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Improvement of arc burn defect of initial contact loss of electric hot incremental sheet forming

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Abstract. Electric hot incremental sheet forming, which is used to form hard-to-form sheet metal, is viewed as the one of rapid prototyping manufacturing technologies. However, the non-uniform stress distribution of forming regions would cause an initial contact loss phenomenon between the tool and the sheet, and an electric arc burn of the part surface is obtained due to the contact loss. In this work, a control method of axial pressure response was proposed to judge the stability of the initial contact between forming the tool and the sheet. A power supply on-off device was designed for electric hot incremental forming, and the calculation model of the initial axial force was established during deformation. Meanwhile, two response pressure values were proposed to control the power supply starting and the current intervention and to ensure the stability of the power supply during the forming process. In addition to this, the axial force and the surface of part were analyzed further in electric hot incremental sheet forming.

Keywords: Incremental forming / electric hot forming / arc burn defect / pressure response / electric control device

1 Introduction

Compared with traditional incremental forming, electric hot incremental forming (EHIF) could broaden the processing range of incremental forming and reduce the deformation resistance of hard-to-form materials, such as aluminum, magnesium and titanium alloys [1–3]. The material has a poor plasticity at room temperature and a good plasticity at elevated temperature due to the action of the close-packed hexagonal structure. Meanwhile, the use of EHIF would improve the formability of the material and the forming quality of parts [4–7]. The electric hot methods are mainly divided into two categories, and the first is integral electric heating, and the other is single point local electric heating [8–11]. The latter is widely concerned due to characteristics of high flexibility, high heating efficiency, and simple equipment.

In electric hot incremental forming, the two processing problems, such as geometric accuracy and surface quality, have been widely studied in recent years. Aiming at above problems, Fan et al. [9] adopted the composite process of reverse drawing and electric hot incremental forming to improve the bottom reverse bulge of titanium alloy parts. Meanwhile, Ambrogio et al. [8] further discussed the relationship between the forming limit angle and the current density in electric hot incremental forming of AA2024-T3, AZ31B-O and Ti-6Al-4V alloys, and established the corresponding limit current density which could provide a reliable reference for the electric hot incremental forming of hard-to-form materials. Due to the point contact characteristic of electric hot incremental forming, the forming tool and the sheet are set as electrodes respectively, and the arc burn defect of part surface is caused due to the contact loss between the tool and the sheet, thus making the whole forming process failure [10]. Although Skjoedt [12] and Shi [13] separately proposed design methods of high-precision machining path to solve the contact loss caused by structural characteristics of parts, the initial contact loss from the non-uniform stress distribution of forming regions is still a key problem restricting the development of electric hot incremental forming.

In this work, a power supply on/off method of pressure response was proposed to improve the phenomenon of arc burns (Fig. 1) caused by the initial contact loss. A novel control system and double boundary control models were separately designed and established to ensure the stable contact between the tool and the sheet and to ensure the

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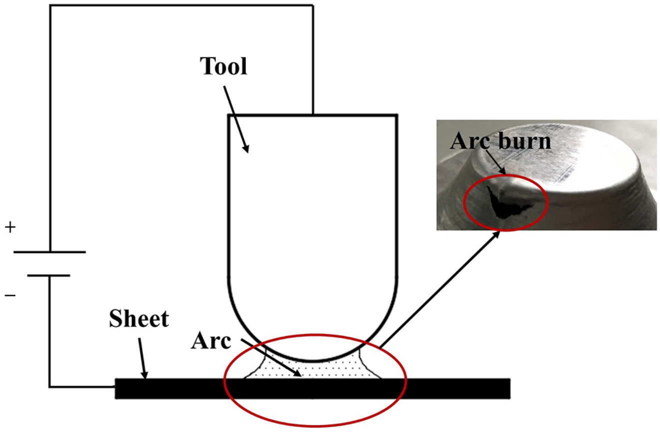

Fig. 1. Sketch of arc burns in EHIF.

