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ARTICLE

Finite Element Analysis of Lightweight Base Plate Considering Strain Rate Effect

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Abstract: The compressive true stress-true strain curves of TC4 alloy with different strain rates at room temperature were obtained by the Instron test machine and split Hopkinson pressure bar (SHPB) device. Johnson-Cook (JC) constitutive model of TC4 alloy was established by fitting the experimentally obtained stress-strain curves. Based on the constitutive model, the impact compression experiment of TC4 alloy at high strain rate was simulated by ABAQUS/Explicit. The reasonability of the parameters for the constitutive model was verified by comparing the experimental results with the simulation data. Results show that the numerical results are in good agreement with the experimental results. In order to achieve the purpose of lightweight mortar, a new lightweight mortar base plate made of TC4 alloy was designed. The finite element model (FEM) of the base plate under impact loading was established considering the strain rate effect of TC4 alloy. The strength and stiffness of the base plate were analyzed, and the variation law of the stress and displacement of the base plate was obtained. The simulation results show that the stiffness and strength of the base plate meet operation requirements.

Key words: base plate; TC4 alloy; strain rate effect; constitutive model; finite element analysis

Mortar is a kind of slippery-bore artillery with curved trajectory, which uses base plate to bear recoil force and fires mainly at high angle [1]. As the rear support of mortar, the base plate bears tremendous impact when firing [2]. In order to be more suitable for modern local war, the requirements of lightweight in weapons is getting higher and higher. Therefore, the lightweight of mortar base plate is of great significance in complex combat environment [3].

Recently, titanium and its alloys, especially the TC4 alloy, are advanced lightweight materials with superior properties, such as high strength-to-weight ratio, low density, high toughness, corrosion resistance, chemical stability, and widely used in the aerospace and defense industries[4-8]. It is well known that material constitutive models are used to describe the relationship between flow stress and strain. The flow stress of TC4 alloy is strongly affected by strain and strain rate, and a series of models have been established [9-12]. The theoretical constitutive model used in finite element simulation still has a big gap with the actual constitutive model of materials, which restricts the improvement of simulation accuracy.

In this study, the dynamic mechanical properties of TC4 alloy at different strain rates were tested. The constitutive model of TC4 alloy considering strain rate effect was obtained by fitting the stress-strain curves, and the parameters of the constitutive model were verified. Finally, the finite element model of the base plate under impact loading was established, and the strength and stiffness of the base plate were analyzed.

1 Mechanical Behavior and Constitutive Model

1.1 Mechanical behavior

The test material was TC4 alloy, and its original microstructure consists of α and β phases, as shown in Fig.1. The chemical composition of as received TC4 alloy is shown in Table1. The same size specimens were adopted for both quasi-static and dynamic tests to ensure the consistency of experimental conditions. TC4 alloy sheet was machined into

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cylinders with an average diameter of 6 mm and an average length of 6 mm. Quasi-static compression tests were carried out on the Instron test machine with the strain rate of 0.01 s^{-1} at room temperature. Dynamic compression tests were carried out using the SHPB test system with the strain rates of 218, 1187 and 5592 s^{-1} at room temperature. To ensure the reproducibility of experimental results, all the compression tests were performed in triplicate using a batch of specimens at each strain rate under identical experimental conditions. The experimental device and principle can be referred to Ref. [13-15].

After the data processing with Matlab program, the true stress-strain curves of TC4 alloy at four different strain rates were obtained, as shown in Fig.2. It can be found that the flow stress and strain in quasi-static experiments are less than those in dynamic experiments. With the increase of strain rate, the dynamic yield strength and elastic modulus of TC4 alloy materials increase under the dynamic loading. Research results show that TC4 alloy has a strong strain rate sensitive effect under impact loading.

