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Optimization of the fatigue resistance of AISI304 stainless steel by ultrasonic impact treatment

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ABSTRACT

The Navarro–Rios model was used to investigate the fatigue resistance of AISI304 stainless steel treated by ultrasonic impact treatment (UIT) in this paper. The finite element model was established using Johnson–Cook materials model to get the needed residual stress and dent profiles, and the damage was also considered in the model. The results show that fatigue property is elevated with the increase of coverage, but would not be developed with the enhancement of impact velocity when it reaches a level for the increase of stress concentration. The optimized UIT parameters for AISI304 are impact velocity of 6 mm/s and coverage of 200%.

1. Introduction

The fatigue lives of engineering components and structures are sensitive to their surface states [1]. In most cases, fatigue damage will initiate at the surface due to the localized stress concentrations or the exposed inclusions in the materials [2]. It is reasonable to enhance the fatigue lives of the materials by means of the surface modification [3]. Ultrasonic impact treatment (UIT) is a new kind of cold working treatment in which a great number of impacts exerting on the specimen surface in a short time for the high frequency of the system, and so far UIT has been widely used in the industry because it is more controllable and convenient to optimize the surface characteristics of the components [4].

UIT has been used to enhance the mechanical properties and the micro structures of titanium, AISI321 stainless steel and aluminium matrix composite. Researchers find out that nanostructured layers are formed on the surface of these materials and the depths of compressive residual stress can reach more than 1 mm [5]. The residual stress could be induced by the treatment, as well as the grain refinement which increases the hardness of the material [6]. It is found that the microhardness of Al matrix composite treated by UIT is about 1.1 GPa even after heated to 623 K [7]. These modifications improve the fatigue limit of different metallic materials [8]. UIT is also successfully applied to enhance the fatigue lives of different types of welded joints [9]. The tensile residual stress, coarse grain and the rough surface of the transition area between welding seam and parent material produced in the process of welding could decrease the fatigue lives of welded joints. The UIT could eliminate the tensile residual stress and produce the compressive residual stress in welded joints. The impact of the pins on the welding toe produces the groove in the transition area which decreases the stress concentration, and the severe plastic deformation induced by UIT could refine the coarse grains in the welded joints. All these are the main features of the UIT promoting the fatigue properties of welded joints [10–12].

With the characteristic profile of residual stress, microstructure change, and near-surface strain hardening developed by the UIT, the indentations are also induced as material responses for the impact of the pins, which increase the surface roughness of the components [13]. In terms of fatigue damage, the strain hardening can retard the propagation of the cracks by increasing the resistance to plastic deformation and the residual stress profile provides a corresponding crack effective opening stress which reduces the driving force for crack propagation [14]. But the dents can accelerate the nucleation and early propagation of cracks for they act as stress raisers which are adverse for the fatigue properties of the materials [15]. To obtain the maximum fatigue strength, the designer needs to consider both beneficial and detrimental aspects of these responses together. According to above researches, it lacks a scientific quantification of the effects of UIT parameters on the fatigue lives of the materials which may degrade the properties of the materials.

In light of the residual stress profile, the magnitude of the strain hardening and the corresponding amount of surface roughness, it is realistic to assume that UIT mainly affects the stages of fatigue

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damage corresponding to the initiation and propagation of short cracks. It is well documented that above stages are responsible for more than 70% of the fatigue life of a component [16]. The Navarro–Rios (N–R) model which is based on the continuous distribution of dislocations proposed by Bilby et al. [17] is successfully applied to analyze short cracks growth which is several times longer than the microstructural dimension defined by the length of a grain [18]. In this study, the N–R model is employed to theoretically investigate fatigue damage of AISI304 stainless steel treated by the UIT. The optimizing input parameters are obtained to improve the fatigue life of the material.

2. The UIT process

As depicted in Fig. 1, the UIT equipment consists of ultrasonic generator with a frequency of about 21 KHz and an output power of about 1.5 kW, piezo-ceramic transducer, step-like ultrasonic horn made of strength material, and the impact head installed on the horn tip. Cylindrical pins located in the impact head can move between the horn tip and the treated surface freely [19]. Considering that pins acquire their kinetic energy from the vibrating of ultrasonic horn tip (E_{us}) (vibration frequency f_{us} and amplitude ξ) and from the moving of the impact head/sample (E_r), the mechanical energy P can be estimated according to the following expressions during each impact [20]:

$$P(W/g/impact) = \frac{f_i E_k}{m} = \frac{f_i}{m}(E_{us} + E_r) \approx \frac{f_i}{m}[2\pi^2 f_{us}^2 \xi^2 m_P + E_r] \qquad (1)$$

$$v = 2\pi f \xi \qquad (2)$$

where $f_i \approx 3 \pm 0.5$ KHz is an impacting frequency, v is the pin velocity, m is the coefficient with the mass dimension, which takes into account the correlation between the pin mass m_P and the sample mass m_s. During the treatment process, the repeated multidirectional impacts at high rates onto specimen surface leads to severe plastic deformation on the materials' surface. The main parameters of the ultrasonic impact equipment in this paper are as follows: the vibration frequency driven by an ultrasonic generator is 20 KHz, the pin's diameter and length is 3 mm and 25 mm, respectively.