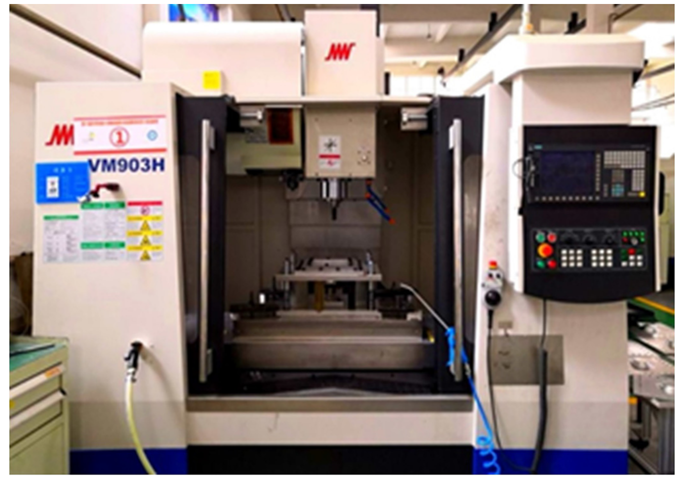

Fig. 2. The machine of electric hot incremental forming.

stable operation of the electric source in the initial stage of electric hot incremental forming. A part with TC4 Ti alloy was fabricated by the novel control method, and the axial force and the part surface were further analyzed in details. In general, the arc burn defect of initial contact loss of EHIF was improved through the power on/off system, which is proposed in the study.

2 Materials and methods

2.1 Design for power on/off device

Figure 2 shows the machine (Model: LNC-M700) of electric hot incremental forming in the experiment, and table sizes are 1000 mm length and 650 mm width, and the repositioning accuracy is 0.001 mm. Figure 3 shows the principle of power supply on/off, the control circuit and the test platform, respectively. In this figure, the power supply on/off system is mainly composed of pressure sensors, MCU control module, A/D conversion module, digital display module, triphase contactor, voltage collector card and DC power supply. In this system, the pressure sensor is fixed the between the baseplate II and the baseplate III, which could realtimely capture the axial force of forming region. The pressure sensor would send out a voltage signal when the pressure sensor collects the pressure of deformation regions. Meanwhile, the signal is transmitted to the A/D conversion module, and the corresponding pressure value could be displayed through the digital tube, and the action results could be calculated through A/D acquisition card. Finally, the control chip would send a low-level signal to obtain the broken circuit of relays when the pressure value is lower than a set value, and the triphase contactor is also a condition of broken circuit in the main circuit. Similarly, the opposite method could be used to connect the main circuit, and then the power supply on/off control is achieved in the initial contact stage of electric hot incremental forming.

In order to ensure the collection accuracy of axial forming force, four pressure sensors separately are arranged at corners of the forming region, and the signal aggregator is used to obtain the sum of four pressure signals, as shown in Figure 4. Meanwhile, the flat film box pressure sensor is adopted to capture the axial forming force and its relevant parameters are listed in Table 1.

2.2 Establishment of control model

In order to determine the stability of initial contact, the control boundary of axial forming force needs to be established. Figure 5 shows the contact region between the tool and the sheet in the initial forming stage, in which the contact region is similar to a spherical surface. Therefore, L_1 is equal to L_2 in Figure 4, and the projected outline of L_1 is similar to L_1 due to the fact that ΔZ is very small. Based on the study of Gao [14], L_1 is written as:

$$L_1 = r\frac{\arccos\left(\frac{r-\Delta Z}{r}\right)\pi}{180}. \tag{1}$$

The circular surface is obtained according to the axial projection of spherical surface, and then the axial projection area (S_Z) of initial forming region is calculated by the formula of circle area and it is written as:

$$S_Z = \frac{1}{2}\pi^3\left(r\frac{\arccos\left(\frac{r-\Delta Z}{r}\right)}{180}\right)^2. \tag{2}$$

