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Fu-Qi Zhao,1 Hao Pan,1,a) Feng-Guo Zhang,1 and Jing-Xing Liu2,a)

AFFILIATIONS
1Institute of Applied Physics and Computational Mathematics, Beijing 100088, China
2Faculty of Civil Engineering and Mechanics, Jiangsu University, Jiangsu 212013, China

*a)Authors to whom correspondence should be addressed: pan_hao@iapcm.ac.cn and jxliu@mails.ucas.ac.cn

ABSTRACT

We present a dynamic theoretical viscoplastic model of voids subjected to external dynamic tensile loadings. The material viscosity and temperature are factors that are considered in the dynamic evolution of voids in viscoplastic materials. We focus on the thermal effect; the temperature affects the thermal softening of the material strength and also the material viscosity. Viscous flow is the dominant growth mechanism under high stresses and rates based on the results of the calculations for dynamic void growth predictions. The factors are independently studied, and the correlations are systematically analyzed.

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I. INTRODUCTION

The growth of voids (such as helium bubbles) under a dynamic load in viscoplastic media is an important factor that causes the damage of materials. We study the dynamic growth of spherical voids by using a viscoplastic model and focusing on the material viscosity and thermal effects.

A. Background

The study of void growth under static/quasistatic loading conditions has been investigated at various length scales in the past.1-5 A hollow-sphere model based on the dynamic compaction equation for porous materials was established by Carroll and Holt,6 where the material porosity and pore size were applied in the calculations of the porosity and initial inner radius, describing the elastic-plastic work in compaction. Based on this study, the viscous dissipation and deviatoric stress effect were introduced in a modified model by Butcher et al.;7 the modeled results were in good agreement with experimental data. Johnson extended this model to rate-dependent materials under dynamic tensile loading conditions.

Rayleigh8 focused on the cavity evolution in a large mass of liquid and established an empirical equation to describe the material viscosity. Based on his work, Poritsky9 focused on the effect of inertia on the dynamic growth of voids in viscoplastic materials.

Seaman10 modified Poritsky’s model and theoretically studied the effect of inertia on viscoplastic materials. He implemented a rigid threshold in his model to indicate the void growth starting point, replacing the material strength in Carroll and Holt’s model. Ortiz11 considered the dynamic growth of a void in a medium obeying power-law strain hardening and rate sensitivity when describing the material strength and observed that the inertial effect dominates the long-term void growth while becoming insignificant when the void is large enough. Molinari et al.12 and Wilkerson et al.13 analyzed the effects of the loading rate, loading amplitude, and inertia. These efforts show that the effects of the inertia and surface are both important in the creation of void growth models, which are introduced and examined in the present work.

It is known that the thermal effect plays an important role in the dynamic development of metals, which was neglected in previous studies. The deformations may be localized around the void under impactlike loading conditions, leading to the thermal softening of the material strength. Wu et al.14 theoretically studied the thermal softening of a single void in viscoplastic materials and noticed that thermal softening promotes the growth of the void, which cannot be ignored in dynamic and adiabatic cases. However, the concept of the thermal effect does not only reflect the softening of materials but also greatly affects the material viscosity. Gudonov et al.15 and Shimoji16 studied the temperature...
dependence of the material viscosity at room and melting temperatures. By using experimental data, Carroll\textsuperscript{9} proposed an exponential correlation to describe the effect of temperature on viscosity. Qi\textsuperscript{15} considered a temperature-dependent gas pressure and viscosity when describing the dynamic helium bubble evolution in aluminum influenced by the temperature change and observed that the room temperature has a great effect on the void growth, which depends on the material viscosity under dynamic loading conditions.

Other factors, such as the gas pressure and surface effect, are also considered in the present study but are not the focal points of this paper. For instance, Donnelly\textsuperscript{20} reviewed experiments and calculations that yielded information on the state of helium in small voids in implanted metals, showing that the gas pressure can be extremely high in metals, which depends on the surface tension/surface energy. Huo\textsuperscript{21} and Liu\textsuperscript{22} reported that the surface effect becomes significant and is non-negligible when the size of the void is small enough (i.e., radius of 10 nm) and established a quasistatic model for nanovoid growth affected by the surface effect.

