Dynamic Constitutive Model of Physical Simulation in High-Speed Blanking for C5191 Phosphor Bronze

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Abstract: Strain hardening, strain rate strengthening and thermal softening data of C5191 phosphor bronze at high-speed blanking are not easy to be obtained with a general measure method, therefore, it is quite difficult to establish the dynamic constitutive model. To solve this problem, the tensile properties at a strain rate of 1 s^{-1} by GLEEBLE-3500, and dynamic tensile conditions at strain rates of 500, 1 000 and 1 500 s^{-1} by split Hopkinson tensile bar (SHTB) apparatus are studied. According to these test data, the classic Johnson-Cook equation is modified. Furthermore, the modified Johnson-Cook equation is validated in the physical simulation model of high-speed blanking. The results show that the strength of C5191 phosphor bronze maintains a certain degree of increase as the strain rate increasing and presents a clear sensitivity to strain rate. The modified Johnson-Cook equation, which has better description accuracy than the classical Johnson-Cook equation, can provide important material parameters for physical simulation models of its high-speed blanking process.

Key words: C5191 phosphor bronze; split Hopkinson tensile bar (SHTB); Johnson-Cook equation; dynamic constitutive model; high-speed blanking

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0 Introduction

Phosphor bronze presents many advantages including good mechanical performance, favorable corrosion resistance, and good wear resistance, as well as little possibility of producing impulse sparks. It is usually applied in wear-resistant parts and elastic elements[1] in fields such as aeronautical and aerospace engineering, electrical machines and equipment, and electronic information components. It is particularly used in connector terminals, and lead frames of integrated circuits in part manufacturing based on information technology including computers, communications, and resource consumption. Moreover, metal parts, including electrical connectors and plugs in aeronautical and aerospace engineering, and data transmission connectors in high-speed vehicles in the era of big data, are manufactured by conducting high-speed precision progressive stamping (HSPPS) on phosphor bronze. HSPPS is a pressing manufacturing technology which is realized by installing precise and complex progressive press dies consisting of multiple processes including blanking, bending, drawing, and forming by high-speed stamping. Such press is equipped with automatic material feeding and receiving mechanisms, thus realizing automatic and efficient mass production. Its stamping speed can range from 800 strokes per minute to several thousands of strokes per minute during mass-production.

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HSPPS is considered as an advanced manufacturing technology with high efficiency and precision as it integrates precision manufacturing, computer technology, automatic control, and green manufacturing. It is a developing technology and leads the trend in precision stamping[2-3].

Blanking is a basic process that accounts for a large proportion of the work in HSPPS. Because the behavior of metals in high-speed blanking is highly non-linear, the plastic deformation and fracture of the materials are confined to a narrow area around the cutting edge. This leads to significant vertical and lateral pressure on the cutting edge, which tends to cause rapid friction heating[4-5]. Meanwhile, during high-speed blanking, there is a small gap, and given the high speed and long processing time, the increased temperature of the materials is therefore quite obvious. Besides, the constitutive model of the materials in the process of high-speed blanking becomes more complex due to the enhancing effect of strain rate and strain hardening under large strain at high speed. Existing results indicate that the time taken to undertake high-speed blanking is short as the process can be over within several microseconds. As the partial temperature of the blanking section reaches 400℃, metals are subjected to large strain (1—3 mm/mm) and ultra-high strain rates (10^3—10^4 s^{-1})[6-8]. On this basis, it is difficult to measure data including temperature, strain, and strain rate, as well as the flow stress induced by high-speed blanking due to the limitations of the measuring instruments and methods, and the gaps between measurements. Therefore, it is a great challenge to establish a dynamic constitutive model that can identify the high-speed blanking process. Refs. [9, 10] obtained the strain and stress curves of QSn6. 5-0. 1 phosphor bronze through conducting uniaxial tensile tests and introduced the results into an finite element analytical model of blanking-induced deformation in HSPPS. Ref. [11] constructed a model constitutive relationship for thin plates under the influence of size effect, and provided a reliable basis of material performance for studies of the mechanism of micro-blanking in HSPPS. Refs. [12-13] conducted a tensile test to explore the size effect on the micro-scale plastic deformation of phosphor-bronze thin plates, and constructed a constitutive model of the size effect based on the thickness of the materials. Falconnet et al.[14] performed a uniaxial tensile test to obtain stress-strain curves of copper alloy thin plates, and built an elastoplastic constitutive equation to simulate blanking. Refs. [15-17] revealed that the mechanical performance and deformation behavior of such materials under dynamic load were significantly different from those under static and quasi-static loads. The elastic modulus, strength, and toughness of materials vary as the strain rate increase. Deformation behaviors of metals mainly focus on the locality and non-isothermal of deformation, as well as the intense effects of shock wave. According to previous research, the mechanical performance measured in tensile tests under quasi-static load fails to represent the dynamic response of materials during high-speed blanking. Hence it is necessary to study the dynamic deformation behavior of materials to understand their mechanical performance under harsh environments. This is considered to be the key to the application of phosphorus bronze components formed by high-speed blanking.

