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Ultrasonic treatment by an intermediate striker: Tool dynamics and material improvement

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ABSTRACT

A dynamic model of the ultrasonic impact tool with an intermediate striker is considered as a two-mass system with two impact joints. Direct measurements of the period of the sequence of impact pulses and duration of a single impact of striker upon the treated surface are assumed as a basis for theoretical description. Amplitude-frequency and phase-frequency characteristics of the impact oscillations of ultrasonic converter and striker are calculated with the use of methods of the theory of vibration-impact systems. An oscillatory stability of ultrasonic vibrations of striker with the rebounding from the converter tip and the surface being treated (impact mode) as well as in-phase ultrasonic vibrations without detachment of striker from the both surfaces is investigated. It is shown, that the amplitude of the impact oscillation of striker weakly depends on the pressing force in the sufficiently wide limits of variation of the pressing force value. Hardening of treated material and redistribution of residual weld stresses is investigated with the use of the metallography methods. The beneficial compressive stresses are generated (induced) inside the narrow surface layer in the result of fine crushing of crystalline grains of metal.

1. Introduction

Multi-striker ultrasonic impact tools are successfully used for vibration machining of weldments [1]. The intermediate needle-like strikers oscillate in the gap between the end face of the ultrasonic converter and the specimen being treated (Fig. 1a). This striker is employed for surface strengthening and plastic deformation of material in the local contact spot. An overview of physics and technology of ultrasonic treatment is given in papers [1,2]. An improvement of fatigue properties is achieved due to material hardening, the redistribution of residual weld stresses and creation of beneficial compressive stresses in the surface layer of the treated material.

Three physical zones of effect of the ultrasonic impact treatment on material properties and microstructure were described in [1,2]: (1) zone of plastic deformation and compressive residual stresses; (2) zone of relaxation of welding residual stresses and (3) zone of nanocrystallization [3] or "White layer" [1]. It is shown [3], that the depth of penetration of the compressive residual stresses measured by different nondestructive techniques well correlates with the depth of plastic deformation that is determined by microhardness measurements.

A comparative investigation of ultrasonic vibration-impact systems with a ball-shape and a needle-shape striker are presented in [1]. It is shown that the greater efficiency of ultrasonic impact treatment is achieved for the needle-like striker. Moreover, the needle-like strikers provide processing of rough welds in difficult-to-access places such as crossing welds. The light-weight (a few grams) strikers reduce their influence on an operation frequency and amplitude of the ultrasonic converter. This allows to keep the low-power ultrasonic converter in resonance under a large pressing force.

Two different modes of ultrasonic vibrations of the intermediate striker in the gap were described in [1]: (a) ultrasonic vibrations of striker with rebounding from the converter tip and the specimen surface, (b) in-phase continuous (without detachment) ultrasonic vibrations of an striker in synchronism with these surfaces. Along with the vibration-impact mode at the drive frequency the possibility excitation of sub-harmonic and non-periodic oscillations of a striker was noticed [2].

Our recent experiments with the advanced tool [4] show that the frequency of periodic impacts of striker upon the treated specimen is equal to ultrasonic frequency [5]. The ultrasonic impact processing is a cyclic alternation of setting-up and failure of vibration-impact oscillations of striker inside the varying gap. A dynamic model of the proposed ultrasonic tool is presented as a system of two concentrated masses with two impact joints [6].

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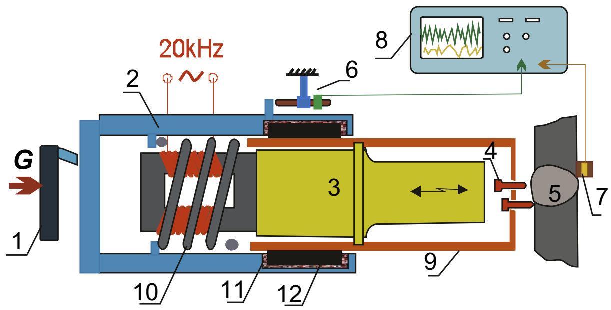

Fig. 1. Ultrasonic tool scheme [4]: 1 – pressing weight, 2 – tool casing, 3 – magnetostrictive vibrator, 4 – intermediate striker, 5 – weld, 6 – displacement gauge, 7 – piezoelectric sensor, 8 – oscilloscope, 9 – holder, 10 – spring, 11 – elastic gasket, 12 – guide rail.

Steady state vibration-impact modes are calculated under the assumption of harmonic oscillation with an unchangeable amplitude and frequency of the ultrasonic vibrator.

However, such theoretical approach cannot take into account the dependence of resonance properties of the ultrasonic vibrator on an external load. It is known [7], that due to a nonlinearity of the impact interaction the resonance amplitude and frequency of the ultrasonic vibrator depend on a pressing force, a contact rigidity, a mass of attached tool and some other structural and technological parameters. Furthermore, two kinds of the vibration-impact operation can be excited in ultrasonic systems with two degrees of freedom [8]: the in-phase mode (when the contacting surfaces move in the same direction) and the opposite-phase mode (when the contacting surfaces move in opposite directions).

This paper considers ultrasonic impact treatment with the unfixed striker as forced oscillations of two nonlinearly connected vibration subsystems. The first subsystem describes a stepped waveguide of the ultrasonic vibrator, which is approximated by a viscous-elastic rod. The second subsystem consists of concentrated mass (equal to the striker's mass) and a rigid stopper, that describes the elastic-dissipative properties of the material being treated. Nonlinearity of contact interaction for both impact joints is described in the frames of harmonic linearization method [7]. The influence of the static pressing force on the amplitude-frequency and the phase-frequency characteristics of ultrasonic converter is investigated.