B. Present study

We present the dynamic evolution of a single spherical void subjected to a remote hydrostatic tensile stress at infinity in an infinite body for viscoplastic materials, as shown in Fig. 1, and focus on several essential factors, such as the material viscosity and temperature, during modeling.

- A viscoplastic model is introduced in this study, which can be used to describe the resistance strength of the matrix material under loading conditions. The strain hardening and viscosity relations are considered in this model, which can be expressed in an integral form.
- The influence of the material viscosity is studied by calculating the void growth under different loading rates in a noninertia case. The effects of the material strength and material viscosity on the void growth are analyzed, and the void growth under dynamic loading conditions is predicted.
- Thermal effects on both material strength and material viscosity are investigated. The mechanical expressions of these effects are presented and combined with the previously established viscoplastic model. A model of the motion of the voids under a dynamic load is derived.

C. Structure of the paper

This paper is divided into five sections. The introduction and background information are provided in Sec. I. The basic theory for the present work is introduced in Sec. II. The theoretical formulation describing the void growth under dynamic loading conditions is proposed in Sec. III, which is based on a viscoplastic model considering the surface, inertial, and thermal effects. A series of calculated results (with illustrations) is presented in Sec. IV, which contributes to the analysis of the influences of the material viscosity and thermal effect. The thermal effects on the material strength, including thermal softening and the influence of the on material viscosity, are also discussed in this section. The conclusion and remarks regarding this paper are provided in Sec. V.

II. BASIC THEORY

Several factors must be considered when analyzing the evolution of a void under dynamic loading conditions, which are discussed in detail below:

The first factor is the strength of the material surrounding the void, which is assumed to be isotropic and continuous. The strength is influenced by viscous and strain hardening,

$$\sigma_e = \sigma(\dot{\varepsilon})^p (1 + f(\dot{\varepsilon})),$$

where $\sigma(\dot{\varepsilon})$ and $f(\dot{\varepsilon})$ represent the contribution of strain and viscous hardening, respectively. A viscoplastic model is introduced in this study to analyze the rate hardening of the matrix material, which can be described as overstress,

$$\frac{\dot{\varepsilon}}{\varepsilon_0} = g\left(\frac{\sigma - \sigma_0}{\sigma_0}\right).$$

The function $g$ characterizes the visous flow characteristics of materials. Equation (2) is based on the viscoplastic model and presents the relationship between the material viscosity and overstress. Diffusion is the dominant growth mechanism under low stresses and rates, while plastic flow dominates at very high stresses and rates, whereby viscous flow is the main process. A linear overstress function expressed can be used to describe the contribution of the material viscosity,

$$\frac{\dot{\varepsilon}}{\varepsilon_0} = g\frac{\sigma - \sigma_0}{\eta}.$$

The material constant $\eta$ in Eq. (3) is called the kinetic viscosity coefficient. Curran\textsuperscript{17} noted that the void growth under a high loading rate is mainly driven by the viscous mechanism and inertia of the
material. He tested the model theoretically and experimentally and determined the material viscosities of several metals under room and melting temperatures.

Note that the viscoplastic model is rigid because of the constant value of $\sigma_0$ in Eq. (3). The stress-strain relationship in the quasistatic case is included in the calculation by Malvern et al. Thus, the strain hardening power-law is introduced to describe the yield stress, 

$$\sigma_0 = \sigma_y \cdot f(\epsilon),$$  \hspace{1cm} (4)

where 

$$f(\epsilon) = \epsilon/\epsilon_y \quad \text{if} \quad \epsilon \leq \epsilon_y,$$

$$f(\epsilon) = (\epsilon/\epsilon_y)^n \quad \text{if} \quad \epsilon > \epsilon_y,$$  \hspace{1cm} (5)

where $n$ is the strain hardening exponent and $\epsilon_y$ is the characteristic plastic strain (yield strain $\sigma_y/E$). Note that the viscoplastic strain will be greater than zero and continue to develop for viscoplastic materials when the overstress is greater than zero. The evolution of the viscoplastic strain occurs only when the overstress is greater than zero.

