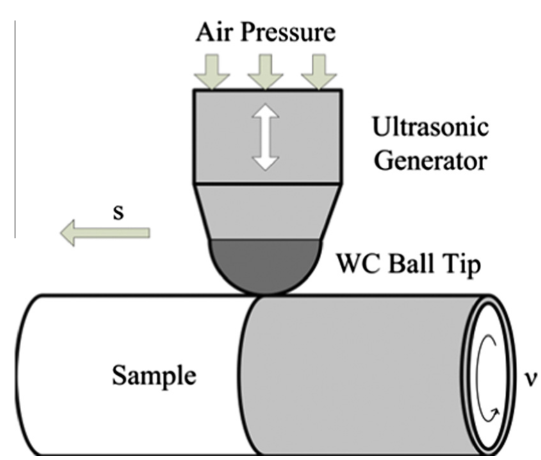

Fig. 2. Process of UNSM.