Applied Surface Science 347 (2015) 596–601

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Numerical analysis of the residual stress in ultrasonic impact treatment process with single-impact and two-impact models

Guo Chaobo, Wang Zhijiang*, Wang Dongpo, Hu Shengsun

Tianjin Key Laboratory of Advanced Joining Technology, School of Materials Science and Technology, Tianjin University, Tianjin, 300072, China

ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form 16 April 2015
Accepted 18 April 2015
Available online 25 April 2015

Keywords:
Controlled parameters
Residual stress
Finite element analysis
UIT

ABSTRACT

Two 3D finite element models of the Ultrasonic Impact Treatment (UIT) process, a single-impact model and a two-impact model, are presented to simulate pin impact on 2024 aluminum alloy. In the single-impact model, the transformation of the energy and transmission of the stress waves are used to analyze the distributions of the stress field and equivalent plastic strain field during the contact and rebound processes. Further, the effects of the initial impact velocity, pin size, and shape on the residual stress distributions are investigated. In the two-impact model, the two-impact process with different distances is investigated to analyze the effects of the second impact on the residual stress field induced by the first impact.

1. Introduction

Ultrasonic impact treatment (UIT) is a cold-work surface treatment that is widely used to improve the mechanical properties of metals. The process uses a high power ultrasound to drive the pin to vibrate and impact the surface of the specimen. The mechanical peening is performed at a high frequency [1]. Because of the plastic deformation at the sub-surface of the specimen, a compressive residual stress layer, which is beneficial in improving the hardness and fatigue life of the specimen, is produced in the impact process. Its principle is similar to surface deformation techniques such as shot peening, hammer peening, and needle peening [2]. However, the UIT technology can produce a deeper compressive residual stress layer and a larger compressive residual stress, because of which it is widely used in the aerospace, automotive, and power industries, and especially in the welding industry [3,4].

In recent years, the mechanical properties of materials have been investigated by many researchers [5,6]. However, the dynamic behavior of the impacted material during the UIT process is rarely reported. It is well known that the strain rate of the materials is high in the impact process, which complicates the elastic-plastic behavior of materials. However, the rapid development of finite element methods makes it possible to simulate the complex impact process. Nonetheless, the UIT numerical model is rarely reported in the literature. Currently, studies focus on shot peening, from which the UIT technology originated. For the shot-peening model, the static loading model was used in early studies, which was not favorable in the impact process because of the high plastic strain rates. Watanabe et al. [7] and Kobayashi et al. [8] revealed the residual stress distributions produced by a single ball using dynamic and static tests. Johnson [9] developed a dynamic model in which a single shot was considered and the depth of the plastic zone with different, controlled parameters was investigated using a pseudo-dynamic approach. Levers and Prior [10], and Rouhaud and Deslaef [11] established 2D dynamic models to simulate the residual stress field. Meguid et al. [12] presented a 3D model with a square contact surface using periodic symmetric cells to simulate a multiple impact process. Schiffner and Helling [13] considered an equilateral triangle impact surface and three symmetric surfaces in their work and investigated the effect of the adjacent shots in the model. Then, 3D models with two symmetric surfaces are established to simulate the dynamic process. Edberg et al. [14] analyzed the residual stress within viscoelastic and elastoplastic materials using a single shot. Based on the models mentioned above, 3D models with one symmetric surface [15] and no symmetric surface [16] were established. Schwarzer et al. [17] proposed to use infinite elements surrounding the target plate to avoid strain wave reflections. The shot peening models provide the fundamentals for the simulation of the UIT processes. The UIT model could be established by improving the shot-peening model.

In contrast to the shot peening process, in the UIT process the size of the pin is large and the distance between the two adjacent indentations, which can be determined before the impacts, is small. The larger pin size will produce more plastic deformation,

* Corresponding author. Tel.: +86 2227405889.
E-mail address: wangzj@tju.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.apsusc.2015.04.128
0169-4332/

so the induced stress will be non-uniform in each layer with different depths. The different distances between the indentations will change the residual stress distributions. In this study, two 3D numerical models of the UIT process are developed, as described in Section 2, to simulate impacts on a 2024 aluminum alloy, and the models are validated by the size of indentations obtained as a result of multiple impacts (Section 3). After a study of the dynamic impact process described in Section 4, the influences of controlled parameters on the residual stress fields are investigated using the one-impact model. Finally, the two-impact model is used to study the effects of the second impact on the residual stress field induced by the first impact.