According to the thin shell analysis method of incremental sheet forming proposed by Silva and Jeswiet et al. [15,16], stress components of the small element are separately described thickness, circumferential and meridional directions, and the relation between the stress components is obtained according to the following derivation:

$$\begin{cases} \sigma_\phi = \sigma_1 > 0 \\ \sigma_\theta = \sigma_2 = \dfrac{r-1.5t}{2r+t}\sigma_\phi \\ \sigma_t = \sigma_3 = -\dfrac{2t}{r+\dfrac{t}{2}}\sigma_\phi \end{cases} \tag{3}$$

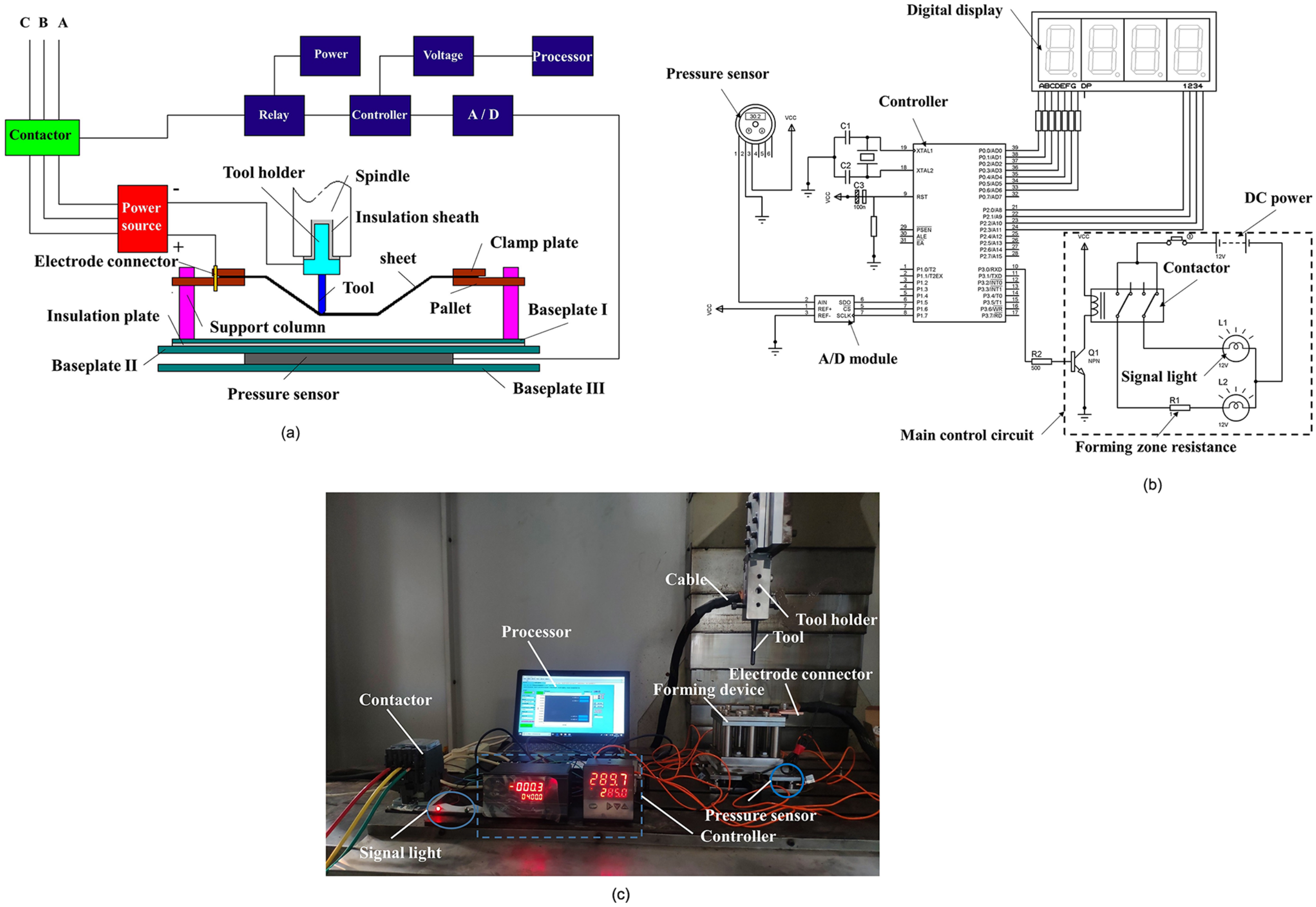

Fig. 3. Principle and test platform of pressure response control: (a) Control scheme, (b) control circuit, and (c) test platform.