In this paper, split Hopkinson tensile bar (SHTB) tests are performed to acquire the mechanical performance of C5191 phosphor bronze under high strain rates at high temperatures. By combining the data with numerical simulation output, the dynamic constitutive relationship for the physical simulation of high-speed blanking is established.

1 Experiment

1.1 Material

The experimental material used in the paper is C519-H phosphor bronze. Its chemical compositions (in weight) are as follows: Zn (5. 5%—

7.0%), P (0.11%—0.13%), Fe ($\leqslant$ 0.02%), Pb ($\leqslant$ 0.05%), Zn ($\leqslant$ 0.20%), and Cu(balance). Under the process of blanking, the anisotropy of the thickness direction of the sheet material is not considered. Therefore, it can be used to obtain the stress-strain relationship of the materials by using isotropic bar tensile experiments. In order to achieve the strain concentration in the center of each specimen, the bars are machined into tensile specimens for tensile test. The dimension of the tensile specimens under low strain rates is shown in Fig. 1 (a) and that under high strain rates is shown in Fig. 1(b). The specimens formed by mechanical processing need to be polished with metallographic sand papers to reduce the stress concentration induced by partial microcracks, and the residual stress caused by mechanical processing. The surfaces of the specimens are then cleaned by ethanol.

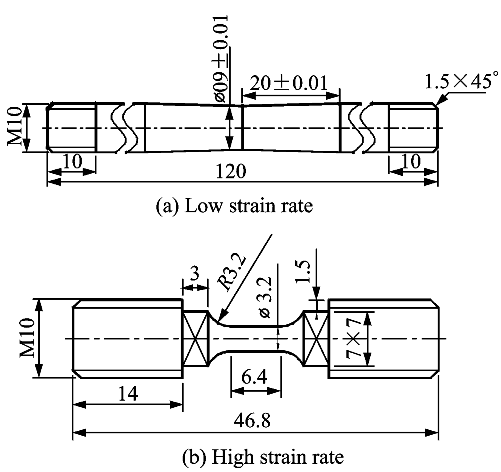


Fig. 1 Geometries of tensile specimens at different strain rates

1.2 Method

The dynamic constitutive equation of the materials must be established by taking lower strain rate data as references. Fig. 2 (a) shows a GLEEBLE-3500 thermal simulator for measuring stress-strain curve of C5191 phosphor bronze under lower strain rate (1 s^{-1}) at room temperature. HSTB is adopted in this dynamic tensile test (Fig. 2(b)). In order to match the test environment with the field application conditions of high-speed blanking, the strain rates of 500, 1 000 and 1 500 s^{-1} are adopted in the temperature range of 20 ℃ and 100—400 ℃, respectively.

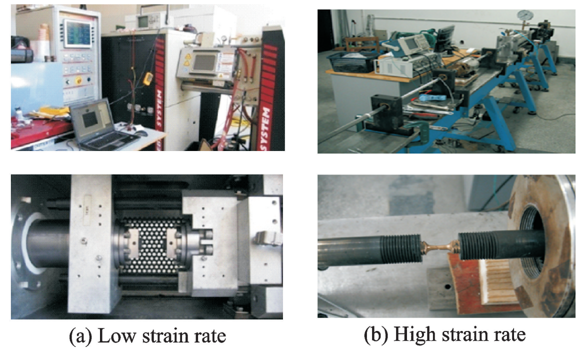


Fig. 2 Experimental apparatus of tensile test at different strain rates

2 Results and Discussion

2.1 Strain-stress curves obtained from dynamic tensile tests at room temperature

The strain-stress curves of C5191 phosphor bronze from dynamic tensile tests at room temperature are shown in Fig. 3(a).

The increase of strain rate causes the flow stress on the specimens to increase. This demonstrates that the influence of strain rate on the strength of the material in the stage of plastic deformation is more prominent. The strain rate sensitivity m is given by[18-19]

$$m=\frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}} \tag{1}$$

where σ is the stress corresponding to the same tensile strain produced at a constant strain rate, and $\dot{\varepsilon}$ is the strain rate.

