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Stress relaxation ageing behaviour and constitutive modelling of a 2219 aluminium alloy under the effect of an electric pulse

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ABSTRACT

In creep age forming (CAF), stress relaxation and the creep process occur during the ageing heat treatment. However, there is a remarkable difference between the deformation and phase transformation activation energies in aluminium alloys. To achieve high-performance and high-precision collaborative manufacturing of large-scale complex panels with high levels of reinforcement, the difference in the energy barriers between the stress relaxation process and the ageing precipitation process needs to be coordinated. An electric pulsed current (EPC) was first introduced into the CAF process for 2219 aluminium. It was found that the EPC can effectively regulate the stress relaxation behaviour during the initial ageing stage. That is, the application of EPC during the first 1 h of the ageing treatment process decreases the stress gradients for different initial stress levels, which makes it possible to reduce the deformation and phase transformation inhomogeneities resulting from stress differences inside a component under a bending load. Meanwhile, the apparent deformation activation energy decreases with the EPC, which decreases the energy barrier difference between the stress relaxation and ageing precipitation from 47 kJ/mol to 18 kJ/mol. Furthermore, the action mechanism for EPC on the stress relaxation process is discussed, and a constitutive model for stress relaxation age forming considering the effect of the EPC is established.

1. Introduction

To manufacture the complex panels of a rocket fuel tank, research on age forming with creep/stress relaxation has been conducted in many developed countries. CAF refers to a combined creep and ageing treatment process in which creep during ageing is the mechanism used to promote the formation and retention of the shape of a metal component. Additionally, ageing treatments can improve a metal's mechanical properties [1]. This process possesses a number of advantages, such as homogeneous deformation, fine forming precision, good repeatability, high efficiency, low residual stress and size stability. The synergy of the forming process's focus on precision and the heat treatment's focus on the mechanical properties enables the manufacture of complex panels [2,3]. CAF has been applied in the manufacture of the skin components of airplanes with small curvatures (the wing panels), which have a low stress state and a small stress gradient along the thickness direction. The influence of stress on the precision and properties is relatively small. However, for large-scale complex panels with high-degrees of reinforcement (the fuselage panels), the internal stress state is very complex: the highest tensile stress is on the die side and the highest compressive stress is on the opposite side. Studies have shown that the difference in stress clearly results in a difference in the precipitation of the creep/stress relaxation ageing process and further results in inhomogeneities in both the deformation and phase transformation. Meanwhile, there is a remarkable difference between the deformation activation energy and the phase transformation activation energy of aluminium alloys [4,5]. Thus, achieving the collaborative manufacture of large-scale, high-performance, high-precision and complex panels is a challenge for the industrial application of CAF.

EPC is considered to be a useful auxiliary energy field that can be employed for metal forming process. Stashenko [6] found that EPC can lower the required load during the creep process. Troitskii [7] found that EPC promotes stress relaxation processes. Wang

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Jingpeng of CAS [8] and Tang Fei of Tsinghua University [9] found that EPC helps decrease the residual stress. Although there have been a few studies on the influence of EPC on age forming or stress relaxation, its influence on CAF processes and a constitutive model have not been developed. Thus, the successful introduction of EPC to the CAF process would be a breakthrough for dealing with the challenges mentioned in the introduction.

Because of its excellent welding properties, corrosion resistance and high temperature mechanical properties, 2219 aluminium is used as the main material for the panels of rocket fuel tanks [10,11]. EPC is applied during the creep/stress relaxation age forming process. Therefore, the possibility of the collaborative manufacture of large complex components using multiple EPC fields and its effects on temperature and stress are studied in this work. Constitutive models for 2219 aluminium fabricated with and without EPC are established, respectively.

2. Material and method

2.1. Material

The material used here was 2219 aluminium rolled plate with pre-deformation provided by the China Academy of Launch Vehicle Technology. The chemical composition is shown in Table 1. Based on GB/T 2039-2012, the plates were cut into 2-mm-thick standard creep specimens with WEDM, as shown in Fig 1.

2.2. Test method

The stress relaxation ageing tests were conducted on an RMT-D10 electronic testing machine used to determine high-temperature creep rupture strength. The precision is ±2 °C for the temperature and ±3 N for stress. The pulsed power supply was switched on after the specimen was fixed in the machine so that the temperature and stress were increased to the desired value. During the entire test, thermocouples were placed on the specimen to detect the temperature of the top, middle and bottom parts, respectively. The temperature of the middle part was taken as the temperature of the specimen. The tests used a home-made insulation device. The specimen was insulated from the thermocouples using mica sheets.