The study of the effect of the ultrasonic impact treatment on microstructure and mechanical properties of a heat-resistant steel have been made with the use of the metallography methods.

2. Ultrasonic tool dynamics

2.1. Experiment

The scheme of the tool for ultrasonic impact machining is shown in Fig. 1 [4]. Ultrasonic converter 3, which have a mounting flange at the node of longitudinal oscillations of the waveguide-concentrator, is pressed by the static force G to strikers 4. The strikers are enclosed into a holder 9 (two strikers are shown) and are free to move along the axis of waveguide. The force of the impacts of the strikers upon the specimen is measured by a piezoelectric transducer 7. The position of tool casing is registered by a linear displacement gauge 6. The vibroprotection of tool casing from the source of the ultrasonic oscillations is provided by a spring 10 and elastic gaskets 11 made of the vibroinsulation material.

Because of a high roughness of the weld surface only, one any striker comes in contact with the highest point of the specimen, while the others are staying in the rest. The machining is carried out alternately by one of the strikers (one after another). Therefore, we consider the oscillations of only one striker of the multi-striker ultrasonic tool.

Dynamical behavior of the ultrasonic impact tool was investigated experimentally by simultaneous measuring the force pulses of striker's impact on the specimen (butt-welded steel plate) and the dynamic drift of tool casing. The electrical signals from a linear displacement sensor 6 and a calibrated piezoelectric gauge 7 were fed to the two-channel digital storage oscilloscope (Fig. 1).

Oscilloscope pictures Fig. 2 with different scanning rates show that the frequency of impacts is equal to the ultrasonic frequency. Periodical variations of the amplitude of impact pulses are caused by the long-period oscillation of tool casing [5]. From the rapid scan-picture the duration of single collision of the striker with the specimen can be estimated as 10 μs that is about one quarter of the ultrasound period. This result indicates the separation of the contact surfaces due to the striker rebound from the specimen. This observation causes us to describe a contact interaction between the striker and the workpiece as the elastic-dissipative collision in the course of the following theoretic consideration.

2.2. Theory

Using the concept of a dynamic compliance operator [7], let us write the equation of longitudinal displacements of the waveguide-concentrator end face $u_1(t)$ and the striker $u_2(t)$:

$$\begin{aligned} u_1(t) &= L_1(\omega)P_1(t) - L_1(\omega)\Phi(u_v, \dot{u}_2) + L_1(0)G, \\ u_2(t) &= L_2(\omega)\Phi(u_v, \dot{u}_2) - L_2(\omega)Q(u_2, \dot{u}_2), \end{aligned} \tag{1}$$

where $u_v(t) = u_1(t) - u_2(t)$ is a relative displacement of contacting surfaces of the waveguide and the striker; $L_n(\omega)$ (n = 1,2) are operators of the dynamic compliance, connecting the displacement $u_n(t)$ with external forces applied to the ultrasonic vibrator.

Following to [7] we consider that the exciting force $P_1(t) = P\cos\omega t$ acts on the end face of the ultrasonic vibrator, $\omega = 2\pi f$, where f is the frequency of the supply generator. Functions $(\Phi u_v, \dot{u}_v)$ and $Q(u_2, \dot{u}_2)$ describe the force of impact interaction of the striker with the waveguide and the specimen respectively. Subtracting the second equation from the first, we obtain the equation for relative motion of contact surfaces of the waveguide and the striker

$$\begin{aligned} u_v(t) = {} & L_1(\omega)P_1(t) - [L_1(\omega) + L_2(\omega)]\Phi(u_v, \dot{u}_v) + L_1(0)G \\ & + L_2(\omega)Q(u_2, \dot{u}_v). \end{aligned} \tag{2}$$

Using the harmonic balance method, we seek solutions of Eqs. (1) and (2) in the following form:

$$u_n(t) = m_n + a_n e^{i(\omega t - \varphi_n)}, \quad n = 1, 2, v \tag{3}$$

where a_1, a_2, a_v are amplitudes; φ_1, φ_2, φ_v are phases of absolute and relative oscillations of the waveguide and the striker; m_1, m_2, m_v are constant components of displacements. Carrying out the harmonic linearization of impact functions we obtain:

$$\Phi(u_v, \dot{u}_v) = f(m_v, a_v) + [k(m_v, a_v) + i\omega\delta(m_v, a_v)]a_v e^{i(\omega t - \varphi_v)}, \tag{4}$$

$$Q(u_2, \dot{u}_2) = g(m_2, a_2) + [q(m_2, a_2) + i\omega\gamma(m_2, a_2)]a_2 e^{i(\omega t - \varphi_2)}, \tag{5}$$

where $f(m_v, a_v)$, $g(m_2, a_2)$ are static components of contact interaction forces; $k(m_v, a_v)$, $q(m_2, a_2)$ are harmonic coefficients of elasticity; $\delta(m_v, a_v)$, $\gamma(m_2, a_2)$ are harmonic coefficients of viscosity. Substituting Eqs. (4) and (5) into Eqs. (1) and (2) and separating oscillatory and permanent components we obtain for the relative oscillations of the contacting surfaces:

$$a_v e^{-i\varphi_v} = L_1(\omega)P\{1 + L_2(\omega)[q(m_2, a_2) + i\omega\gamma(m_2, a_2)]\}L_0^{-1}(\omega), \tag{6}$$