By processing the experimental stress-strain data based on Eq. (1), the varying trend of the sensitivity index m with the variation of strain rate is given in Fig. 3(b). As strain rate increases, m also increases significantly. However, m tends to decrease gradually at high strain rates ($>10^3$ s^{-1}). The strain hardening index n, which is more sensitive to uniform plastic deformation, increases in the dynamic tensile test (Fig. 3 (c)). n is considered as an important index for the measurement of the capability of metals in terms of their uniform plastic deformation ($n=\frac{\partial \sigma}{\partial \varepsilon}$). Its values reflect the possibility that one material may undergo micro-plastic deformation [20-21]. Hence, the C5191 phosphor bronze exhibits an apparent strain hardening and an increasing strain rate. The dynamic mechanical response of the material under high strain rates (10^3—$10^4\ s^{-1}$) in high-speed blanking needs to be investigated further.

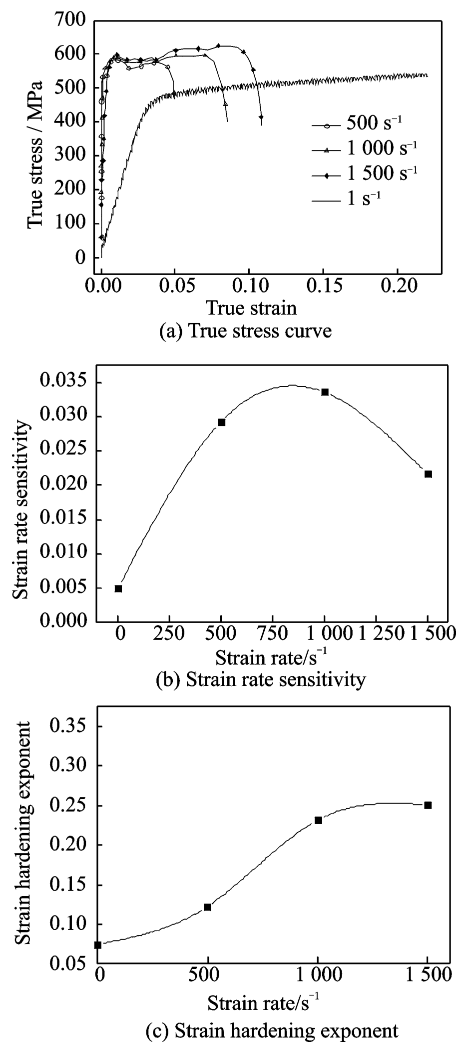


Fig. 3 Tensile mechanical properties of C5191 phosphor bronze under different strain rates at room temperature

2.2 Strain-stress curves obtained under high strain rate at different temperatures

To explore the effect of different temperatures on C5191 phosphor bronze under high strain rate, SHTB tests are conducted to get strain-stress curves (Fig. 4). With the increasing temperature, the material is subjected to decreased flow stress and undergoes thermal softening. This suggests that the thermal effect affected the rheological properties of the material. Studying the dynamic flow stress changes of materials under high strain rates is helpful to analyze the deformation caused by high-speed blanking at the maximum local temperature of 400 ℃.

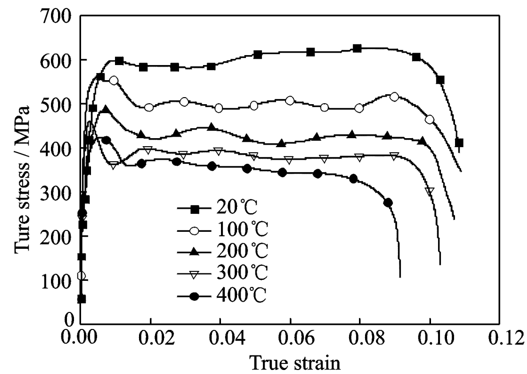


Fig. 4 True stress-strain curve at different temperatures under strain rate of 1 500 s^{-1}

2.3 Dynamic constitutive model and its modification

Johnson-Cook constitutive model and its modified version are usually adopted in the analysis of the dynamic mechanical properties of materials under high strain rates at high temperatures. Johnson-Cook model can describe flow stress as a product of three items, i. e., strain hardening, strain rate, and softening temperature, by considering the effect of temperature and strain rate on materials[22]

$$\sigma(\varepsilon_p, \dot{\varepsilon}, T) = (A + B\varepsilon_p^n)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right) \cdot \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)\right)^m \quad (2)$$

where σ is the flow stress; $\varepsilon_p, \dot{\varepsilon}, T$ are the strain, strain rate and temperature, respectively; A is the initial yield stress at room temperature by referring to strain rate $\dot{\varepsilon}_0$ and the reference temperature T_r; B and n are the strain hardening modulus and the hardening exponent of the material; C is the strengthening strain rate; m denotes the thermal softening index of the material; T_r and T_m are the room temperature and melting temperature.

