

Studies on Deformation and Failure Behavior of Ti-6Al-4V Alloy for Aircraft Structures

P S Ranjit* and A Chennakesava Reddy**

The dynamic response of Ti-6Al-4V alloy at high strain rate is investigated with tensile split Hopkinson bar test using plate type of specimens. High strain rate tensile tests are then performed with the above said material in order to construct their appropriate constitutive models for use in aircraft structures under dynamic conditions.

Keywords: Stress, Strain, Strain rate, Mechanical behavior

Introduction

Aircraft structures are generally constructed from sheet metals of deep-drawing quality. The dynamic behavior of the materials is different from the static one because of inertia effect and the propagation of stress waves. An adequate experimental technique has to be developed for the corresponding strain rate level. A high strain rate testing apparatus was devised by Kolsky (1963) in 1949, which is known as split Hopkinson pressure bar (Follansbee, 1978). The stress-strain curves for the high strain rate ranging from 1000 to 10,000/s can be acquired from the stress waves propagating through the incident and the transmission bars in the apparatus. The split Hopkinson pressure bar apparatus can be modified for high strain rate tensile tests. Even though there are some difficulties in the design of grips, these grips are not considered for simplicity. For anvil effect, successful high strain rate tensile tests need control of state variables such that the stress, strain and strain rate in the specimen must be homogeneous (Johnson *et al.*, 1986). Hence, the geometry of a specimen used in high strain rate tensile test is important for acquiring uniform deformation.

Nicholas (1981) used threaded bar type tensile specimens to obtain high strain rate stress-strain curves for about 15 to 20 different materials. Lindholm and Yeakley (1968) performed high strain rate tensile tests with hat type specimens. The above said tests were easy to perform but the design of hat specimens was

* Assistant Professor, College of Engineering, University of Petroleum & Energy Studies, Dehradun, Uttarakhand, India. E-mail: ranjit+uinn@yahoo.co.uk; psranjit@ddn.upes.ac.in

** Professor, Department of Mechanical Engineering, JNTU College of Engineering, JNT University, Ananthapur, India. E-mail: dr_acreddy@yahoo.com

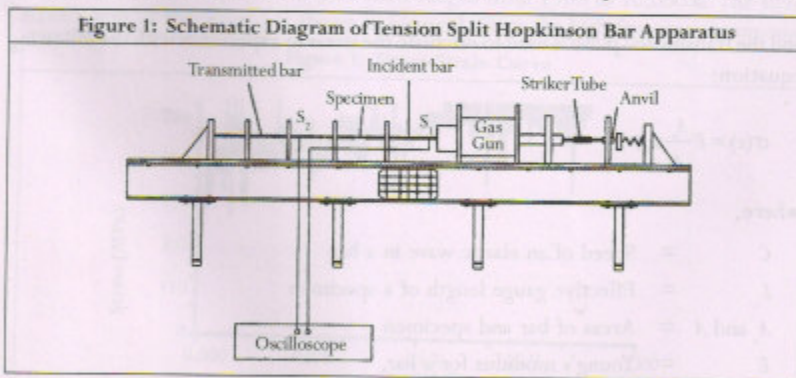
complicated and expensive. In these experiments, wave distortion occurs at the clearance of the threaded region of the specimen. Staab and Gilat (1991) investigated the effect of the bar type specimen geometry in direct tension split Hopkinson bar tests. When the length to diameter ratio of the specimen was greater than 1.50, the experimental results showed that the dynamic tensile strength was consistent. Zhao and Gary (1996) performed compression tests for Ti-6Al-4V alloy plates for the aircraft structure using compression split Hopkinson pressure bar apparatus. The above-said methods give results for different material models which are used in numerical analysis of crashes. The material behavior cannot be described in a general way, hence, it is necessary to describe the various types of constitutive relations to describe the dynamic behavior of materials. Johnson and Cook (1983) proposed a constitutive model and found five material constants (obtained from Hopkinson pressure bar apparatus) in the constitutive relation for materials subjected to large strains, high strain rates and high temperatures.