EPC was applied lengthwise along the specimen. The parameters of the one-directional pulse are: a maximum current density of $j_{\max} = 80A/cm^2$, a frequency of $f = 1000Hz$ and a duty ratio of $D = 50\%$. EPC is applied for only the first 1 h of the test.

3. Results and discussion

3.1. Influence of the EPC on the stress relaxation ageing behaviour of 2219 aluminium

The tests are conducted at 165 °C for 11 h. The conventional/EPC stress relaxation curves are shown in Figs. 2 and 3 for different initial stresses (120–225 MPa), respectively.

As shown in Fig 2, there are three stages in the stress relaxation process for 2219 aluminium: the rapid relaxation stage, the transit relaxation stage with a decreasing relaxation rate and the steady relaxation stage. Because of the high effective stress during the primary period of stress relaxation, abundant mobile dislocations and vacancies interact with a low-resistance, short-range barrier, causing the stress to decrease rapidly. With the activation effect of the stress and temperature, the dislocations glide or climb, the elastic deformation becomes plastic, and the effective stress decreases. Meanwhile, the precipitation of the second-phase particles increases the short-range barrier, which slows the relaxation rate, and, subsequently, the steady relaxation stage begins [12]. When the initial stress range is between 120 and 195 MPa, the higher the initial stress is, the higher the remaining stress after the same time of stress relaxation is. However, when the initial stress exceeds 195 MPa and the stress relaxation time exceeds 1 h, the trend is reversed.

Table 1
The main chemical composition of the 2219 aluminium alloy (mass%).

Element	Cu	Mg	Mn	Fe	Si	Zn	Zr	Al
Content (wt%)	5.8–6.8	0.02	0.2–0.4	0.3	0.2	0.1	0.1–0.25	Bal.

The EPC decreases the sensitivity of the stress relaxation to the initial stress (as shown in Fig 3). The EPC is only applied during the first 1 h of the test. For different initial stresses, the remaining stress after 11 h of EPC stress relaxation approaches the same value (the difference of the remaining stress after 11 h of the conventional stress relaxation is 73 MPa, whereas that for the EPC stress relaxation is 29 MPa). Therefore, by using EPC, the homogeneity of the stress increases, the difference in deformation and phase transformation is reduced and the precision and comprehensive properties of the components are improved.

Comparisons of the stress relaxation curves for different initial stress states are shown in Fig 4.

As shown in Fig 4, the influence of the EPC on the stress relaxation behaviour depends on the initial stress. First, during the EPC application period (1 h), stress relaxation is promoted, and as the initial stress increases, the degree of promotion increases and reaches a peak at 195 MPa. However, after removing the EPC, the follow-up effects vary: (1) at 120 MPa, the previous EPC retards stress relaxation, (2) at 150 MPa, the EPC rarely produces any response, and (3) at 180 MPa or higher, the EPC promotes stress relaxation, which increases first and then decreases with the increase of the initial stress (peak at 195 MPa). Meanwhile, the remaining stress increases first and then decreases with the increase in the initial stress, reaching a peak at 195 MPa. Therefore, we can conclude that the conventional stress relaxation cannot decrease the stress gradients effectively, whereas the application of EPC can significantly decrease the stress gradients. Furthermore, the inhomogeneities in the deformation and phase transformation can be decreased and the window for CAF can be expanded.

3.2. The establishment of a stress relaxation ageing constitutive model for 2219 aluminium based on the creep theory

3.2.1. A theoretical analysis of the stress relaxation ageing constitutive model based on the creep theory

During the stress relaxation process, the total strain $^{\varepsilon}{}_{s}$ is equal to the sum of the elastic strain ε_e and the plastic strain ε_p:

$$\dot{\varepsilon}_e + \dot{\varepsilon}_p = 0 \tag{1}$$

where $\dot{\varepsilon}_e$and $\dot{\varepsilon}_p$ stand for the elastic deformation and plastic deformation rates, respectively. Meanwhile, the elastic deformation rate can be defined using Young's modulus E (73.8 GPa for 2219 aluminium [13]) so that the stress relaxation rate is defined as [14]:

$$\dot{\varepsilon}_e = \frac{1}{E}\dot{\sigma}_r \tag{2}$$

Thus:

$$\dot{\varepsilon}_p = -\frac{1}{E}\dot{\sigma}_r \tag{3}$$