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Experimental research on constant-current source ultrasonic strengthening characteristics of 7075-T651 aluminum alloy †

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Abstract

7075-T651 aluminum alloy, which is is widely used in aircraft structural parts, exhibits high-strength deformation. This study proposes using ultrasonic impact enhancement technology to improve the fatigue resistance of this alloy and extend its service life. The principle of ultrasonic impact enhancement is based on equivalent impedance control. The surface-strengthening effect is verified via experiments. Results revealed that the surface roughness of the workpiece decreases from an original value of 0.713 μm to as low as 0.353 μm. The microhardness of the surface increases from 201 to 260 $HV_{0.1}$. The residual stress of the surface also increases from −25 to −312 MPa. Under the constant impedance threshold, the surface roughness of the workpiece decreases and the surface microhardness as well as residual stress increase with increasing current output. Under the constant output current, the surface roughness of the workpiece decreases to its minimum value, the microhardness gradually increases, and the residual stress reaches its maximum value with increasing impedance threshold.

Keywords: Ultrasonic strengthening; Equivalent impedance; Constant current; Surface roughness; Microhardness; Residual stress

1. Introduction

High-strength aluminum alloys are widely used in aviation because of their superior properties, which include lightweight structures, good strength, high toughness, and good heat resistance. 7075-T651 alloy, also known as Al-Zn-Mg-Cu super hard aluminum alloy, exhibits typical high strength and is one of the most important structural materials in aviation, aerospace, weapons, transportation, and other industries. This alloy is also used to produce aircraft structural components and other high-strength structural stressors [1-3]. Moreover, it exhibits ultra-high-strength deformation, with yield strength close to its tensile strength but poor plasticity.

Scholars have reported that aluminum alloys are sensitive to damage induced by corrosion fatigue [4-6]. In recent years, a large number of comprehensive studies have been performed to improve the strength, ductility, toughness, corrosion resistance, and fatigue properties of alloy materials. Current research has been focused on developing methods to improve alloys' material performance and prolong their service life by investigating fracture, fatigue, corrosion, aging, and other issues.

In engineering practice, surface-strengthening techniques are often used to extend the service life of aircraft structures. Surface deformation enhancement technology aims to improve the fatigue life of a material by strengthening important key parts without changing its structure or increasing its weight. This technology comprises shot peening, rolling, and internal crushing. Thus far, ultrasonic peening, ultrasonic rolling, ultrasonic impact, and other strengthening technologies have emerged. Ultrasonic peening is a new technology in which an ultrasonic transducer that emits high-power ultrasound as driving energy for metals or ceramic pellets via a horn is used to shot-peen a surface [7-10]. Ultrasonic impact treatment (UIT) technology utilizes high-power ultrasound as a driving energy. This technology converts electrical energy into mechanical energy using a piezoelectric ceramic or magnetostrictive transducer. After amplification and massing of energy by the condenser, UIT induces impact pinning to affect the weld joint surface at a frequency of 20 kHz. This phenomenon leads to the generation of local plastic deformation and residual compressive stress on the material surface. Hence, UIT can reduce the welding residual stress, improve the weld toe geometry, decrease welding deformation, and consequently increase the fatigue resistance of the welded joint [11-16].

Rodopoulos et al. [17] studied the effect of UIT on the fa-

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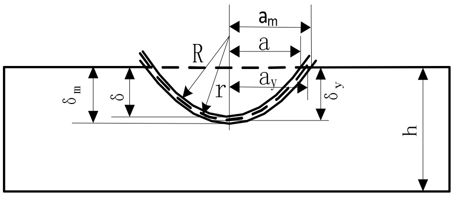

Fig. 1. Diagram of ultrasonic impact enhancement.

tigue resistance and microstructure of a 2024-T351 aluminum alloy friction-stir-welded joint. Although the high compressive residual stress introduced by UIT greatly reduces the fatigue crack growth under a low stress intensity factor, the effect of this method might be small at a high stress intensity factor. Feng et al. [18] conducted impact strengthening on five groups of D36 steel plates with different folds and analyzed the effect of initial surface shape and impact head size on the stress distribution and microhardness. The folding defects affect the surface fatigue life, thus requiring a firing pin with a large diameter when the folding surface is large.

