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Validation of the Tabulated Johnson-Cook Model for a Dynamic Compression Simulation

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Abstract. MAT224 is a tabulated version of the Johnson-Cook model in LS-DYNA. Compared with the original Johnson-Cook material, MAT224 was developed to simulate the dynamic response of a material by just defining the effective stress as a function of effective plastic strain at different strain rates and temperatures, thus avoiding the tedious parameter fitting procedures in the traditional Johnson-Cook model. However, the stability and precision of solution is strongly dependent on the effective stress versus effective strain curves in MAT224, and unreasonable curve data will lead to warnings or errors in the process of solution. In the current study, a two-dimensional axisymmetric finite element model for the Ti-6Al-4V titanium alloy under dynamic compression was built, and MAT224 was employed. By investigating the effects of the curve numbers, strain ranges, data points, as well as changing tendencies, on the simulation results, the stability and the reliability for MAT224 are systematically studied.

Introduction

Johnson-Cook model [1] has been widely used to perform simulation by taking the strain-rate strengthening effect and thermal softening effect into account. However, for the original Johnson-Cook model (see *MAT_15 in LS-DYNA software [2]), in order to obtain its parameters, it needs a lot of experimental data to be fitted, and the fitting procedure is quite complicated as well as time-consuming. Fortunately, MAT224, as a tabulated version of the Johnson-Cook model in LS-DYNA software, omits the tedious fitting procedure for related parameters and just needs the user to input a series of effective stress versus effective strain curves at different strain rates and temperatures in a tabular format, making it become a high-efficiency Johnson-Cook model. It might be mentioned, however, these curves need certain correction before being used in MAT224, because the curve numbers, data points in a curve, as well as curve tendencies will affect the final results inevitably. In the current study, two ideal tables of effective stress versus effective strain curves at different strain rates and temperatures are imported and used as a group of reference curves for MAT224 to simulate a classic dynamic compression test. Subsequently, by changing the curves artificially and compared with the reference group of curves, the stability and the reliability for MAT224 are systematically studied.

Finite element modeling

Boundary and loading conditions. As shown in Fig.1, the two-dimensional axisymmetric finite element model is only composed of specimen (Φ5×5) as well as parts of input bar and output bar, and the non-reflection boundary condition was applied on both of the upper and bottom sides of the model to ensure that on which the stress wave did not reflect. The model is subjected to uniaxial dynamic compression by prescribing a velocity along the y-axis negative direction on the nodes of upper side as well as a displacement constraint along y-axis direction on the nodes of the bottom side. The loading curve is defined as follows: the velocity in the compression direction is increased linearly from 0 to the peak velocity(V_{peak}) which is given by Eq.1 within 5μs, and then kept constant until t= 75μs to ensure a constant strain rate of 4000/s, and finally decreased linearly to 0 at t=80μs.

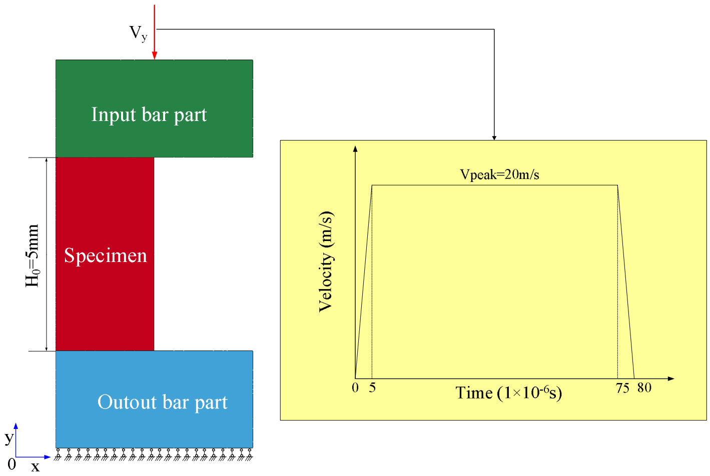


Fig. 1. Two-dimensional axisymmetric finite element model for dynamic compression process and the corresponding boundary and loading conditions