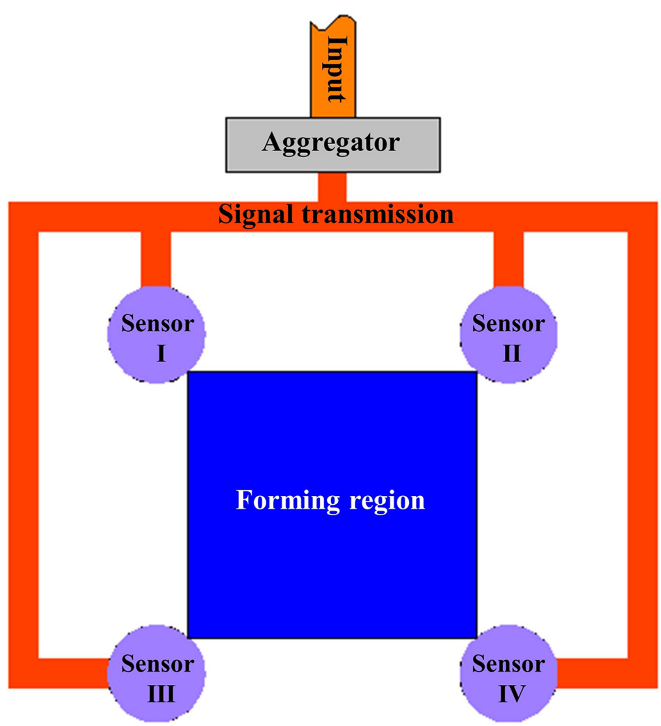

Fig. 4. Pressure sensor arrangement.

Table 1. Parameters of pressure sensor.

Type	Value
Sensitivity (mV/V)	2.0 ± 0.1
Repeatability (≤%F·S)	±0.03
Working temperature (°C)	−20 to 80
Input resistance (Ω)	700 ± 20
Output resistance (Ω)	700 ± 5
Safety overload (≤%F·S)	150
Insulation resistance (MΩ)	≥5000
Excitation voltage (V)	5–15

where σ_ϕ, σ_θ, and σ_t are separately meridional, circumferential and thick stress, and t is the sheet thickness. r is the radius of forming tool. Meanwhile, the equivalent stress (($\overline{\sigma}$) of forming region is further written as:

$$\overline{\sigma} = \frac{\sqrt{3}}{2}\left|\sigma_\phi - \sigma_t\right|. \tag{4}$$

According to equations (3) and (4), the relation between the thick stress and the equivalent stress could be established and it is written as:

$$\sigma_t = -\frac{2}{\sqrt{3}}\frac{2t}{r+2.5t}\overline{\sigma}. \tag{5}$$

In electric hot incremental forming, Johnson-Cook model is usually used to establish the stress-strain relation (Eq. (6)) of material according to the study of Honarpisheh [17].

$$\overline{\sigma}_g = (A + B\overline{\varepsilon}^n)\left(\frac{1 + Cln\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \tag{6}$$

where $\overline{\sigma}_g$ is the equivalent stress in electric hot incremental forming. A, B, C, m, and n are separately material constants, and $\dot{\varepsilon}_0$ is the initial strain rate, and T_m and T_r are separately the melting and the room temperature, and Table 2 further shows values of these parameters for TC4 titanium alloy.