The second factor is the thermal effect. The study of the thermal effect is often based on the softening of the material strength. The plastic deformation of materials occurs under a dynamic load, and most of the plastic work is converted into heat under adiabatic conditions, which leads to an increase in the local temperature and softening of the material strength. The thermal softening effect has been verified in many experiments, and the same results have been obtained in molecular dynamic simulations. Under a dynamic load, the thermal softening effect leads to an unstable and disturbing evolution. This conclusion was also confirmed by finite element analysis. Plastic work produced during deformation can be partly stored in the form of internal microstructural rearrangement but is mainly transformed into heat (of the material), leading to a local temperature rise under adiabatic conditions. The procedure, which was introduced by Chung et al., can be described as follows:

$$\rho c_p \frac{dT}{dt} = \frac{k}{R^2} \frac{1}{\rho} \frac{\partial}{\partial r} \left( \frac{r^2 \partial T}{\partial r} \right) + \lambda \sigma \cdot \epsilon^p,$$  \hspace{1cm} (6)

where the first term $\frac{k}{R^2} \frac{1}{\rho} \frac{\partial}{\partial r} \left( \frac{r^2 \partial T}{\partial r} \right)$ represents the thermal diffusion; $\rho$ is the density; $\lambda$ is the coefficient of the plastic work transformed into heat, which usually set to be 0.9 in calculations; $k$ is the thermal conductivity of the material; and $r$ is the normalized radius calculated using the current radius $r$ and initial radius $R$. The equation indicates a size effect; the thermal diffusion for void growth increases with decreasing void size. Thermal diffusion can be ignored in the adiabatic case, and a simplified form of the calculation of the temperature increases can be used,

$$\rho c_p \frac{dT}{dt} = \lambda \sigma \cdot \epsilon^p.$$  \hspace{1cm} (7)

Linear thermal softening can be described,

$$\dot{\epsilon} = (1 - cT^*) \epsilon,$$  \hspace{1cm} (8)

where $c$ is the thermal softening coefficient, $T^*$ is the temperature increase, and $\epsilon$ is applied to the term described in Eq. (4) as a type of thermal “softening effect” on material strength. Subsequently, the effect of the temperature on the stress can be introduced in the form of a “thermal softening factor,” as shown above, in the adiabatic case.

However, the thermal effect on the material viscosity includes another type of “softening effect.” Gudonov et al. proposed interpolation equations for the dependence of the viscosity on the loading parameters, based on experiments. Based on Gudonov’s research, Carroll established an exponential dependence for the thermal effect on the viscosity of several metals, in which parameters are determined from viscosities at room melting temperatures. Carroll et al. established an exponential equation describing the thermal activation of viscous flow,

$$\eta = \eta_0 \exp(B(1/T)),$$  \hspace{1cm} (9)

where $\eta_0$ is the viscosity at room temperature, $T$ is the current temperature, and $B$ (set to 2970 for copper) is a constant, which can be determined based on the viscosities at room and melting temperatures. Equation (9) shows that the material viscosity decreases with increasing temperature.

III. THEORETICAL MODEL

The inertial effect becomes important when the material is subjected to impact-like loading conditions. To study the dynamic growth of a void under transient external loading conditions, the equation of motion can be used,

$$\frac{\partial \sigma_r}{\partial r} + 2\sigma_r = \rho \ddot{r},$$  \hspace{1cm} (10)

where $\rho$ is the mass density. By integrating both sides of the equation, the mechanical conservation relationship of a void in the process of motion can be obtained, while $p\dot{r}$ on the right side of the equation can be regarded as inertia. Therefore, the key question is how the acceleration $\dot{r}$ of each particle around the void can be determined. An incompressible assumption is used in this study to solve this problem, and the following equation is used for the characterization of the evolution of a void:

$$R^2 - R_0^2 = r^2 - r_0^2,$$  \hspace{1cm} (11)

where $R$ and $r$ are the radii of the initial and the current status, respectively, and the subscript “0” represents the inner surface of a void. The acceleration can be obtained by taking the derivative of both sides of this equation with respect to time $t$,

$$\dot{r} = \frac{R^2}{r^2} \dot{R}, \quad \ddot{r} = -\frac{\partial}{\partial r} \left( \frac{R^2 \dot{R}}{r} + \frac{2R \dot{R}^2}{r^2} - \frac{R^4 \ddot{R}}{2r^4} \right).$$  \hspace{1cm} (12)

Based on Eq. (12), the entire fields of velocities and accelerations can be determined based on the deformation of the inner surface of the void.