$$V_{peak} = \dot{\varepsilon}_{ave} \times H_0 \tag{1}$$

where $\dot{\varepsilon}_{ave}$ is the average strain rate and H_0 is the initial height of the specimen. In this investigation, $\dot{\varepsilon}_{ave}$ =4000/s and H_0=5.0mm. Therefore, the peak velocity V_{peak} is 20 m/s. In addition, the macro stress and macro strain of the specimen is defined by Eq. 2 and Eq. 3:

$$\sigma_{mac} = \left|\vec{f}\right| \times 2\pi / A_0 \tag{2}$$

$$\varepsilon_{mac} = \dot{\varepsilon}_{ave} \times t \tag{3}$$

where $\left|\vec{f}\right|$ is the reaction force per radian on the contact area between input bar part and specimen, A_0 is the initial cross-section area of the specimen and t is the loading time.

Material properties. Both of the input bar and output bar are made of maraging steel in the dynamic compression test[3], and the isotropic hypoelastic material model (see *MAT_ELASTIC in LS-DYNA software) is used to describe the input bar part and output bar part. The *MAT_ELASTIC model parameters for maraging steel used in the study are listed in Table 1.

Table 1 *MAT_ELASTIC model parameters for maraging steel

ρ/(Kg • m^{-3})	E/(GPa)	ν
7750	197	0.3

Correspondingly, MAT224 is employed to model the specimen. As shown in Eq. 4 and Eq. 5, the flow stress σy is expressed as a function of plastic strain εp, plastic strain rate and temperature T (using serials of effective stress versus effective strain at different strain rates and temperatures to perform).

$$\sigma_y = kl(\varepsilon_p, \dot{\varepsilon}_p) \cdot kt(\varepsilon_p, T) \tag{4}$$

$$T = T_R + \frac{\beta}{C_p \cdot \rho} \int \sigma_y \cdot \varepsilon_p \tag{5}$$

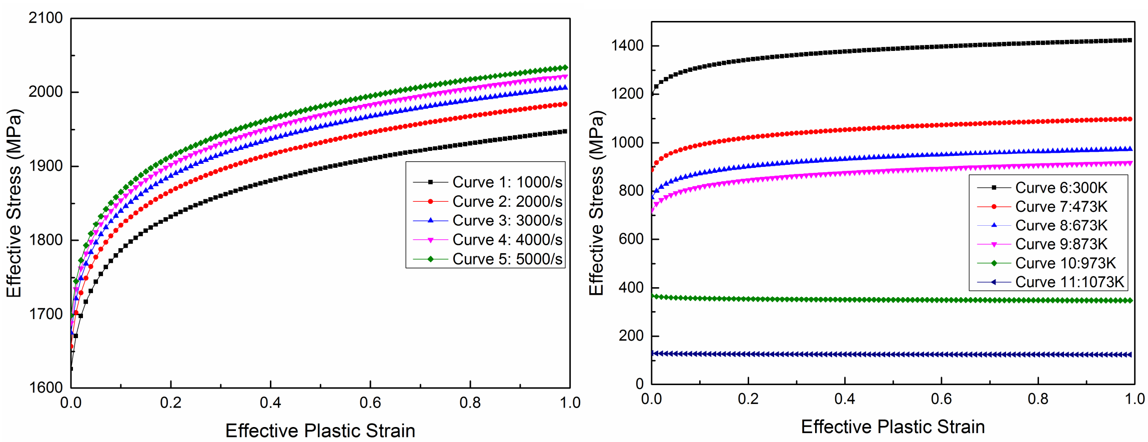
where k is scale factor, TR is room temperature, β is amount of plastic work converted into heat, C_p is specific heat, ρ is mass density.

The basic parameters of MAT224 for Ti-6Al-4V used in the study are listed in Table 2.

Table 2 MAT224 basic parameters for Ti-6Al-4V

ρ/(Kg • m^{-3})	E/(GPa)	ν
7750	197	0.3

As shown in Fig. 2, there are five effective stress versus effective strain curves at different strain rates, and the corresponding strain rates are 1000/s, 2000/s, 3000/s, 4000/s, 5000/s, defined as Curve 1-5, respectively (see Fig. 2 (a)); there are six effective stress versus effective strain curves at different temperatures, and the corresponding temperatures are 300K, 473K, 673K, 873K, 973K, 1073K, defined as Curve 6-11, respectively (see Fig. 2 (b)). Besides, for each curve, the range of strain is 0-0.99 while the number of data points is 100. It might be mentioned that all the curves given in this study are ideal, because the critical fracture strain is not taken into account.