In this paper, the high strain rate tensile tests have been carried out with a split Hopkinson pressure bar apparatus, designed specifically for sheet metals. Tensile tests are performed for several sheet metals of deep-drawing quality. Experimental results from both the quasi-static and dynamic tests are interpolated to construct a constitutive relation, which can be applied to the crash analysis of aircraft structures made up of sheet metals.

2. Tension Split Hopkinson Bar

A striker tube is fired from a gas gun and impacts an anvil, as shown in Figure 1. From the impact, a tensile pulse is generated in the incident bar, which propagates into the specimen. A part of the incident pulse is transmitted into the specimen and propagates through the transmitted bar as the tensile pulse. The rest of the pulse is reflected into

Figure 1: Schematic Diagram of Tension Split Hopkinson Bar Apparatus

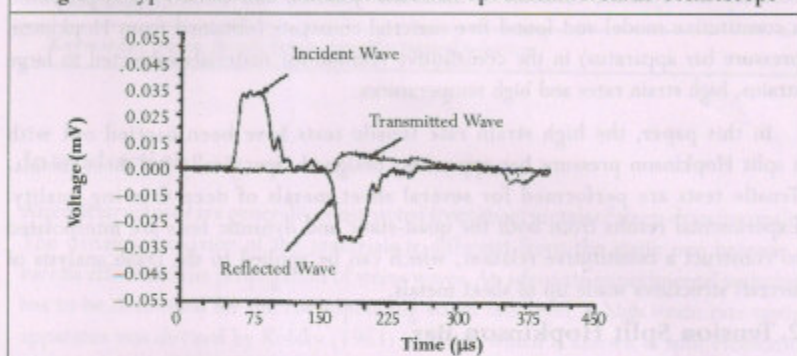


the incident bar as the compressive pulse. The transmitted and reflected pulses are measured at the points of attached strain gauges S_1 and S_2 . Strain gauges are attached to the two bars at equal distances from each end of the bars. The signals from the strain gauges are monitored and acquired by an oscilloscope.

Figure 2 represents the incident, reflected and transmitted pulses recorded in the experiment. The reflected pulse measured by an oscilloscope is used to calculate the strain rate in a specimen using the following equation:

$$\dot{\epsilon}(t) = 2 \frac{C}{L_s} \epsilon_R(t)$$

Figure 2: Typical Forms of Waves Obtained of Specimen 1 from an Oscilloscope



This strain rate is integrated with respect to time in order to obtain the strain in a specimen as:

$$\epsilon(t) = \int \dot{\epsilon}(\tau) d\tau$$

and the transmitted pulse is used to calculate the stress in a specimen with the following equation:

$$\sigma(t) = E \frac{A_s}{A} \epsilon_t(t)$$

where,

- C = Speed of an elastic wave in a bar
- L_s = Effective gauge length of a specimen
- A_s and A = Areas of bar and specimen
- E = Young's modulus for a bar.

The subscripts R and T indicate the reflected and transmitted pulses in the above equations. Incident and transmitted bars are made of either maraging steel or 4340 steel to satisfy the one-dimensional theory of elastic wave propagation, since the bars must have enough mechanical strength not to deform plastically. To avoid the overlap of the incident and reflected pulses at strain gauges S_1 and S_2 , the bars must be long enough to satisfy the one-dimensional theory. The striker tube is made of the same material as the bars, and its length determines the duration of the incident pulse, as expressed by:

$$\Delta_i = 2 \frac{L_i}{C}$$

where L_i = Length of the striker tube.

3. Experimental Results and Constitutive Relations of Sheet Metals

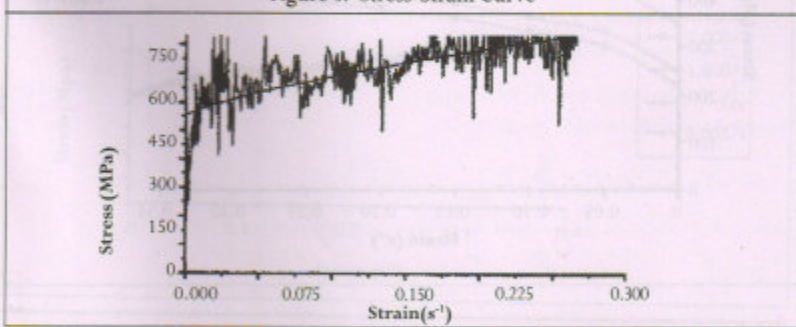
The sheet metals used in the experiments are shown in Table 1. The quasi-static tensile tests were carried out at strain rates of 0.03/s and 1/s with the Instron 5500 and

