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DETERMINATION AND VALIDATION OF JOHNSON-COOK STRENGTH MODEL PARAMETERS OF Ti-6Al-4V

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ABSTRACT

In this study, Johnson-Cook strength model parameters of Ti-6Al-4V alloy were determined by quasistatic tensile, dynamic compression tests and the parameters were validated by simulation studies. Quasistatic tensile tests were performed under 0.001, 0.01, 0.1/s at room temperature and dynamic compression tests were conducted under 554, 1198, 1727/s at room temperature. Compression tests were also done at elevated temperatures (150 and 230ºC) in order to obtain high temperature behavior of the material. Johnson-Cook model parameters were determined by curve fitting to the test data. To validate the parameters, dynamic compression tests conducted at Split-Hopkinson Pressure Bar at three strain rates were modelled with 3D Lagrangian simulation studies by using Ls-Dyna software. Numerical results were in good agreement with test results especially for lower strain rates.

Keywords: Ti-6Al-4V alloy, Split-Hopkinson pressure bar, Johnson-Cook strength model

INTRODUCTION

Titanium alloy, Ti-6Al-4V is mostly used in aerospace, automotive, biomedical and defense industries due to its superior corrosion resistance, good weldability, good strength to weight ratio and high ductility [Meyer et al., 2008, Zhang et al., 2019, Despax et al., 2020]. Due to critical applications of this alloy, investigating of mechanical properties and deformation behavior of Ti-6Al-4V under various strain rates and temperatures has great importance [Lee and Huang, 2005]. In aerospace applications, characterization of the titanium alloy among high strain rates and high temperatures is crucial for the investigation of the engine failures and damage of the high velocity debris from engine. Numerical and experimental methods are used simultaneously in order to determine behaviors of Ti-6Al-4V alloys at extensive conditions.

Mechanical behaviors of Ti-6Al-4V under various strain rates and temperatures from quasistatic to dynamic conditions have been determined by several authors in the literature. Lee and Huang [Lee and Huang, 2005] studied dynamic shear deformation of Ti-6Al-4V at the

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strain rates between 1800-2800/s and temperatures between -100-300ºC. Chen et al. [Chen et al., 2018] investigated compression deformation under high strain rates (2500-10000/s) and temperatures (20-900ºC). Damage behaviors of the samples under test conditions were simulated by using Johnson-Cook material model. Peirs et al. [Peirs et al., 2010] studied shear behavior of Ti-6Al-4V hat-shaped samples under quasistatic (0.083 mm/s) and dynamic conditions (1500 mm/s and 3000 mm/s). Dynamic compression tests were carried out using Split Hopkinson pressure bar. Fractures observed at experimental studies were compared with numerical studies.

The aim of this study is to determine and validate Johnson-Cook strength model parameters of Ti-6Al-4V alloy with experimental and numerical studies.

EXPERIMENTAL METHOD

Owing to calculation of Johnson-Cook strength model parameters, quasistatic tensile tests were performed with dog-bone samples at three strain rates 0.001, 0.01, 0.1/s. Dynamic compression tests were performed with cylindrical samples (l/d=1) at three strain rates (554, 1198, 1727/s) and at two elevated temperatures (150, 230ºC) by using Split-Hopkinson Pressure Bar test system (Figure 1). At least two tests were done for each condition to ensure the repeatabilities and averages of the results of these tests were obtained.

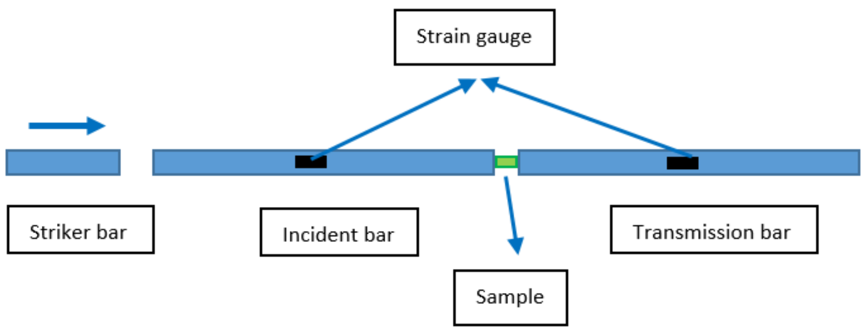

Figure 1. Schematic view of dynamic compression test device, Split-Hopkinson pressure bar.

NUMERICAL METHOD

In order to validate determined strength model parameters (A, B, n, C and m), the dynamic compression tests with three strain rates conducted at Split-Hopkinson test device were modelled with 3-D Lagrangian method in Ls-Dyna software. The dynamic compression test simulation model is shown in Figure 2. Bars and sample were modelled using hexahedron elements. Element size for the bars is 2 mm. Prior to validation simulations, element size dependency study for the test sample was carried out at 1198 /s with three element sizes (0.7, 0.5, 0.4 mm) to determine the effect of element size on deformation behavior. Strength model 15-JOHNSON-COOK was used for the sample. Johnson-Cook strength model is widely used for metals for various strain rates and various temperatures [Johnson and Cook, 1983]. This model is described by the equation given below.

$$\sigma = \left[A + B e_p{}^n\right]\left[1 + C \ln \frac{\dot{e_p}}{\dot{e_0}}\right][1 - T^{*m}] \quad (1)$$

where A is the yield stress at reference strain rate, B and n are strain hardening parameters, C is the parameter related to strain rate, m is the parameter corresponding to temperature dependency.