1.2 Establishment of JC constitutive model

At present, the constitutive models describing strain rate-dependent dynamic response of metal materials mainly include pure empirical constitutive models based on effective experimental data and physical constitutive models based on material deformation mechanism. JC model has been widely used because of its simplicity in expression and application to various crystal structures. Therefore, the JC model was chosen as the dynamic constitutive model for TC4 alloy. In this work, the constitutive model of TC4 alloy at room temperature was studied, so the Johnson-Cook constitutive model can be simplified as follows:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*) \quad (1)$$

$$\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0 \quad (2)$$

where σ is flow stress, ε is plastic strain, $\dot{\varepsilon}^*$ is dimensionless strain rate, $\dot{\varepsilon}$ is strain rate, and $\dot{\varepsilon}_0$ is reference strain

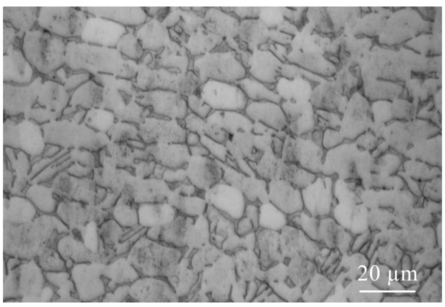

Fig.1 Orininal microstructure of TC4 alloy

Table 1 Chemical composition of TC4 alloy (wt%)

Al	V	C	O	H	Fe	Ti
5.92	3.94	0.02	0.08	0.002	0.13	Bal.

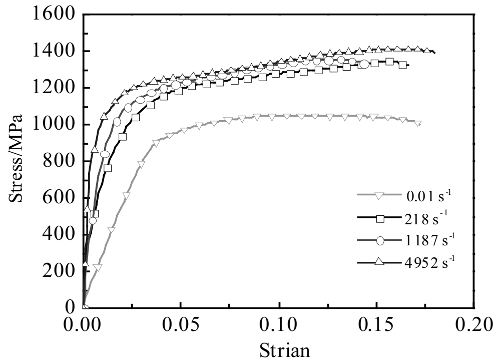

Fig.2 True stress-true strain curves of TC4 alloy under different strain rates

rate; A, B, C and n are material parameters, which can be obtained by fitting stress-strain curves. After a series processing of the stress-strain curves, all the material coefficients of the JC model are obtained and given in Table 2. Therefore, the established JC model of TC4 alloy can be written as the following expression:

$$\sigma = (867 + 588\varepsilon^{0.44})[1 + 0.0192\ln(\dot{\varepsilon} / 0.01)] \quad (3)$$

Fig.3 shows the comparison of the stress-strain curves obtained from the tests and predicted by JC constitutive model. It can be seen that the predicted flow stress curves are in good agreement with the experimental curves in the plastic stage. Because the temperature softening effect is not considered, the error is relatively large in the stage after large deformation, and the related work will be carried out later.

1.3 Verification of JC constitutive model parameters

Constitutive model plays an important role in numerical simulation of impact test, especially JC constitutive model. The parameters of JC model obtained from dynamic mechanical property tests must be verified before applied to

Table 2 Material constants of TC4 material for JC model

Parameter	A/MPa	B/MPa	n	C	$\dot{\varepsilon}_0$ /s^{-1}
Value	867	588	0.44	0.0192	0.01

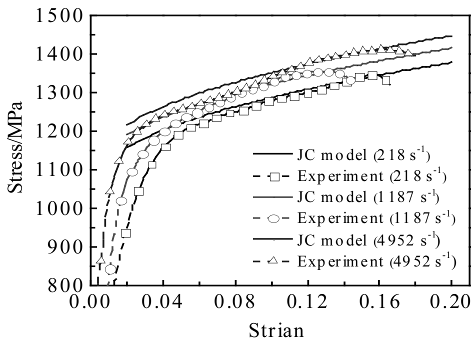

Fig.3 Comparison between experimental results and predicted results based on JC model

engineering practice. The dynamic response of TC4 alloy under impact loading was analyzed using ABAQUS/Explicit. The JC constitutive model obtained in this work was used to describe the stress-strain characteristics of TC4 titanium alloy. The JC failure model was used to describe the damage failure behavior of the material. The specific material parameters are shown in Table 3.