(a) Curves at different strain rates (b) Curves at different temperatures

Fig. 2. Two ideal tables of effective stress versus effective strain curves at different strain rates and temperatures for MAT224

Results and discussions

In the current study, it is assumed that the 11 curves defined in section 2.2 are enough and reasonable to describe the constitutive behavior for the specimen shown in Fig.1. So, the obtained macro stress vs. macro strain based on the 11 curves is defined as the benchmark curve. In this section, some of these curves are changed artificially and their corresponding simulation result is compared with the benchmark curve, so as to investigate the stability and the reliability for MAT224.

Effect of stress-strain curves at different strain rates on the simulation results. In order to study the effect of range of strain rates, all of the six curves at different temperatures (Curve 6-11 as mentioned in section 2.2) are included, and only two curves are selected from the five curves (Curve 1-5 as mentioned in section 2.2). Three Cases are taken into account: Case 1: 1000/s and 2000/s; Case 2: 1000/s and 5000/s; Case 3: 4000/s and 5000/s. As shown in Fig. 3, the macro stress versus macro strain curves obtained from Case 1~3 are compared with the benchmark curve. It is evident that the macro stress versus macro strain curve of Case 2 is closest to the benchmark curve, while Case 1 and Case 3 are relatively far away from it, indicating that 1000/s and 5000/s correspond to a wider range strain rate are preferable for simulation.

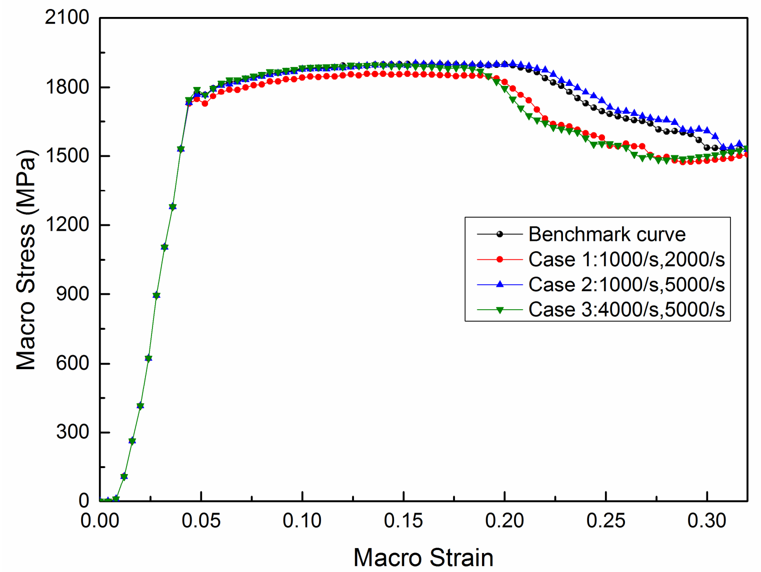


Fig. 3. The macro stress versus macro strain curves obtained from Case 1~3 and the benchmark curve, indicating that 1000/s and 5000/s correspond to a wider range strain rate are preferable for simulation

Effect of stress-strain curves at different temperatures on the simulation results. As for the effect of range of temperatures, the same research methods as those of strain rates are employed. All of the five curves at different strain rates (Curve 1-5 as mentioned in section 2.2) are included, and only two curves are selected from the six curves (Curve 6-11 as mentioned in section 2.2).There are also three Cases: Case 4: 300K and 473K; Case 5: 300K and 1073K; Case 6: 973K and 1073K. As illustrated in Fig. 4, the macro stress versus macro strain curves obtained from Case 4~6 are compared with the benchmark curve. Obviously, all of the macro stress versus macro strain curves of Case 4~6 has no decline stage, quite different from the benchmark curve, indicating that only two curves from the six curves, even with a wider range (Case 5), cannot reflect the thermal softening effect.