The following boundary conditions are applied in Eq. (10): $\sigma_r(r, t) = 0$ when $r = r_0$ and $\sigma_r = p\ddot{r}$ (applied load) when $r \to \infty$, where $r_0$ is the inner radius of the void under external loading conditions. Note that the boundary conditions on the inner surface of a void can be expressed as $p\ddot{r} = \rho \ddot{r}$, representing the difference between the pressure and surface tension, leading to a value of 0 when $r = r_0$ at the initial state.

The surface effect, which is neglected in Carroll’s study, is used as a boundary condition for Eq. (10). The surface effect is due
to the difference between the coordination numbers of the surface and bulk atoms and can be expressed in the form of surface tension and surface energy. Vitos proposed a surface energy (γ) value ranging from 0 to 5 N/m. Based on Zhang’s work, the surface elasticity effect is weak and can be ignored in micromechanical models. Thus, the surface effect associated with the void surface can be expressed as surface tension/energy in the form of a Laplace-Young equation,

\[ p_{\text{surface}} = \frac{2\gamma}{r}, \]

(13)

where \( r \) is the radius of the void. The \( p^s \) value is on the scale of 10^6 Pa when the void radius is ~10 nm and the surface effect becomes significant at the nanoscale. Based on Eq. (13), the value of \( p^s \) decreases with increasing void radius. The surface effect can be neglected when the void is large enough.

Thus, it is important to determine the gas pressure inside the void. We know that the existence of helium bubbles in materials is due to the surface effect and the shear resistance of the matrix material. Glam proposed a simplified method and pointed out that the initial gas pressure is balanced by the surface tension and solid yield stress,

\[ p^{\text{gas}}_0 = \frac{2\gamma}{n_0} + \sigma_0. \]

(14)

For instance, the surface tension of a nanovoid reaches a magnitude of ~10^0–10^3 Pa, which is larger than that of the yield stress of aluminum under room temperature (10^3 Pa).

The matrix material is subjected to plastic deformation and a temperature increase under dynamic loading conditions, but heat is not exchanged between the void surface and gas due to the adiabatic environment. Therefore, the plastic deformation of the matrix material has no effect on the change in the gas temperature. The gas pressure can be determined as follows:

\[ p^{\text{gas}}_0 = \left( \frac{R_0}{R} \right)^3 p^{\text{gas}}_0, \]

(15)

where \( p^{\text{gas}}_0 \) is the initial pressure obtained from Eq. (14) and \( m \) is the gas coefficient, which is constant for different types of gases (i.e., \( m = 5/3 \) for helium). The temperature change in the gas has no influence on the boundary conditions in Eq. (10) and thus is not considered in the present work.

For a quasistatic process, where the change in gas pressure is determined by the ideal gas equation, the coefficient \( m \) becomes a constant of 1. In this case, the process can be considered to be isothermal and the temperature does not affect the evolution of the void.

By integrating both sides of Eq. (10) and considering the boundaries discussed above, we obtain

\[ p^{\text{pp}} + \left( \frac{2\gamma}{n_0} + \sigma_0 \right) \left( \frac{R_0}{R} \right)^3 = \int_{r_0}^{\infty} \frac{2\eta(\epsilon)}{r} dr + \int_{r_0}^{r_0} \frac{2\eta(\epsilon)}{r} dr + p(r_n r_0 + 3r_0^2/2) + \frac{2\gamma}{n_0}, \]

(16)

which can be simplified as follows:

\[ p^{\text{pp}} + p^{\text{gas}} = p^{\text{strength}} + p^{\text{viscous}} + p^{\text{inertial}} + p^{\text{surface}}, \]

(17)

where \( p^{\text{strength}} = \int_{n_0}^{n_0} \frac{\sigma_0}{n} \text{d}n \) is the contribution of the material strength, which is influenced by the strain hardening and thermal softening; \( p^{\text{viscous}} = \int_{n_0}^{n_0} \frac{n(t) \text{d}n}{T} \) is the contribution of the viscosity of the material; \( p^{\text{inertial}} = \rho \left( n r_0 + 3r_0^2/2 \right) \) represents the inertia of the material; and \( p^{\text{surface}} = \frac{2\gamma}{n_0} \) is the surface effect. Note that the material viscosity coefficient \( \eta \) is a function of the strain \((\dot{\epsilon}(\epsilon))\), which indicates an indirect relationship among the material viscosity, temperature, and strain. The equilibrium condition for the motion of a void under dynamic loading conditions is revealed in the simplified form of Eq. (17).