Meanwhile, the equivalent strain of contact regions is calculated according to the result of Chang et al. [18], and it is written as:

$$\overline{\varepsilon} = \frac{2}{\sqrt{3}}\ln\left(\frac{2r}{2r\cos\alpha + t\cos\alpha}\right). \tag{7}$$

where α is the forming angle of parts. According to the above analysis, the axial forming force (F_Z) of initial contact stage is achieved by the following derivation:

$$F_Z = \frac{2}{\sqrt{3}}\frac{t}{r+2.5t}\overline{\sigma}\pi^3\left(r\frac{\arccos\left(\frac{r-\Delta Z}{r}\right)}{180}\right)^2. \tag{8}$$

2.3 Material and process parameters

The square cone with TC4 titanium alloy is adopted to verify the stability of the power on/off system, and the profile dimension of forming part is shown in Figure 6. Table 3 shows the chemical composition of TC4 titanium alloy. The sheet with 1 mm thick is cut by 90 × 90 mm and used to fabricate the design part.

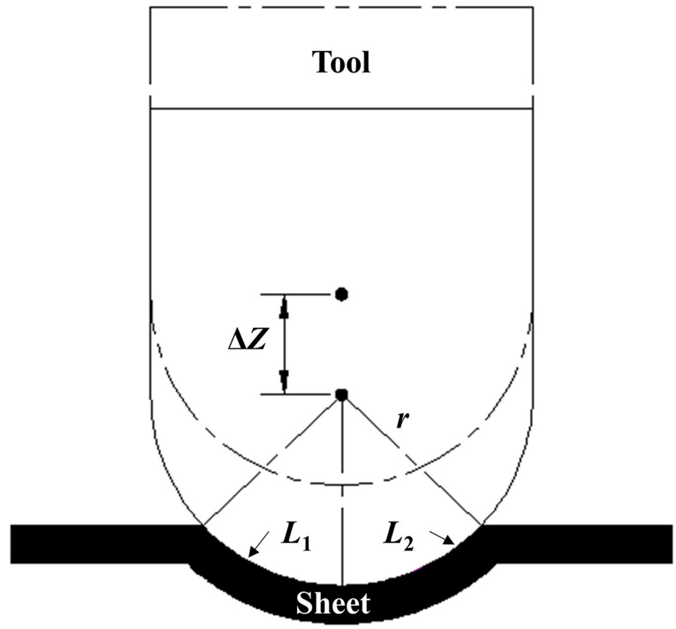

Fig. 5. Sketch of the initial contact region.

In electric hot incremental forming, some parameters, including the forming temperature (T), the step size (Δh), the feed rate (v), the tool diameter (D), and the current intensity (I), would play a significant role to obtain a qualified part, and Table 4 further shows values of these parameters designed.

3 Results and discussion

3.1 Analysis of control boundary

Figure 7 shows the action result of a control boundary, in which an axial force of 484.1 N obtained by equation (8) was viewed as a critical line of power on. If the initial axial forming force is greater than 484.1 N, the power supply will start and provide current to the deformation region. However, the thermal softening phenomenon of material will be obtained due to Joule heating effect, and the axial forming force will drop sharply in the initial stage of current action. The minimum axial force (284.3 N) is lower than 484.1 N, and the percentage between the two values is 58.7%, namely the percentage less than 1. Therefore, the supply will be interrupted abnormally, and then the forming quality of parts is also influenced.

In order to solve the above problem, the interactive control method of double critical values, namely power start and current intervention critical values, is proposed to ensure the stable operation of the power supply. The critical value of power start is obtained based on the model

Table 2. Parameters of Johnson-Cook model for TC4 titanium alloy.

Parameter	A (MPa)	B (MPa)	C	m	n	$\dot{\varepsilon}_0(s^{-1}(s^{-1})$	T_m (°C)	T_r (°C)
Value	968	380	0.0197	0.577	0.421	1	1655	25