Fig.4 shows the finite element model (FEM) simulation results of impact compression test of TC4 alloy specimens at the strain rate of 4952 s^{-1}. It can be seen that the finite element simulation results are in good agreement with experimental results and predicted results based on JC model. The validity of JC constitutive model in describing the high strain rate mechanical properties of TC4 alloy and the accuracy of material parameters are verified by comparison.

2 Finite Element Analysis of Base Plate

2.1 Finite element model

A new type of lightweight base plate made of TC4 alloy was designed according to development tendency, which has the advantages of convenient carrying, high reliability and fast operation. It is generally true that the firing angle of mortar is from 45° to 85°. When the mortar fires on the rigid ground at the firing angle of 45°, the working condition of the base plate is the worst. In this work, the finite element analysis of the base plate was carried out under the most disadvantageous working condition.

The three-dimensional geometrical model of base plate was imported into ABAQUS, and the meshing was automatically selected. When the meshing was not suitable, the ideal finite element model can be obtained by adjusting the element size or number. The element types of C3D8R and C3D10M were selected to simulate the mortar breech and base plate. The finite element mesh model of the base plate has 42 073 elements and 72 098 nodes, as shown in Fig.5. A universal contact with a tangential friction coefficient of 0.1 and a normal "hard" contact were established [17]. The calculation parameters and constitutive model of TC4 alloy were determined in the former part of this paper. The load-time curve applied to the base plate was obtained by the theoretical calculation of interior ballistics, as shown in Fig.6.

Table 3 Material parameters of TC4 [16]

ρ/kg·m^{-3}	E/GPa	Poisson's ratio	T_{melt}/K	A/MPa	B/MPa	n	C	$\dot{\varepsilon}$/s^{-1}	D_1	D_2	D_3	D_4	D_5
4430	135	0.33	1878	867	588	0.44	0.0192	0.01	−0.09	0.27	0.48	0.014	3.87