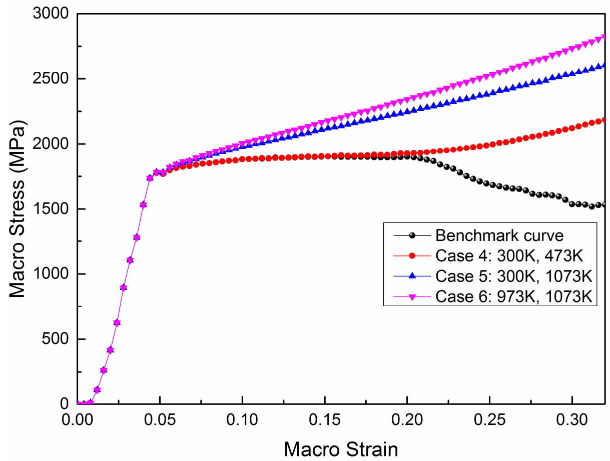


Fig. 4. The macro stress versus macro strain curves obtained from Case 4~6 and the benchmark curve, indicating that only two curves from the six curves at different temperatures cannot reflect the thermal softening effect

Effect of range of strain on the simulation results. As mentioned in Section 2.2, the range of strain for each curve is 0-0.99. Considering the realistic fact that the critical fracture strain for Ti6Al4V alloy is normally less than 0.4, the effect of the range of strain is investigated as the following three Cases: Case 7: 0-0.2; Case 8: 0-0.3; Case 9: 0-0.4. As shown in Fig. 5, the macro stress versus macro strain curves obtained from Case 7~9 are compared with the benchmark curve. It is evident that the macro stress versus macro strain curve of Case 9 is closest to the benchmark curve, while Case 7 and Case 8 are relatively far away from it, indicating that a wider range of train (0-0.4) for each curve is preferable for simulation.

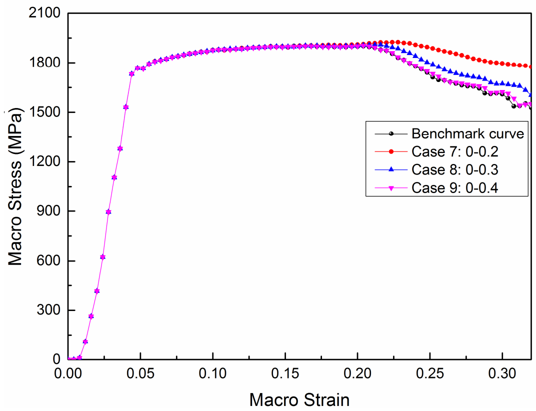


Fig. 5. The macro stress versus macro strain curves obtained from Case 7~9 and the benchmark curve, indicating that a wider range of train (0-0.4) for each curve is preferable for simulation

Effect of data points on the simulation results. It might be noted that the number of data points of each curve in the reference group of curves for MAT224 is 100. So, the data points for each curve are intuitively reduced to a smaller number to investigate their effects on the final result. There are two Cases taken in to attention: Case 10: 11 data points; Case 11: 21 data points. As illustrated in Fig. 6, the macro stress versus macro strain curves obtained from Case 10 and Case 11 are compared with the benchmark curve. Obviously both of the macro stress versus macro strain curves are coincided with the benchmark curve, indicating that the number of data points has little influence on the results.

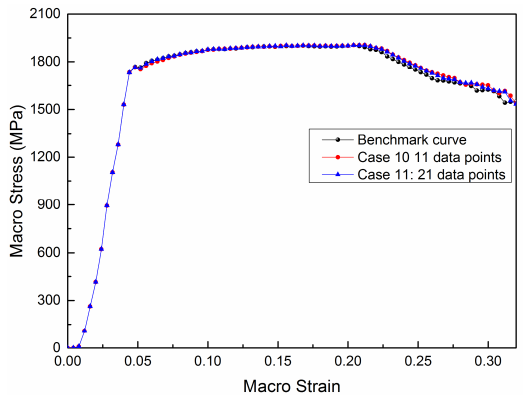
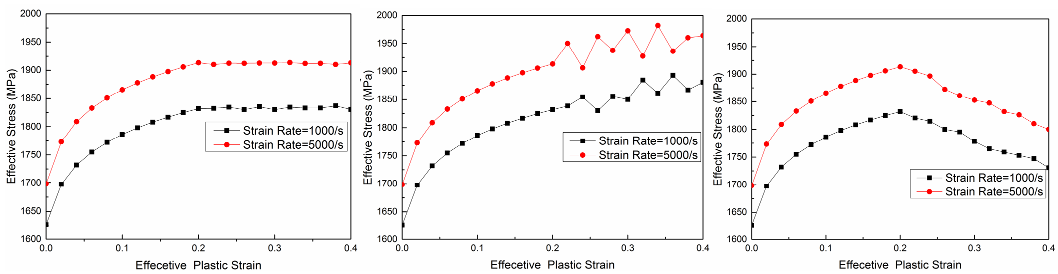