Based on the physical concept of the Johnson-Cook model, and the stress-strain curves obtained from tensile tests at room temperature at the reference strain rate ($1\ s^{-1}$) and reference temperature shown in Fig. 3(a), the initial yield stress A can be obtained. Thereafter, Origin software is used to perform regression of the stress-strain curve, thus obtaining the values of B and n, respectively. The values of C and m can be obtained from SHPB tensile tests at room temperature and other different temperatures, and the detailed data processing are given in Refs. [23-24]. The fitting parameters of the Johnson-Cook model are listed in Table 1.

Table 1 Fitting parameters of Johnson-Cook model for C5191 phosphor bronze

A	B	n	C	m
449.42	195.57	0.494 7	0.031	1.53

Johnson-Cook model in the existing research can describe the mechanical performance of metals under the deformation induced by high strain rates at high temperatures. However, the deformation process of the material and the deformation history of the metal material have not been taken into account[23-25]. Given the strain in the blanking process can reach 1—3 mm/mm, however, the strain in a tensile test is far less than that. The Johnson-Cook model needs to be constructed by modifying the strain hardening behavior based on SHPB test data. As a standard material for dynamic tensile test, the dynamic Johnson-Cook constitutive model of oxygen-free copper must be built by adding a strain hardening index. In this way, the effect of the process of tensile deformation on the mechanical performance of the materials can be precisely described as[26]

$$\sigma_{JC} = (A + B\varepsilon_p^n + B_1 e^{-n_1 \varepsilon_p})(1 + C\ln\dot{\varepsilon}) \cdot \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)\right)^m \tag{3}$$

Based on the parameters of typical Johnson-Cook constitutive model, the modified model in this research adds two parameters, B_1 and n_1. In order to obtain the values of the two parameters, Origin software is used to fit the dynamic tensile stress-strain curves under different strain rates. The fitting results of the modified index of strain hardening are shown in Fig. 5. It reveals that the strength of the modified strain hardening is slightly higher than that of the unmodified. The fitting precision increases from 0.919 4 to 0.949 8. The modified Johnson-Cook model can be expressed as

$$\sigma_{JC} = (449.42 + 195.57\varepsilon_p^{0.494\,7} + 0.16\,2e^{-0.18\varepsilon_p}) \cdot (1 + 0.031\ln\dot{\varepsilon})\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)\right]^{1.538} \tag{4}$$

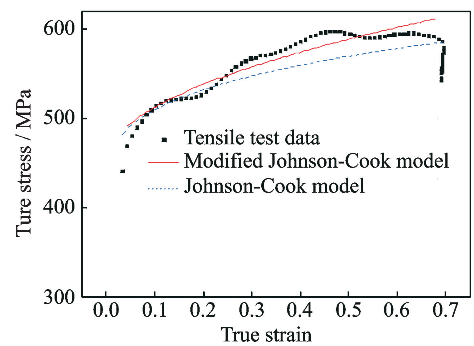


Fig. 5 Comparison between fitting results and experimental data of strain hardening function for Johnson-Cook model

3 Verification of the Modified Johnson-Cook Model in Simulation of High-Speed Blanking

The height of the bright area of the blanking section is used to characterize the quality of this section. The proportions of the bright area in the blanking section can reflect the section quality. By introducing the obtained Johnson-Cook model of C5191 phosphor bronze into DEFORM software, the process of high-speed blanking is simulated.

In this paper, the grid deletion method is used to deal with those grids corresponding to the critical ductile damage values of the materials, namely the C value for fracture creation, when the blanking crack occurs. On this basis, the process of the formation of the blanking section is simulated and the morphology of the blanking section is obtained for comparison with the morphologies of the blank sections in real production at the Jiangsu Engineering Technology Research Centre of Precision High-Speed Dies. Moreover, the precision of the simulated process of high-speed blanking is further validated by combining the variation of the blanking forces obtained by comparing experimental and measured data.