There are two important practical parameters in the UIT process which have been universally accepted and adopted by engineers. They are the intensity of treatment and the coverage. The intensity is determined by the pin velocity according to the above equations, and the coverage is defined by the total treated surface area divided by the deformed area. In this study, the pin velocity (changed from 3 m/s to 8 m/s according to the equipment parameters in which the E_r is ignored) and the coverage (changed from 16% to 200%) are chosen as the input parameters for the optimization to gain a better fatigue life of the treated AISI304.

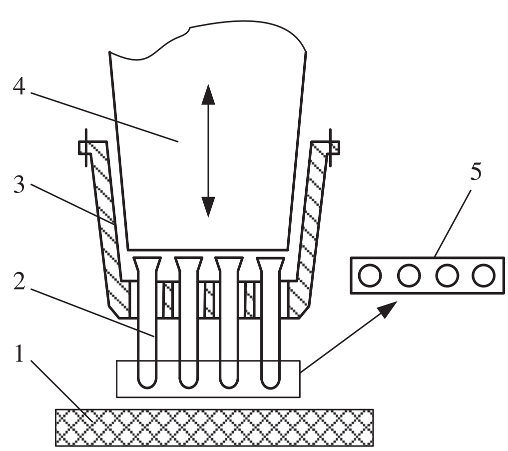

Fig. 1. Impact head used in UIT: (1) sample, (2) pin (s), (3) head body, (4) ultrasonic horn, and (5) the array of pins on the head.

3. FEM model development

The residual stress profiles developed by UIT with different input parameters are important for our research. There are many methods to get the residual stress field of the materials after the treatment. The directly measurements using the instrument like XRD are expensive and time-consuming for large amount of treated materials, and it is hardly to gain the whole three dimensions (3D) information of the stress field.

The finite element method (FEM) has been proved to be an effective method to get the material response during the dynamic process by many researchers, and the validity of FEM has been demonstrated by many experiments [21]. In this paper, a 3D FEM model is developed to gain the residual stress and the surface dent profile of the material after the treatment with different input parameters. In the model, the damage is also considered to find out whether there is small crack initiation during the UIT process which may weaken the fatigue life of the treated materials.

3.1. Specification of constitutive material behavior

During the UIT process, the impact velocity is high and the effect of strain rate cannot be ignored. For this reason, the Johnson–Cook material model is employed as the hardening law [22]. In the model, the Von Mises flow stress, $\bar{\sigma}$, is expressed as:

$$\bar{\sigma} = \left[A + B(\bar{\varepsilon})^n\right]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \qquad (3)$$

where A is the initial yield strength of the material at ambient temperature (T_r), B is the strain hardening coefficient, and C represents strain rate sensitivity. The equivalent plastic strain rate $\dot{\bar{\varepsilon}}$ is normalized with a reference strain rate $\dot{\bar{\varepsilon}}_0$. T is the current temperature, and T_m is the melting temperature of the material. The parameter n takes into account the strain hardening role, and the parameter m models the thermal softening effect. Material properties and Johnson–Cook parameters of the stainless steel AISI 304, which we used as the target metallic material, are given in Table 1 [23]. Considering the high speed and heavy impact pins, a strain rate-dependent, critical plastic strain-based fracture criterion is employed to simulate whether failure would happen during UIT process. The fracture strain is established as a tabular function of strain rate, based on the experimental work of Lichtenfeld et al. [24] on grade 304 stainless steel, i.e. The fracture strain is assumed to decrease by 20% compared to the quasi-static value (measured experimentally) for a strain rate of $10^4\ s^{-1}$. This progressive reduction in fracture strain is shown in Fig. 2.

Table 1
Simulation parameters for AISI 304 [21].

Material	S30403
A (MPa)	310
B (MPa)	1000
C	0.07
n	0.65
m	1.0
$\dot{\bar{\varepsilon}}_0$	1.0
T_m (°C)	1673
Density ρ (Kg/m^3)	7900
Young's modulus E (GPa)	200
Poisson's ratio υ	0.3