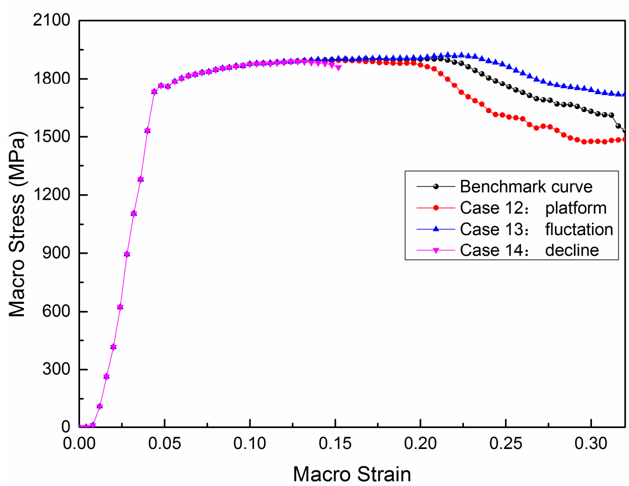
Fig. 6. The macro stress versus macro strain curves obtained from Case 10~11 and the benchmark curve, indicating that the number of data points for each curve has little influence on the results

Effect of curve tendencies on the simulation results. As shown in section 2.2, all the input 11 curves for MAT224 are in monotonic increase tendency for the effective stress. So, studying the curve tendencies in other ways makes sense in practical applications. As shown in Fig. 7, three cases are taken into account within the range of strain 0.2-0.4. Case 12: platform; Case 13: fluctuation; and Case 14: decline. As illustrated in Fig. 8, the macro stress versus macro strain curves obtained from Case 12~14 are compared with the benchmark curve. For Case 14, it prompts warnings, "plasticity algorithm did not converge", in the process of solution and eventually unable to continue to solve. The macro stress versus macro strain curve of Case 13 is closer to the benchmark curve, compared with Case 12. In conclusion, the curve tendency of monotonic decline is not acceptable if using MAT224, and the fluctuation in curve has little influence on the results.



（a） Case 12: platform （b） Case 13: fluctuation （c） Case 14: decline

Fig. 7 Changing the curve tendencies for the two curves at 1000/s and 5000/s for Case 9.



（a） Case 12: platform （b） Case 13: fluctuation （c） Case 14: decline

Fig. 8 The macro stress versus macro strain curves obtained from Case 12~14 and the benchmark curve, indicating that the curve tendency of decline is not acceptable if using MAT224, and the fluctuation in curve has little influence on the results

Conclusion

In this study, a two-dimensional axisymmetric finite element model for the Ti6Al4V titanium alloy under dynamic compression is established, and MAT224 with two ideal tables of effective stress versus effective strain curves at different strain rates and temperatures are employed. Subsequently, by changing the curves artificially and compared with the simulation result of the original group of curves, the stability and the reliability for MAT224 are systematically studied, and the conclusions are obtained as follows: (1) two curves at different strains rates should be included at least, and a wide strain-rate range is preferable; (2) curves at different temperatures should be included more than two curves, and the temperature ranges should be defined as wide as possible; (3) A wide range of effective plastic strain is preferable, but its number of data points has little influence on the results; (4) the curve tendency of monotonic decline is not acceptable, and the fluctuation in curve is allowed.

Acknowledgements

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