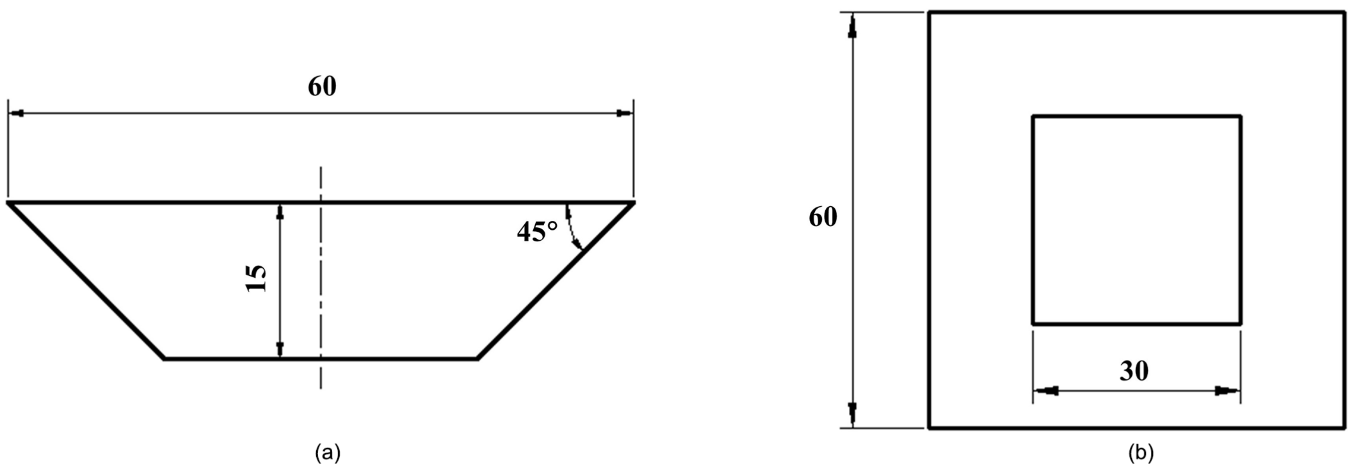

Fig. 6. The profile size of square cone: (a) front view and (b) vertical view (unit: mm).

Table 3. The chemical composition of TC4 titanium alloy.

Composition	Al	V	Ti	Fe	Si	C	N	H	O	Others
Content (%)	5.5–6.8	3.5–4.5	Residual	0.3	0.15	0.1	0.05	0.0015	0.2	0.4

Table 4. Values of forming parameters.

Parameter	Value
D (mm)	6
v (mm min^{-1})	900
Δh (mm)	0.1
I (A)	400
T (°C)	500

of initial axial force and the equivalent thermal stress of material. Therefore, the corresponding model is written as:

$$F_Z{}' = \frac{2}{\sqrt{3}}\frac{t}{r + 2.5t}\overline{\sigma}_g\pi^3\left(r\frac{\arccos\left(\frac{r-\Delta Z}{r}\right)}{180}\right)^2 \tag{9}$$

where F'_Z is the critical value of power start, and $\overline{\sigma}_g$ is the equivalent thermal stress of material under the designed temperature. The power start value of 246.4 N is achieved according to equation (9). The percentage between 284.3 N and 246.4 N is greater than 1, and then the supply will be not interrupted abnormally. Meanwhile, the current intervention critical value is calculated according to equation (8). In order to eliminate the fluctuation of deformation force, the critical value of current intervention is increased by 5%, and the current intervention value of 508.0 N is obtained based on equation (8) and corresponding process parameters.

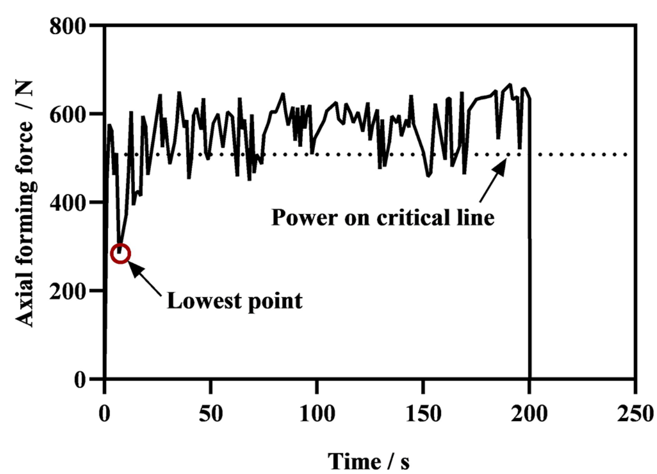

Fig. 7. Action results of a control boundary.