Bars were modelled with 01-ELASTIC material model in order to model elastic deformation. GRUNEISEN equation of state was used for modelling of test sample under dynamic compression test. The velocities of striker bar in compression models were 11.14, 15.52, 18.96 m/s. These velocities corresponded to three strain rates at dynamic compression tests.

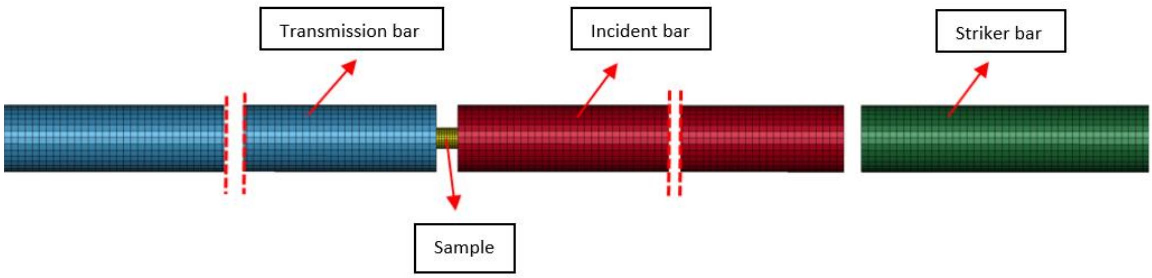

Figure 2. Dynamic compression test model used in simulations.

RESULTS AND DISCUSSION

Stress-strain curves under quasistatic tensile tests are given in Figure 3. As can be seen in the graph, as strain rate increased from 0.001/s to 0.1/s, yield strengths of the samples increased about 7 % and ductility decreased about 36 %. Samples tested at three strain rates showed no significant strain hardening behavior.

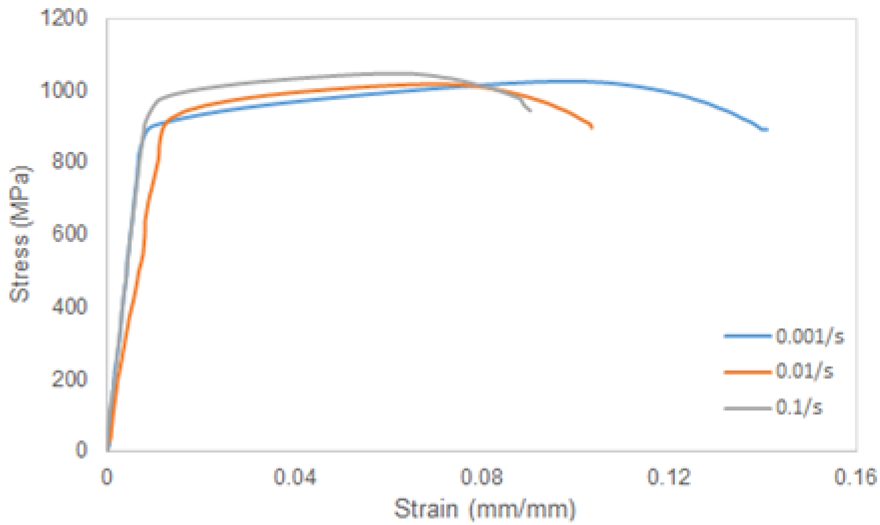

Figure 3. Stress-strain graph of quasistatic tensile tests.

Stress–strain curves obtained at dynamic compression conditions are shown in Figure 4. As given in the figure, the increase of strain rate from 554/s to 1727/s led to increase of yield strengths of the samples nearly 7 %. In addition, strain also increased about 167 % as strain rate increased. The yield strengths of the samples tested under dynamic conditions were determined higher compared to the yield strengths of the samples tested under quasistatic conditions. Moreover, there was nearly no strain hardening behavior, as also seen in quasistatic tensile tests, for the samples tested under high strain rates. The stress-strain graphs of two tests performed for the same strain rate (554/s) were given in the figure to illustrate the repeatability of test conditions. El-Magd and Abouridouane studied high strain rate behavior of Ti-6Al-4V alloy at the strain rates between 2304-4131/s [El-Magd and Abouridouane, 2006]. Similar strengths were obtained in the current study compared to that study. However, they observed strain hardening behavior for all strain rates.