Most ultrasonic impact techniques are manually controlled, and the effect of surface treatment is often difficult to achieve [19-21]. Therefore, we propose an ultrasonic impact enhancement technology based on equivalent impedance control. This method combines ultrasonic shot peening and ultrasonic impact processing technology to automate the enhancement process and predict the enhancement effect. Controlling the size of equivalent impedance enables the control of the magnitude of the processing force while maintaining the processing gap within a certain range. The proposed technology improves the consistency of the processing surface and offers an automated process.

2. Experimental procedures

2.1 Principle of ultrasonic impact enhancement

In ultrasonic impact enhancement, the tool head is hemispherical and each impact can be equivalent to the impact of a rigid ball on an elastic–plastic sheet. If deformation remains within the elastic range, then this process is similar to Winkler foundation. The elastic modulus of the foundation can be equal to the elastic modulus of the sheet, i.e., $k = E$. According to the Winkler foundation model, the relationship between load P and displacement δ is [22]:

$$P = \frac{\pi}{4}\left(\frac{ka}{h}\right)\frac{a^3}{R} = \frac{\pi ER}{h}\delta^2, \delta = \frac{a^2}{2R}. \quad (1)$$

The maximum compressive strain δ / h reaches the yield strain ε_y of the material, i.e., $\delta = \delta_y = h\varepsilon_y = \frac{Yh}{E}$ at that moment; the yield load is $P_y = \frac{\pi Y^2 hR}{E}$.

When the impact continues, i.e., when $\delta > \delta_y$, an elastoplastic stress distribution exists below the rigid sphere. If the material is perfectly elastoplastic, the elastic–plastic boundary is at $r = a_y$ (Fig. 1) and the vertical displacement is $u = \delta_y$ at this point. Given that $u_z(r) = \delta[1-(r/a)^2]$, the following relationship must be established.

The stress distribution can be expressed as $\left(\frac{a_y}{a}\right)^2 = 1 - \frac{\delta_y}{\delta}$ and $\delta_y = \frac{Yh}{E}$.

Therefore, the contact force can be calculated as

$$\sigma_z(r) = \begin{cases} Y & 0 \le r \le a_y \\ \frac{Eu_z}{h} = \frac{E\delta}{h}\left[1-\left(\frac{r}{a}\right)^2\right] & a_y < r \le a \end{cases}. \quad (2)$$

The contact force can also be calculated as

$$P = 2\pi\int_0^{a_y} Y_r \bullet dr + 2\pi\int_{a_y}^{a} \frac{E\delta}{h}\left[1-\left(\frac{r}{a}\right)^2\right] r \bullet dr = \pi YR(2\delta - \delta_y). \quad (3)$$

Eq. (3) holds when $\delta \ge \delta_y = Yh/E$. By combining Eqs. (1)-(3), we obtain

$$\frac{P}{P_y} = \begin{cases} \left(\frac{\delta}{\delta_y}\right)^2, & \delta \le \delta_y \\ 2\frac{\delta}{\delta_y} - 1, & \delta \ge \delta_y \end{cases}. \quad (4)$$

The relationship between load and displacement is expressed as a curve in Fig. 2.

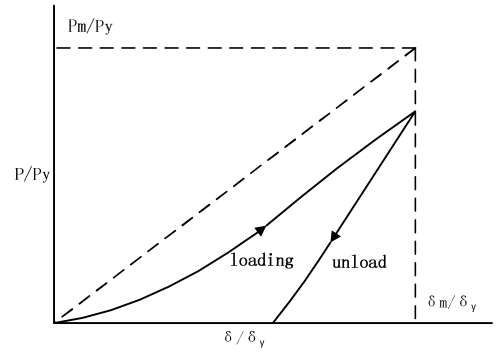

Fig. 2. Relationship between load and displacement.