Figure 8 shows the action result of double critical value, in which the minimum axial force is between 246.4 N and 508.0 N. The value after the lowest point is both greater than the minimum axial force and fluctuating in a small range. Therefore, the problem caused by the single control boundary is solved effectively.

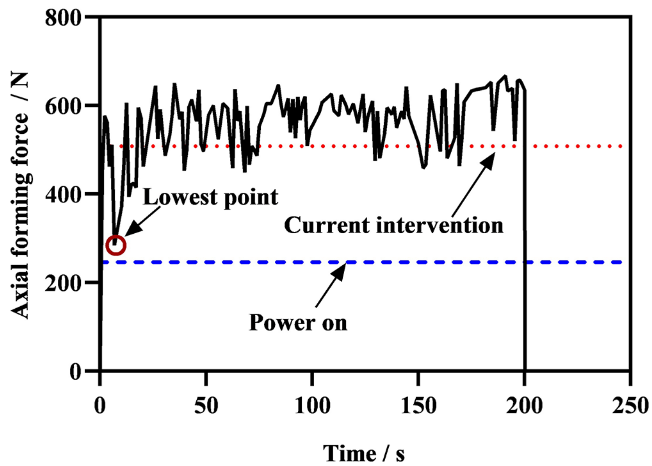

Fig. 8. Action results of double critical value.

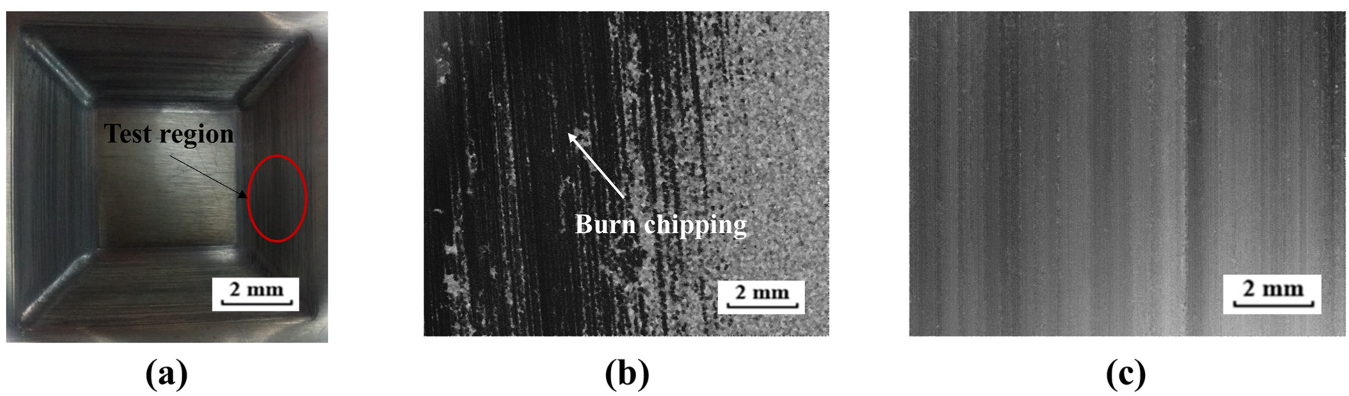

Fig. 9. The profile and surface topography of forming part: (a) test region and (b) effect before improvement and (c) effect after improvement.

3.2 Surface topography of parts

The laser scanning confocal microscopy (Type: OPTELICS C) was used to analyze the 3D surface topography of test regions. The resolution used was 0.18 μm, and the magnification was 100. Figure 9 shows the surface topography of machining region before and after improvement, in which the machining surface before improvement has obvious burn marks. On the contrary, the machining surface after improvement is relatively smooth and has no an obvious phenomenon of arc burns. Meanwhile, Figure 10 shows the testing result of 3D surface topography before and after improvement, in which the 3D surface before improvement has an obvious mutation and a peak point of 85 μm. The surface after improvement is gradual and has no an obvious mutation phenomenon.

Meanwhile, the peak point of the surface after improvement is 40 μm, and it is significantly less than the result before improvement. According to the above analysis, the use of novel control method could obtain the part without arc burn and with surface fine and smooth. In general, the surface of test regions is fine and smooth and has no obvious rigid machining marks, and the microscopic defect of arc burns is not observed under the action of the power on/off device.