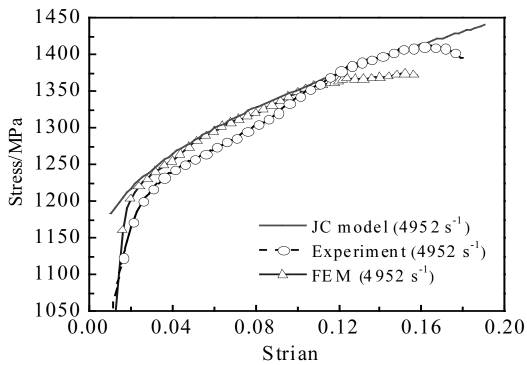

Fig.4 Comparison between simulation results and experimental results

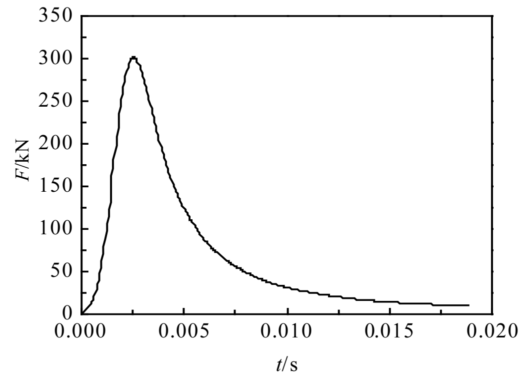

Fig.6 Load-time curve of the impact loading applied on the base plate

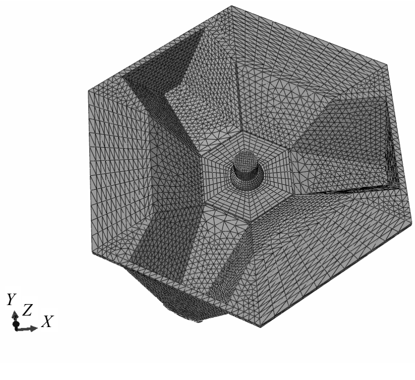

Fig.5 Three-dimensional model of lightweight base plate

2.2 Analysis of simulation results

Results show that the calculation convergence of the finite element model of base plate established by ABAQUS/Explicit is good. Fig.7 shows the stress nephogram of the base plate when the mortar fires on the rigid ground at the firing angle of 45°. It can be seen from the stress nephogram that the maximum stress of the base plate appears at a supporting bar, and the maximum stress is 343.7 MPa. Fig.8 is the displacement nephogram of the base plate with a maximum displacement of 3.543 mm.

According to the previous analysis, it can be found that the stress of base plate is much smaller than the yield

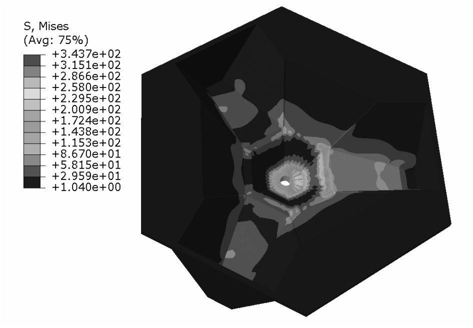

Fig.7 Stress nephogram of base plate

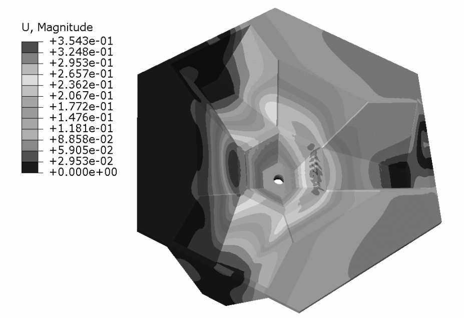

Fig.8 Displacement nephogram of base plate

strength of TC4 alloy considering strain rate effect. The strength space of base plate is large enough, which can reach the demand of rapid-fire and single-shot of mortar. The simulation results show that the strength and stiffness of base plate placed on the rigid ground meet the design requirements, so it can better meet the conditions on other ground.

3 Conclusions

1) The quasi-static compression tests and dynamic SHPB tests are carried out to obtain the mechanical behaviors of TC4 alloy with different strain rates at room temperature. Research results show that TC4 alloy has obvious strain rate sensitive effect under impact loading.

2) Based on the stress-strain curves obtained from experiments, the JC constitutive model of TC4 alloy is established. ABAQUS/Explicit is used to simulate the impact compression process of TC4 alloy. It is shown that the numerical results are in good agreement with the experimental results.

3) The finite element model of lightweight base plate made of TC4 alloy under impact loading is established. The simulation results show that the stiffness and strength of the base plate meet operation requirements, providing reference for further design and research of base plate.

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考虑应变率效应的轻量化座钣有限元分析

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摘　要：室温条件下，采用Instron实验机和分离式Hopkinson压杆（SHPB）实验装置对TC4钛合金进行压缩实验，得到了不同应变率下的真应力-真应变曲线。通过对应力-应变曲线拟合分析，建立了TC4钛合金的Johnson-Cook(JC)本构模型。基于该本构模型，采用ABAQUS/Explicit对TC4钛合金高应变率下的冲击压缩实验进行了数值模拟，通过实验结果与仿真数据的对比分析，验证了该本构模型参数的合理性。为实现追击炮轻量化的目标，设计了一种新型轻量化TC4钛合金质追击炮座钣。通过建立冲击载荷下追击炮座钣的有限元模型，考虑材料的应变率效应，对座钣的强度和刚度进行了分析，得到了座钣的应力和位移的变化规律。

关键词：座钣；钛合金；应变率效应；本构模型；有限元分析

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