2.2 Diagram of the ultrasonic impact enhancement system

Ultrasonic impact strengthening is a new method for improving surface deformation. The working principle is surface plastic deformation caused by the high-speed impact of the tool head on the surface of the metal material driven by ultrasonic vibration. The plastic deformation layer on the metal surface changes the residual compressive stress field and the microstructure of the material. This, the mechanical properties,

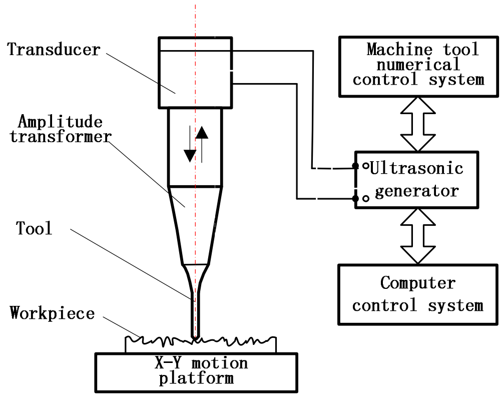

Fig. 3. Diagram of the ultrasonic impact enhancement system.

such as strength, hardness, corrosion resistance, and fatigue life of the metal material, are improved. The principle of ultrasonic impact enhancement is shown in Fig. 3.

The equipment for ultrasonic impact enhancement consists of an ultrasonic generator, an ultrasonic vibration system, and a machine body. The ultrasonic generator, also called an ultrasonic power supply, is an important part of the power ultrasound system. The generator transforms ordinary alternating current (AC) into a high-frequency AC signal to excite the ultrasonic transducer, provide energy for reciprocating vibration on the tool face, and affect the surface to be machined. The ultrasonic vibration system consists of an ultrasonic transducer, an amplitude transformer horn, and a tool. The transducer converts electrical energy into acoustic energy, amplifies and collects amplitude through a horn, and strikes the surface of the workpiece with a tool to strengthen its surface. The machine body achieves *X–Y* table motion control and feed movement along the *Z* axis. The ultrasonic impact enhancement technology based on equivalent impedance control integrates ultrasonic shot peening and ultrasonic processing technology. The tool is designed to be hemispherical, with impact similar to that of a single shot. Through its trajectory, the tool achieves uniform coverage of the workpiece being processed and controls tool feed movement via equivalent impedance control.

2.3 Equivalent impedance control strategy

In an ultrasonic vibration system, the relationship between the equivalent impedance of the piezoelectric transducer and the load changes is analyzed on the basis of mechanical–electrical analogy. The larger the load of the transducer, the higher the equivalent impedance will be [23, 24]. When a constant-current source is used to excite an ultrasonic transducer, the amplitude of the tool face is proportional to the operating current of the ultrasonic power supply and the series resonant impedance increases with decreasing gap between the tool balance position and the workpiece [25]. In ultrasonic impact enhancement, the ultrasonic vibration of the tool continuously impacts the material surface. A gap is observed between the tool and the workpiece, and the gap size reflects load changes. When the ultrasonic impact is strong, the load and the equivalent impedance increase. By contrast, under smaller loads, the equivalent impedance is lower.

In ultrasonic impact enhancement, the size of the load is a function of the magnitude of force, which is directly related to surface deformation. The magnitude of the control force can ensure the surface treatment effect. For ultrasonic vibration frequencies > 20 kHz, the response frequency of the general force measurement system often cannot meet the requirements, thereby complicating the structure of the entire system. We developed a constant-current-type ultrasonic generator. The digital signal processor (DSP) is the core of the system. The complex programmable logic device is mainly responsible for data transmission. DSP is mainly responsible for providing direct digital synthesizer signals, tracking frequency, and monitoring circuits. The system is self-designing. The impedance information of the transducer can be extracted in real time using the ultrasonic generator. When a constant-current source is used to excite the ultrasonic transducer, the amplitude of the tool face is proportional to the operating current of the ultrasonic power supply. The series resonant impedance of the ultrasonic vibration system and the tool balance position are negatively correlated with the gap between workpieces [24]. An automatic feed adjustment system based on equivalent impedance control is designed to ensure the stability of the machining force during ultrasonic impact enhancement. This system uses an ultrasonic generator to detect real-time voltage and current signals at both ends of the transducer. Thus, real-time load impedance data are obtained. The measured value is compared with the impedance threshold set in the computer system. When the measured value is greater than the impedance threshold, the computer control system sends a pulse signal to the machine motion control via the ultrasonic generator DSP to bring the tool back. The computer control system moves the tool forward when the measured value is smaller than the impedance threshold. In ultrasonic impact enhancement, the mechanical properties of the machined surface are improved to a certain extent by changing the magnitude of the impedance threshold.

