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Numerical modelling and experimental approach for surface morphology evaluation during ultrasonic shot peening

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ABSTRACT

Surface morphology of severely plastically deformed AISI-1018 steel plates, induced by ultrasonic shot peening process, was investigated by using finite element method and experiments. Experiments were conducted and the surface morphology of the peened samples was measured by non-contact 3D profilometry. Effect of the diameter of the shot and processing time on the surface morphology of the samples was investigated and discussed. In addition, a three dimensional FE simulation model was developed to simulate the deformation and plastic strain of the peened surface after single impact. And a numerical algorithm was proposed to predict the surface morphology of the sample after multiple impacts. The proposed algorithm was verified experimentally and the simulation results show a reasonable agreement with the experimental results.

1. Introduction

The superior properties of nanostructured materials have drawn more and more attentions due to their promising mechanical properties [1–6]. Nanocrystalline materials may exhibit increased strength/hardness, improved toughness, reduced elastic modulus and ductility, enhanced diffusivity, higher specific heat, enhanced thermal expansion coefficient (CTE), and superior soft magnetic properties in comparison with conventional polycrystalline materials [7].

Various processing techniques have been developed to achieve the nanostructured materials and the use of severe plastic deformation (SPD) for the processing of bulk ultrafine-grained materials is now widespread [8–10]. Ultrasonic shot peening has been known to be one of the effective methods for generating nanostructured materials and has been used to generate nanostructured layer on the surface of the peened materials [11–13]. By impacting the surface of a component with spherical shots accelerated by high-power ultrasonic vibration, various microstructures can be obtained in deformed layer, from nanometer-sized grains to submicrometer-sized and micrometer-sized crystallites. These ultrafine-grained microstructures induced by intense plastic deformation during ultrasonic shot peening can significantly improve mechanical performance of the materials and allow easier surface alloying and diffusion heat treatment to be performed at lower temperatures [14–16].

However, a potential drawback of the ultrasonic shot peening technique is rough surface generated by the repeated impacts of the shots. The rough surface may take away the beneficial effects of a surface nanocrystalline microstructure. This phenomenon may induce stress concentration at specific points, thereby facilitating crack initiation under fatigue conditions [17,18]. Therefore, the surface morphology of shot peened materials should be predicted and controlled. The understanding of the mechanism responsible for surface morphology during ultrasonic shot peening process is of scientific interest and technological importance. And an accurate and reliable numerical model for surface morphology prediction during ultrasonic shot peening is still urgently required.

It is well-known that numerical simulation can be considerably helpful to save the costly and time consuming experiments. Several approaches have been suggested in the literature for numerical simulations for conventional shot peening process. Bhuvaraghan et al. used the discrete element method (DEM) in combination with the finite element method (FEM) to obtain reasonably accurate predictions of the residual stresses and plastic strains during shot peening process [19]. Bagherifard et al. developed a finite element model of severe shot peening to predict the treatment conditions that lead to surface nanocrystallization. A method to assess the formation of nanostructured layer of materials based on the values of the equivalent plastic strain is proposed

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[20]. Ma et al. developed a routine using finite element method to perform a molecular dynamic simulation and calculate the dislocation density generated by ultrasonic SP [21].

Although the FE simulation method can predict the residual stresses and plastic strains in a single impact, the 3D modelling of the real ultrasonic shot peing process, in which many successive impacts take place, is very hard to perform because of the huge computing time and memory space required. In this investigation, a numerical model cooperating with the FE simulation method for surface morphology prediction during ultrasonic shot peening process was proposed and verified. The surface morphology of AISI-1018 plates induced by ultrasonic shot peening technique was investigated via physical experiments and FE simulation method. The AISI-1018 steel samples were shot peened and their surface morphology was measured by non-contact optical profilometer. Experimental results suggest that the surface morphology of peened sample can be affected by the processing time and diameter of shots. To reveal the mechanism responsible for surface morphology during ultrasonic shot peening process, a finite element model was established on the Abaqus software platform to simulate a single impact behavior. In addition, a numerical algorithm for surface morphology evolution during ultrasonic shot peening process was proposed subsequently to simulate multiple impacts condition. The calculated results show a reasonably agreement with the experimental results, confirming the accuracy and reliability of the proposed numerical model.