2. Finite element models for UIT process

In the UIT process, a sinusoidal electric field is delivered by an ultrasonic wave generator. The electric energy is then transformed into an ultrasonic vibration by an energy transducer and amplified by an ultrasonic horn. The horn knocks the pins onto the surface of the specimen, in which the kinetic energy of the pins functions as the driver of plastic deformation on the surface of the specimen. As the high impact energy occurs at the moment the pins contact the specimen, it is beneficial in producing a compressive residual stress at the sub-surface of the specimen.

2.1. Geometry and boundary conditions for the finite element model

For the characteristics of the UIT process, two 3D models were developed using ABAQUS/Explicit finite element code to simulate the residual stress distributions within the target plate. The single-impact model, as shown in Fig. 1a, is utilized to analyze the residual stress regulations with different controlled parameters. The two-impact model is established to analyze the effect of the distance between the two impacts on the residual stress field, in which the two impacts are substituted by a process where two pins impact the plate successively, as shown in Fig. 1b.

In the two models, the target plates are both of size 8 mm × 8 mm × 5 mm, as shown in Fig. 2. The cells of the plates are hexagonal elements with reduced integration (C3D8R) elements. The base of the target plate is restrained against all displacements. All side faces are surrounded by infinite elements to provide quiet boundaries for keeping the reflection of dilatational and shear waves from the region of interest. The pins are of a size Φ 4 mm × 30 mm and the pin tip is semi-ellipsoid. The pin is meshed with tetrahedral (C3D4) elements.

The pin velocity is an important initial condition for the simulation of the UIT process. The initial pin velocity is determined by the collision of the ultrasonic horn. Chaise et al. [18] reported that the average pin velocity could be as large as the maximum initial velocity of the horn in the ultrasonic shot peening process. The maximum initial velocity of the horn is

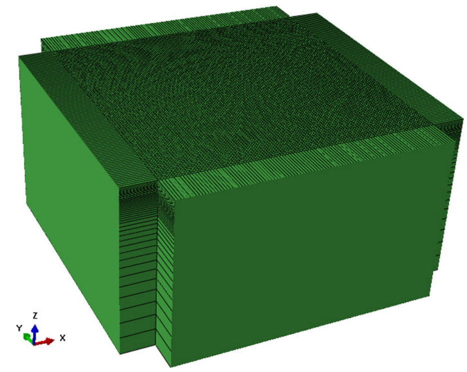

Fig. 2. The cells of the material plate.

$$v_{\text{inimax}} = 2\pi Af \tag{1}$$

In this study, the vibration frequency of the horn f is 20 kHz and the amplitude A is 16 μm. Therefore, the initial velocity of the pins v_{inimax} is 2.0 m/s.

In the impact process, the friction coefficient is another important parameter. In this study, the friction coefficient between the pin and the specimen is set to be 0.25.

2.2. Material model

Since the deformation of the pin is much lesser than the target plate, the pin is assumed to be rigid and the target plate is considered as a non-linear kinematic hardening material. Because of the large deformation of the elastic-plastic material, the Johnson–Cook equation is applied, as expressed by

$$\sigma = \left[A + B(\varepsilon)^n\right]\left[1 + C\ \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T}\right)^m\right], \tag{2}$$

where A, B, C, m, and n are the material constants to be determined. Herein, the Johnson-Cook properties are 369 MPa, 684 MPa, 0.0083, 1.7, and 0.73, respectively, which are the same as those reported in Ref. [19]. Because of the little variation in temperature during the impact process, the influence of temperature is ignored.

3. Model validation

Because of the high impact frequency of the impact process, it is not possible to obtain the results only by one impact. In this study, the finite element model is validated indirectly by the indentation diameter obtained by the UIT process. The profiles of the indentations created on the target plate by UIT are shown in Fig. 3.

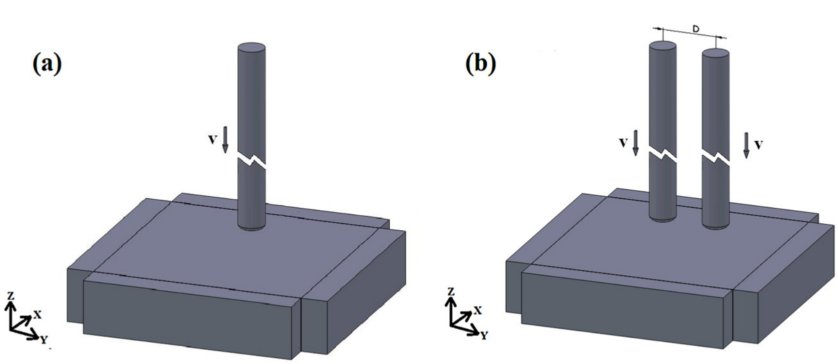

Fig. 1. Impact models with single impact and two impacts. (a) The single-impact model; (b) the two-impact model.