2.4 Experimental equipment and processing parameters

The ultrasonic impact enhancement experimental system based on equivalent impedance control is shown in Fig. 4. According to the frequency impedance characteristics of the transducer at the resonance point, the equivalent impedance of the vibration system increases with increasing load because the transducer operates at the series resonance point. When the load is increased, the output power of the ultrasonic power supply increases. Thus, the use of constant-current power supply excitation is conducive to the power output of the power supply. With the constant-current ultrasonic power as the driving energy, the ultrasonic impact enhancement technology converts electrical energy into mechanical energy via

Table 1. Experimental parameters of ultrasonic strengthening of 7075-T651 aluminum alloy.

Frequency *f* (kHz)	28
Tool (spherical) diameter *D* (mm)	3
Time *T* (min)	30
Current amplitude I_{rms} (mA)	200, 250, 300, 350
Impedance threshold *Z* (Ω)	70, 75, 80
Surface roughness *Ra* (μm)	0.713
Microhardness ($HV_{0.1}$)	201
Residual stress σ (MPa)	−25

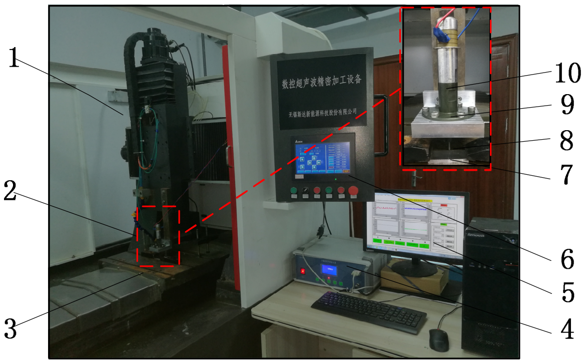

Fig. 4. Ultrasonic impact enhancement experiment system (1. Feed system, 2. Vibration system, 3. *X–Y* motion platform, 4. Ultrasonic generator, 5. Computer control system, 6. Machine control panel, 7. Workpiece, 8. Tool, 9. Amplitude transformer horn, 10. Transducer).

the transducer, and the amplitude is amplified, thereby driving the tool head to impact the machined surface. Thus, local plastic deformation and residual compressive stress are formed on the material surface. The ultrasound tool head adopts an approach based on equivalent impedance control. This approach can achieve constant force control. With 7075-T651 aluminum alloy as the processing object, we performed surface-strengthening treatments. The effects of the processing current and the impedance threshold on the machined surface roughness, residual stress, and microhardness were studied.

Single-factor analysis was used to conduct experiments on the ultrasonic impact enhancement technology. The specific test conditions are shown in Table 1.

3. Results and discussion

3.1 Real-time impedance under different threshold

During the experiment, the output current was set to 300 mA according to the output power of the power supply, and the impedance threshold was set to 70, 75, or 80 Ω. The impedance value of the vibration system during the process was collected in real time through the power supply system. Fifty values were acquired every minute. The measurement results are shown in Fig. 5. The real-time impedance value fluctuates around the threshold, and the real-time impedance

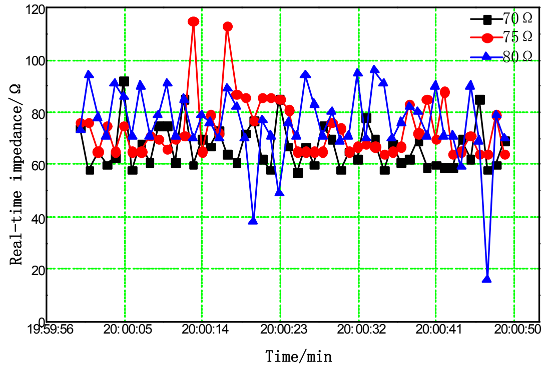

Fig. 5. Impedance under different impedance thresholds.

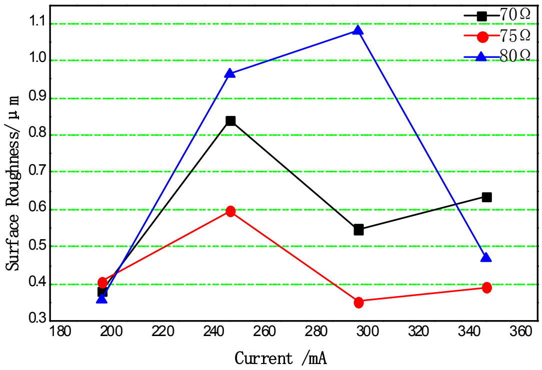

Fig. 6. Effect of current on surface roughness.

value reflects the processing state. When the impedance is large, the workpiece surface is not flat. When the impedance is small, the workpiece is flat. Discrete points appear in the real-time impedance values because of unevenness of the material and manufacturing errors. However, the process is stable.