The form of the present model described in Eq. (17) is similar to Seaman’s model for void growth in viscoplastic metals, as

\[ p^{\text{pp}} + p^{\text{gas}} = a_0 + \frac{\eta_0}{\rho_0} \bar{r}_0 + p^{\text{inertial}} + p^{\text{surface}}, \]

(18)

where \( p^{\text{strength}} = a_0 \) is the yield stress which is taken as a rigid threshold in this model to indicate the void growth starting point. Note that the term of material viscosity \((p^{\text{viscous}} = \frac{\eta_0}{\rho_0} \bar{r}_0)\) is derived from Rayleigh’s equation, which is different from the present model shown in Eq. (16). Predictions for void growth by the present model and Seaman’s model will be compared in Sec. IV A.

The resistance based on the viscosity of the material can be expressed as an integral of the strain rates/velocities from the inner surface of the void to the far distance. Note that this expression is very similar to the description of the equation presented by Rayleigh, but the viscous resistance term in Rayleigh’s equation only reflects the velocity of the inner surface of the void, which differs from the equation in this work. Based on the incompressible assumption, the strain rates/velocities of the particles around the void gradually decrease from the inner surface to the far distance. It is known that the resistance of the material depends on the viscosities, velocities, and current radii of the particles. How is the material viscosity-dependent resistance distributed around the void? This question will be answered based on the tests described in Secs. IV A and IV B.

IV. RESULTS AND ANALYSES

The void growth under hydrostatic tensile loading conditions is investigated to study the influences of temperature. The load without inertial and thermal effects in the isothermal case is presented in the calculations to investigate the inertial effect of the material. The material properties, which are used for the analysis of the growth of a helium bubble subjected to dynamic tensile load, are listed in Table 1; they are based on the research of Carroll, and Qi.

An external uniform tensile load \((p^{\text{pp}})\) is applied to the outer surface of the void (i.e., \( R = R_0 \)), which is shown in Fig. 2. The applied loading starts at a value of 0 \((t = 0)\) and linearly increases with time up to a value of \( P_0 \) until \( t = t_1 = 80 \text{ ns} \), keeping the constant value until \( t = t_2 = 100 \text{ ns} \) resulting in a loading rate of 0.05 GPa/ns. The platform value of \( P_0 \) of the applied load is set to be 4 GPa in Secs. IV A and IV B.

A. Influence of the material viscosity

The influence of the material viscosity is studied in this section. Figure 3 shows the prediction for the void growth under an external dynamic load \(p^{\text{pp}}\). Comparisons of the present model and Seaman’s model are made in this figure.
As shown in Fig. 3, the tendencies are similar for both the present model and Seaman's model. At first, the void grows extremely slowly with increasing applied load $p_{app}^{\text{app}}$. Fast growth starts at $\sim 60$ ns when the growth is unstable and limitless, even without a further increase in the external load. Generally, the growth rate predicted by the present model is larger than that of Seaman's model. It is important to study the inner factors that cause this phenomenon.

Therefore, it is interesting to determine the role of the material viscosity in the dynamic void growth. To address this question, the resistances for the material strength ($p_{\text{strength}}^{\text{app}}$) and viscosity ($p_{\text{viscous}}^{\text{app}}$) depending on time are shown in Fig. 4, for an initial radius of 1 nm.

As shown in Fig. 4, for the present model, the effect of the material viscosity is so small that it can be ignored in the initial growth process. The resistance of the material viscosity rapidly increases when the void grows to a certain extent. This is due to a change in the particle velocity around the void, which is equal to the resistance at $\sim 60$ ns due to the material strength. It keeps increasing, and
suddenly changes at 80 ns, which is due to the change in the applied external load \( p_{app} \) when stops to increase at \( t_1 = 80 \) ns. The material viscosity plays a very important role in preventing void growth; it is dominant, which agrees with Curran’s description.\(^{24}\) The resistance of material strength is set to be a constant in Seaman’s model with no strain hardening effect, which is much smaller than that in the present model. On the other hand, the resistance of material viscosity is overestimated by Seaman’s model, leading to a lower void growth rate shown in Fig. 2.