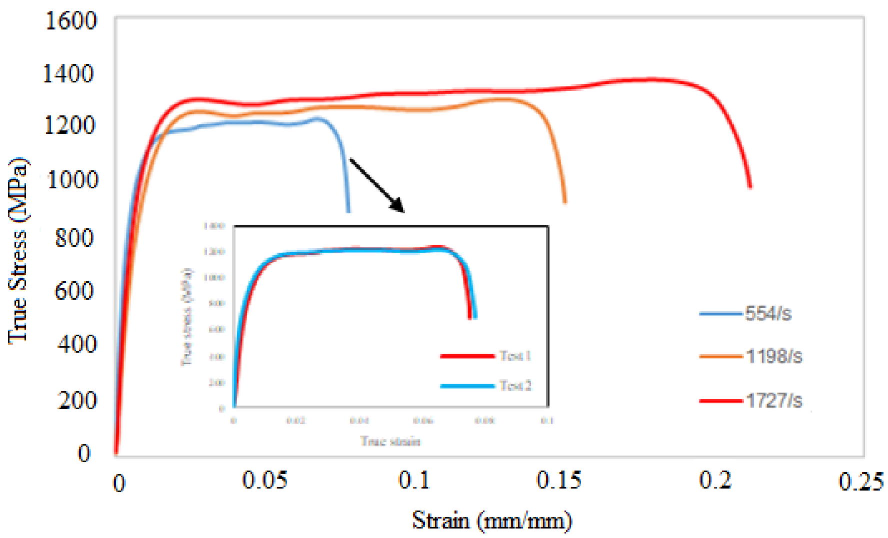

Figure 4. Stress-strain graph of dynamic compression tests.

Johnson-Cook strength model parameters of Ti-6Al-4V material were determined by curve fitting the data obtained from quasistatic tensile tests and dynamic compression tests at room temperature and elevated temperatures. The strength parameters are listed in Table 1.

Table 1. Determined Johnson-Cook strength model parameters of Ti-6Al-4V.

Material	**A (MPa)**	**B (MPa)**	**n**	**C**	**m**
Ti-6Al-4V	966	448	0.55	0.022	0.578

The results of the element size study are given in Table 2. Final diameters and lengths were compared with the final dimensions of test sample tested at 1198/s. According to the table, for all element sizes same diameters were obtained whereas the difference in the final length compared to the test sample increased as element size decreased from 0.7 mm to 0.4 mm. Due to better results in comparison with test sample and less CPU time, element size of 0.7 mm was chosen for the rest of numerical studies.

Table 2. Comparison of element sizes in terms of differences in diameter and length.

Element size (mm)	**Difference in Diameter**	**Difference in Length**
0.7	2.2 %	6.1 %
0.5	2.2 %	6.1 %
0.4	2.2 %	6.5 %

In Figure 5, cylindrical simulation samples before and after compression at Split-Hopkinson pressure bar are illustrated. After dynamic compression, the diameters of the samples enhanced about 5, 10, 14 % whereas the length decreased nearly 9, 17, 22 % due to plastic deformation as strain rate increased from 554/s to 1727/s.

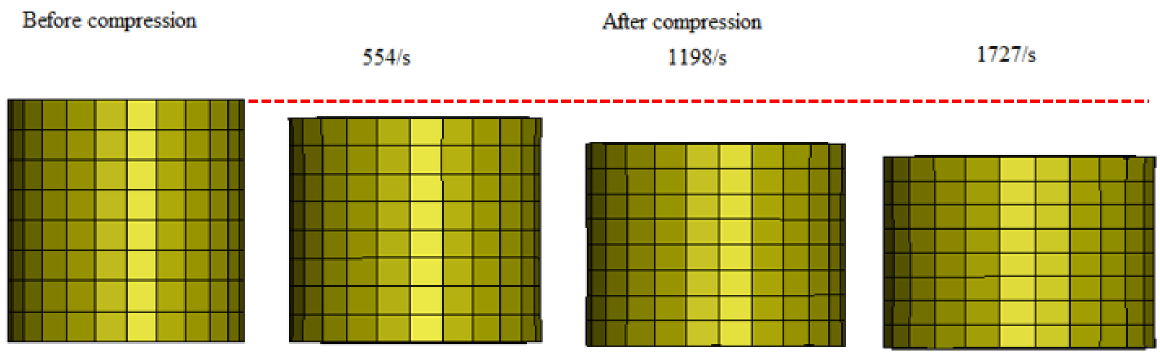

Figure 5. Cylindrical sample in the simulation before and after dynamic compression.

Simulations performed with determined Johnson-Cook parameters were compared with test results in terms of final dimensions of the samples at three strain rates. The results of the comparisons are given in Table 3 as differences in these dimensions. As the results in the table investigated, it can be seen that the numerical results are in good agreement with test results. However, as the strain rate increased the differences in dimensions of the samples increased. This indicates that Johnson-Cook strength model is inadequate to provide flow behavior for a wide range of deformation [Samantaray et al., 2009].

Table 3. Differences of the dimensions of the samples.

Strain rate (/s)	**Difference in Diameter**	**Difference in Length**
554	1.9 %	4.7 %
1198	2.2 %	6.1 %
1727	2.2 %	7.4 %

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