3.2 Effect of current on surface quality

3.2.1 Effect of current on surface roughness

Surface roughness refers to the roughness of the machined surface with small pitches and minute peaks and valleys. Plastic deformation occurred on the workpiece surface after the ultrasonic impact enhancement. At the same time, the surface roughness also changed.

The effect of output current on the surface roughness is shown in Fig. 6. When the impedance threshold is constant, the surface roughness decreases with increasing current output.

3.2.2 Effect of current on surface microhardness

Hardness reflects the ability of a material to resist pressure induced by a hard material pressed into its surface. Microhardness improves the mechanical properties of the workpiece surface. Different output currents increase the surface microhardness to different extents (Fig. 7). When the impedance threshold value was set to 80 Ω, the microhardness value of the workpiece surface first decreased and then increased with

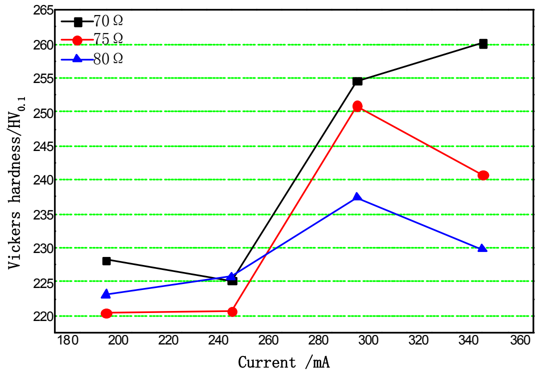

Fig. 7. Effect of current on microhardness.

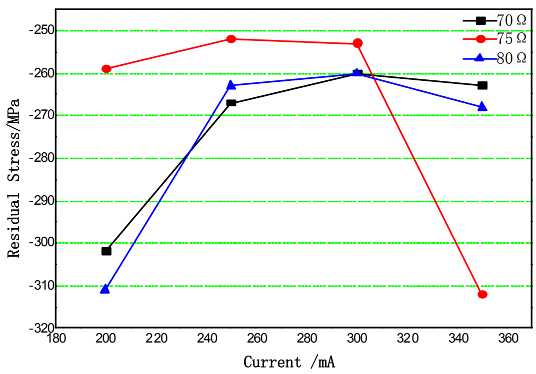

Fig. 8. Effect of current on surface residual stress.

increasing current output. When the impedance threshold was set to 70 and 75 Ω, the microhardness value of the workpiece surface first increased and then decreased with increasing current output. A comparison of the three sets of data shows that the microhardness increases when the current output value increases. Under the impact of the impedance threshold, when the output current value is large, system processing becomes unstable, thereby increasing the current output and decreasing the microhardness.

3.2.3 Effect of current on surface residual stress

Residual stress on the workpiece surface can improve the fatigue strength and wear resistance [26, 27]. Moreover, the ultrasonic impact enhancement improves the residual stress on the surface. Different output currents exert some influence on the increase in the residual stress on the surface (Fig. 8). The residual stress on the workpiece surface increased with increasing current output when the impedance threshold value was set to 70 or 80 Ω. When the impedance threshold was set to 75 Ω, the residual stress of the workpiece surface first increased and then decreased with increasing current output. A comparison of the three sets of data shows that the residual stress value increases with increasing current output. At negative residual stress values, smaller values indicate greater residual stress. A good residual stress value can be obtained when the output current is small.

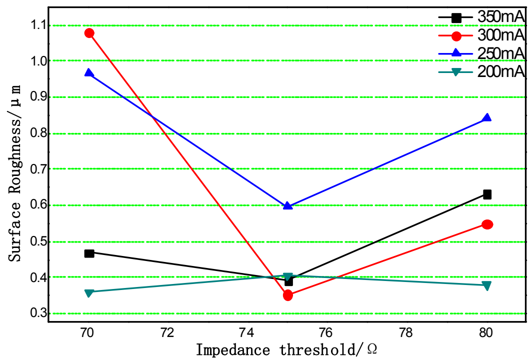

Fig. 9. Effect of impedance threshold on surface roughness.