Additionally, the resistance of the material strength, which is influenced by strain hardening and thermal softening, varies during the dynamic void growth (dashed line in Fig. 4). The threshold method, based on which \( p_{strength}^{strength} \) is constant (i.e., method used in Seaman’s\(^{11}\) and Qi’s\(^{19}\) studies), is not an accurate way to describe the void growth under a dynamic load.

It can be assumed that the material strength plays a major role in the void growth under a quasistatic load. The material viscosity becomes increasingly important with increasing loading strain rate. For example, the influence of the material viscosity is dominant under ultrahigh strain rate loading conditions, while the effect of the material strength can be ignored in this case. In general, the growth process of voids is characterized by a competition between these two factors, and the competitive advantage changes with changing load rate.

Another way to test the influence of the material viscosity is to directly change the value of the viscosity coefficient \( \eta \). It is easy to understand that the effect of material viscosity becomes stronger with increasing viscosity coefficient and void growth will be more difficult; thus, calculations are omitted in this section. This is a direct effect of the material viscosity depending on the change in the coefficient. Material viscosity impedes the void growth under a dynamic load. Based on the correlation in Fig. 4, it can be concluded that the material viscosity plays an important role in the dynamic evolution of voids, especially under high-rate load conditions.

### B. Influence of the thermal effect

The influences of the thermal effect mainly include two aspects in this study: first, strength softening caused by a temperature increase during plastic deformations under a dynamic load and second, viscous softening based on Eq. (9). Both processes affect the evolution of dynamic void growth.

The temperature distribution for the calculation in Fig. 3 is shown in Fig. 5. The temperature increases on the inner surface of the void until it reaches a maximum; subsequently, it decreases to 0 at the far distance, which can be explained with the incompressible assumption described in Eq. (11). As shown in Fig. 5, the temperature on the inner surface of the void can reach as high as \( \sim 1200 \) °C, which is close to the melting temperature (1355 °C). Note that the adiabatic assumption is only appropriate under transient load conditions. If the loading process lasts long enough, heat transfer will occur and the thermal softening effect will be greatly weakened.

The temperature has a softening effect on the material strength, which is called “strength softening” in the literature. Based on Eq. (9), the material viscosity correlates with the temperature. The material viscosity decreases with increasing temperature. In other words, the temperature has a softening effect on material viscosity, which is called “viscous softening” in this paper. Most studies on “strength softening” were based on quasistatic experiments at different temperatures, which are independent with these studies of “viscous softening” in dynamic cases. From a physical point of view, both softening effects can promote the void growth under a dynamic load.

Since the material viscosity has a relationship with the temperature, the resistance of material viscosity around the void must be unevenly distributed due to the influence of temperature distribution. Figure 6 shows the resistance distributions of material viscosity...
at different locations at a time of 80 ns and 90 ns. In general, the resistance is small due to the thermal softening effect on material viscosity even though the strain rate is large near the inner surface of the void; the resistance is small due to the small strain rate even though the temperature is low far away from the void.

However, the proportions of these two “softening” effects in dynamic void growth remain unclear. The resistances of the material viscosity $p_{\text{viscous}}$ and material strength $p_{\text{strength}}$, on the other hand, affect the void growth. Thus, these resistances are compared in Fig. 7 to determine their thermal softening effects on materials.

Figure 7 shows the predictions for the resistances of the material viscosity and material strength for adiabatic (solid lines) and isothermal cases (dashed lines), respectively. It can be concluded that both factors have a significant influence of the material strength affected by the temperature and strain rate.

V. CONCLUSIONS

In this work, we focus on the dynamic response of a void. A viscoplastic model is applied to material strength calculations to determine the effects of the material viscosity and temperature on the material strength.

1. The material viscosity impedes the void growth under a dynamic load. Compared with the viscous effect and the early void growth stage, it is affected more by the strain hardening of the materials. However, this advantage cannot be sustained with increasing void growth. The material viscosity plays a dominant role in the void growth when under a high loading rate.

2. The resistance of material strength cannot be simplified into a constant (threshold) that the strain hardening effect should be taken into consideration in a problem of dynamic void growth.

3. The resistance of material viscosity has a certain distribution rule around the void. The resistance of the nearest and the farthest positions of the void is small, which is affected by both temperature and strain rate.

4. The temperature affects the material strength and viscosity and promotes void growth. The influence of “viscous softening” is greater than that of “strength softening” in viscoplastic material under a dynamic load.

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