The physical model of the process of high-speed blanking is illustrated in Fig. 6(a), and the geometric parameters of blanking process are listed in Table 2. The punch, die, and stripper plate are considered to be rigid, whereas the sheet metal material is considered to be plastic. It is useful to reduce the number of elements by defining a different mesh density in different zones of the sheet. For example, a very dense mesh is defined in the shearing region (relative element size of about 0.000 01), whereas a coarse mesh is used for the outside areas. The total numbers of elements and nodes are 16 004 and 15 644, respectively. For the finite-element simulation with an initial temperature of 20 ℃, the punch penetration depth is increased by 0.004 mm for each step and the calculation is interrupted after every 10 steps. Additional simulation parameters and boundary conditions are shown in Table 3.

Table 2 Geometric parameters of blanking process

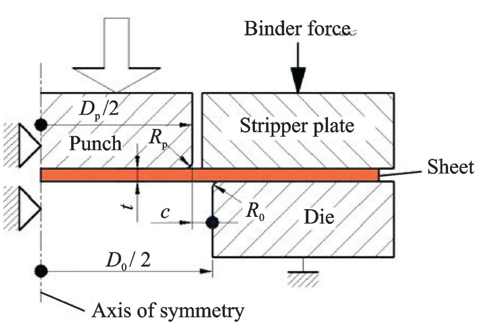
mm

Thickness	Dimension	Clearance	Fillet	Stripper gap
0.12	ϕ0.5	0.007	0.01	0.003

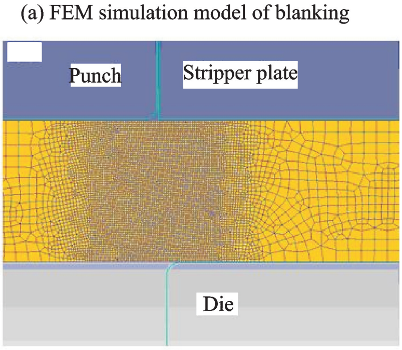
Table 3 Object boundary conditions

Punch	Die	Stripper plate	Sheet metal	Heat transfer coefficient	Thermal softening coefficient
Rigid body $V_x=0$ $V_y=1\ 000$ mm/s	Rigid body $V_x=V_y=0$	Rigid body $V_x=V_y=0$ $P_y=5$ MPa	Plastic body (Axisymmetric) $V_x=0$, $V_y=$ free	0.95	0.8

As the fracture of the blanking is found on the interface between the punch and die, the grids of the materials surrounding the blanking gap are locally refined (Fig. 6(b)). The blanking speed is set to 1 000 mm/s, which is equivalent to 1 200 strokes per minute in practical production.



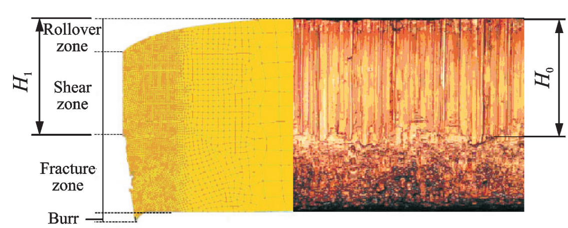
(a) FEM simulation model of blanking



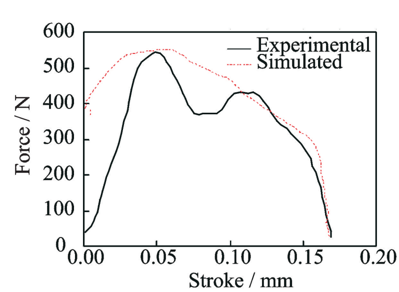
(b) Different mesh densities in different zones of sheet

Fig. 6 Simulation model of high-speed blanking

The morphology of the blanking section is shown in Fig. 7(a), and the comparison results of blanking forces are illustrated in Fig. 7(b). The ratios of H_1 and H_0 to the thickness of the materials are 53.392 9% and 53.719 7%, respectively. While the simulated and actual maximum blanking forces are 553 and 545 N. The results show that the modified Johnson-Cook constitutive model for C5191 phosphor bronze can better predict the height of the bright areas in its blanking section and the variation of blanking force.



(a) Burnish length



(b) Blanking force

Fig. 7 Comparison between simulated and experimental results

4 Conclusions

(1) The strength of C5191 phosphor bronze increases to different extents during dynamic tensile test at high strain rate, which shows obvious sensitivity to strain hardening and strain rate.

(2) The dynamic constitutive relationship for C5191 phosphor bronze is obtained based on Hopkinson tensile test. The modified Johnson-Cook equation takes strain hardening into account and has higher accuracy than the typical form.

(3) The obtained dynamic constitutive equation can describe the dynamic deformation characteristics of C5191 phosphor bronze under large strain and high strain rate.

This study provides the technological parameters for the FEM numerical simulation of high-speed blanking of C5191 phosphor bronze.

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