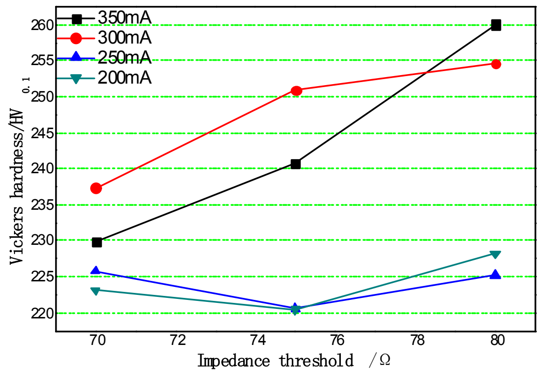

Fig. 10. Effect of impedance threshold on surface microhardness.

3.3 Effect of impedance threshold on surface quality

3.3.1 Effect of impedance threshold on surface roughness

The effect of the impedance threshold on the surface roughness is shown in Fig. 9. Under constant output current, the surface roughness has a minimum value. When the impedance value was set to 75 Ω, the current output value was 200 mA and the roughness reached 0.353 μm.

3.3.2 Effect of impedance threshold on surface microhardness

Impedance threshold affects the vibration system. Specifically, a large threshold will cause an unstable system. Different thresholds also affect the microhardness of the machined surface (Fig. 10).

Under the same current output, a larger impedance threshold will result in greater surface microhardness. When the current was set to 250 mA, the microhardness of the surface exhibited the minimum value because of surface roughness. When the surface was flat, the measurement value was accurate. When the surface was not flat, the measurement error was large.

3.3.3 Effect of impedance threshold on surface residual stress

Impedance threshold reflects the magnitude of the processing force. When the set value is high, the processing force is

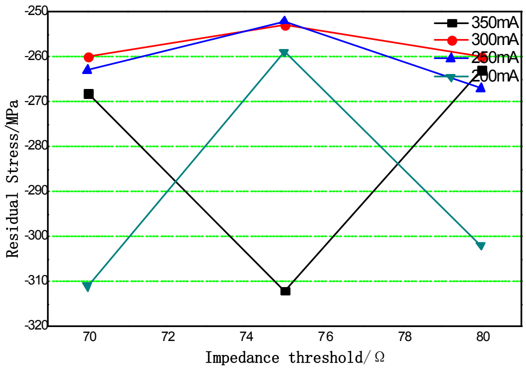

Fig. 11. Effect of impedance threshold on surface residual stress.

also large. The magnitudes of the surface residual stress under different impedance thresholds are shown in Fig. 11. When the impedance threshold was set to 75 Ω, the surface residual stress value exhibited the maximum or minimum value. Thus, a large threshold is not always beneficial.

4. Conclusions

Ultrasonic impact enhancement technology based on equivalent impact control realizes automated processing by setting different impedance thresholds and trajectories of the machined tool. After the 7075-T651 aluminum alloy was strengthened by ultrasonic impact, the surface roughness of the workpiece was reduced and the microhardness and residual stress was improved. From a comprehensive analysis of the experimental results, the following conclusions are drawn.

(1) Ultrasonic impact enhancement technology based on equivalent impedance control reduces the surface roughness of the workpiece to a certain extent. The surface roughness is affected by the precision of the machine tool, the manufacturing precision of the tool head, the movement mode of the tool head, and the initial surface quality of the workpiece.

(2) The current value substantially affects the surface microhardness and residual stress. Increasing the output current, i.e., increasing the power output of the power supply, can increase both the surface microhardness and the residual stress.

(3) As a key factor in the control system, the impedance threshold plays a vital role in improving the surface quality of the workpiece. The impedance threshold should be slightly larger than the no-load impedance to reduce the surface roughness and increase the residual stress. Under a constant output current, the impedance threshold should be appropriately increased to improve the surface microhardness. An excessively large impedance threshold will destabilize the vibration system and cause serious heat problems with the tool head. Thus, the maximum impedance threshold cannot exceed twice the no-load impedance value.

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Nomenclature

f	: Working frequency of ultrasonic vibration system
D	: Tool (spherical) diameter
$Irms$	: Current amplitude
Z	: Impedance threshold
Ra	: Surface roughness
σ	: Residual stress
$HV_{0.1}$	: Microhardness when the load is 100 g

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