4 Conclusions

In this study, the control method of pressure response is proposed to improve the defect of arc burns in the initial forming stage of EHIF. The result of the study can increase the fabricability of hard-to-form materials in rapid manufacturing industry, and the manufacturing efficiency is also improved. Meanwhile, the intelligence level of the rapid forming industry is increased through the application of the study.

– It is concluded that the power cannot stably work due to that the power on/off system do not consider the effect of thermal softening. For the forming of TC4 titanium alloy, the use of the critical value of 484.1 N cannot control the stable operation of the control system due to the fact that the scale between 284.3 N and 484.1 N is less than 1, and the power can be unusually interrupted.

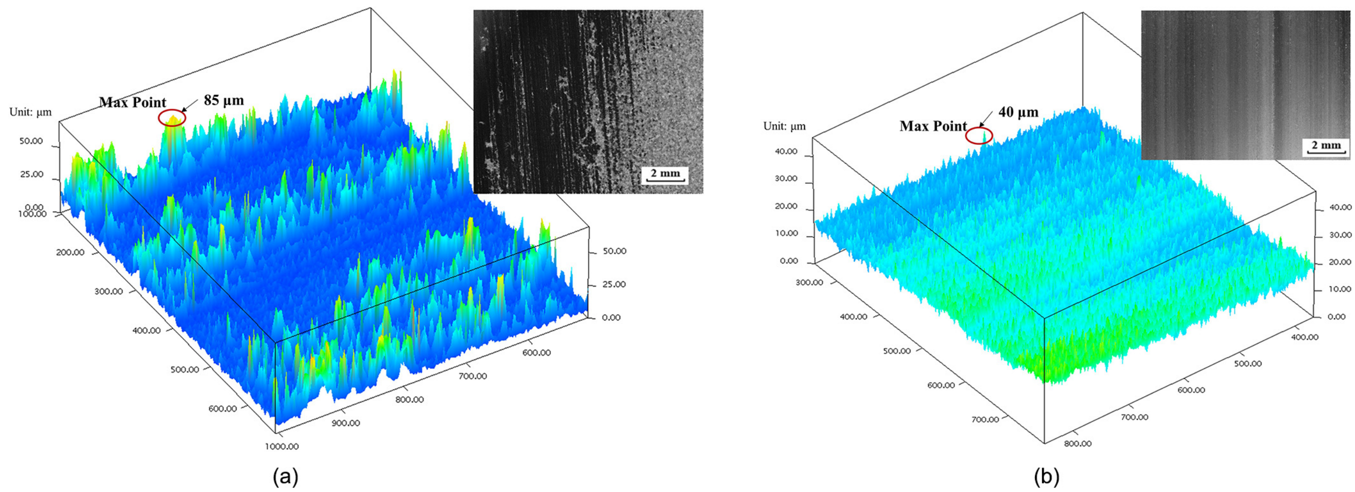

Fig. 10. The testing result of 3D surface topography: (a) Effect before improvement and (b) effect after improvement.

Therefore, the forming process is unsuccessful under the action of only one critical value, and the manufacturing efficiency is fairly low.

- During the electric hot incremental forming of TC4 titanium alloy, two boundary values (246.4 N and 508.0 N), such as the power start value and the current intervention value, are adopted to eliminate the effect of thermal softening on power supply stability, namely that the scale between 284.3 N and 246.4 N is greater than 1. Therefore, the problem caused by abnormal power failure is effectively solved.
- As for the surface quality of forming parts, the surface of part is fine and smooth and has no an obvious phenomenon of arc burns under the action of the control system. Meanwhile, the max 3D surface topography of 40 µm is less than the value of 85 µm of before improvement, and the part is gradual and has no an obvious mutation phenomenon. In general, the novel control method proposed is not only achieving the accurate intervention of current but also ensuring the working reliability of power supply during initial forming, and then the initial arc burn caused by contact loss is availably avoided and the whole forming process is effectively ensured.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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