2. Experimental procedure

AISI-1018 steel plates with a nominal thickness of 3 mm were used for the experiments. Fig. 1 shows setup for the ultrasonic shot peening experiments. The equipment consists three parts: the ultrasonic generator, transducer and the horn. The specimen was fixed at the top of the cylindrical container with inner diameter of 20 mm. The distance between the sample and the horn is 10 mm. The shots, commercial S550 stainless steel shots, with a diameter of 1.4 mm, 3.9 mm or 6.4 mm were loaded in the container to provide the desired impacts on the surface of the specimen. Powered by the ultrasonic generator with the frequency of 20 KHz, the shots impact the specimen with an average velocity of 3.6 m/s and frequency of 70 impacts per second per shot measured by high speed camera. Experiments with peening time of 10, 20 and 30 min were performed. Each specimen was processed on one side only with no temperature control during the process. The process parameters during ultrasonic shot peening process, e.g. processing time *T* and the diameter of the shots *D*, were studied experimentally according to the full factorial experimental design listed in Table 1. The number of shots *N* was that which provides 60% coverage of the entire surface of the horn. For shots with diameter of 1.4 mm, 3.9 mm and 6.4 mm *N* is 96, 19 and 6, respectively. And the number of impact for shots with diameter of 1.4 mm, 3.9 mm and 6.4 mm is 403,200, 79,800 and 25,200, respectively with the peening time of 1 min.

3. Results and discussion

3.1. Surface morphology

Fig. 2 shows the surface morphology for the peened samples under different peening conditions. Fig. 2(a-1)–(a-3) are the surface morphology of peened sample with the shot diameter of 1.4 mm and processing time of 10 min, 20 min and 30 min, respectively. It can be seen in Fig. 2(a-1)–(a-3) that with the increment of the peening time, the boundary between the peened area and unpeened area becomes more and more obvious. This phenomenon can also be observed in Fig. 2(b-1)–(b-3) and (c-1)–(c-3) showing the surface morphology of peened sample with the shot diameter of 3.9 mm and 6.4 mm, respectively. That is because with the increasing of peening time, the plastic deformation at the peening area becomes more and more serious.

To get the quantity information of the peened surface, a noncontact 3D profilometry was utilized and the surface morphology of the samples under different peening conditions was measured. Fig. 3 shows the measured results under different peening conditions. Two cross lines on each figure were plotted and used to measure the profile of the rough surface. According to the previous research [18], peak–valley (*P*–*V*) value was used to describe the surface morphology of the peened sample. Each measurement was performed on three samples under the same peening condition and the average value was used. Table 2 shows the measured *P*–*V* value of the peened samples under different peening conditions.

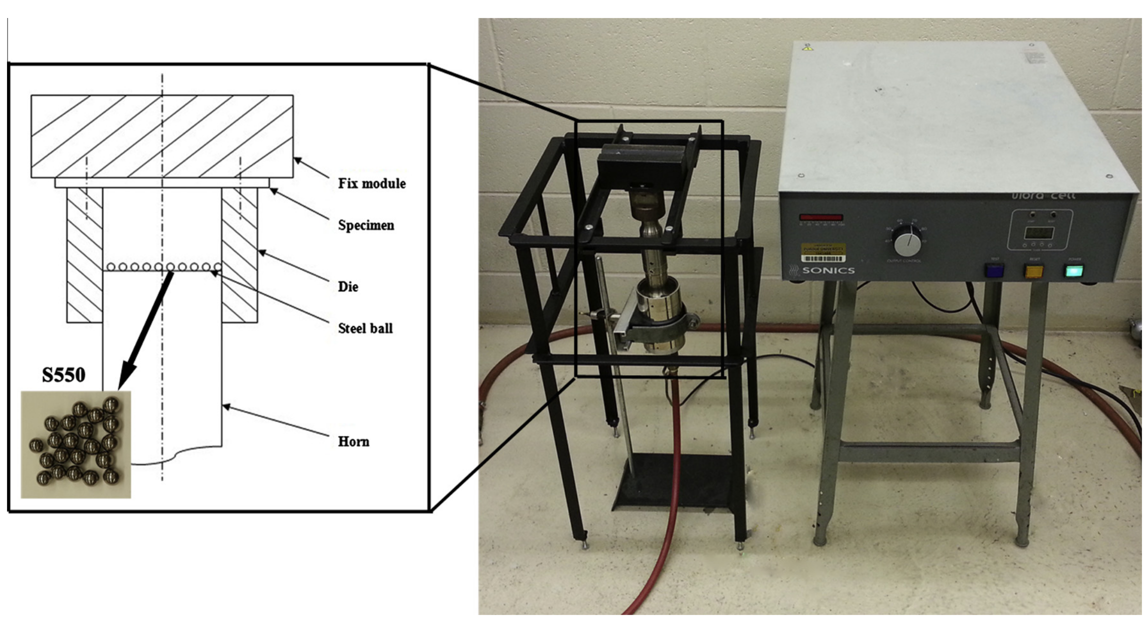

Fig. 1. Design and setup of the ultrasonic shot peening experiments.