Table 1: Sheet Metals Used in Experiments

Description	Name	Thickness (mm)	Quality
Specimen I	60TRIP	1.3	GRADE 5
Specimen II	60TRIP	1.4	GRADE 5
Specimen III	60TRIP	1.5	GRADE 5
Specimen IV	60TRIP	1.6	GRADE 5
Specimen V	60TRIP	1.7	GRADE 5

8032. The test result at the strain rate of 1/s was chosen as the reference stress-strain curve to determine the constants in the Johnson-Cook constitutive relation. The strain rates acquired in the present experiments ranged from 1500 to 10,000/s. The stress-strain curve of Specimen 1 is shown in Figure 3. Since the high frequency component

Figure 3: Stress-Strain Curve



of incident wave is attenuated in the bar, the dynamic stress-strain curve from the Hopkinson bar test is oscillatory. The experimental results are shown in Figure 4 for several materials and used to construct constitutive relations of sheet metals.

In this work, the Johnson-Cook constitutive relation is applied to sheet metals. The conventional Johnson-Cook model for the yield stress is (Lin, 2005):

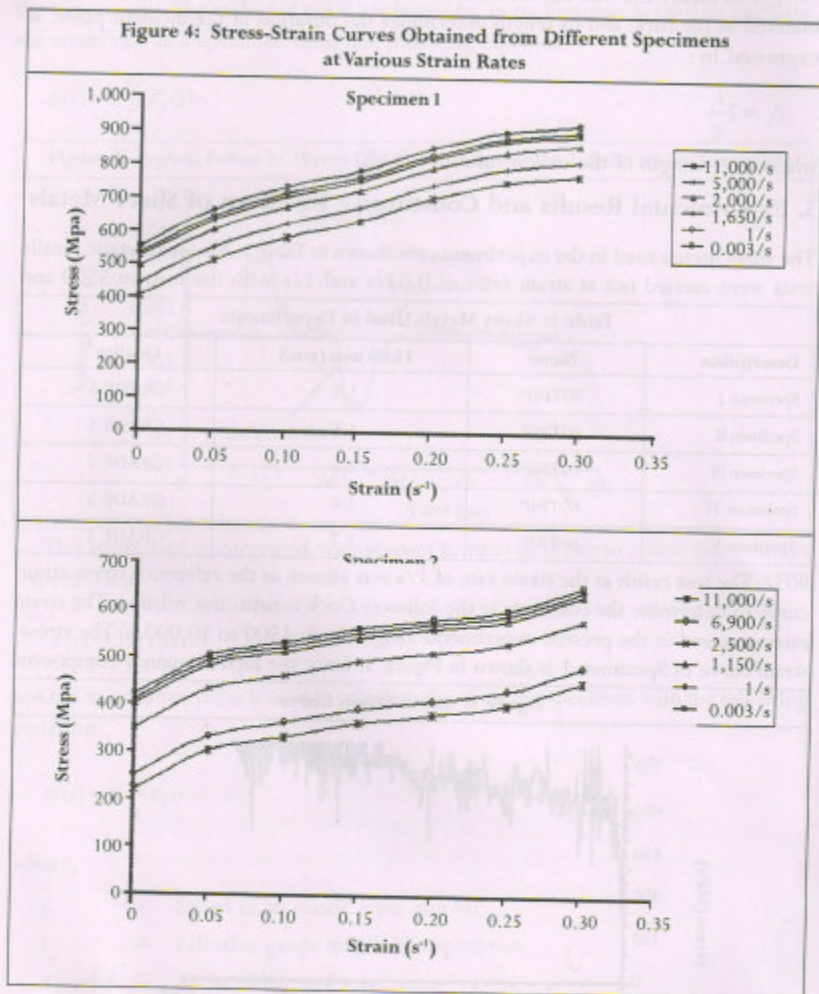
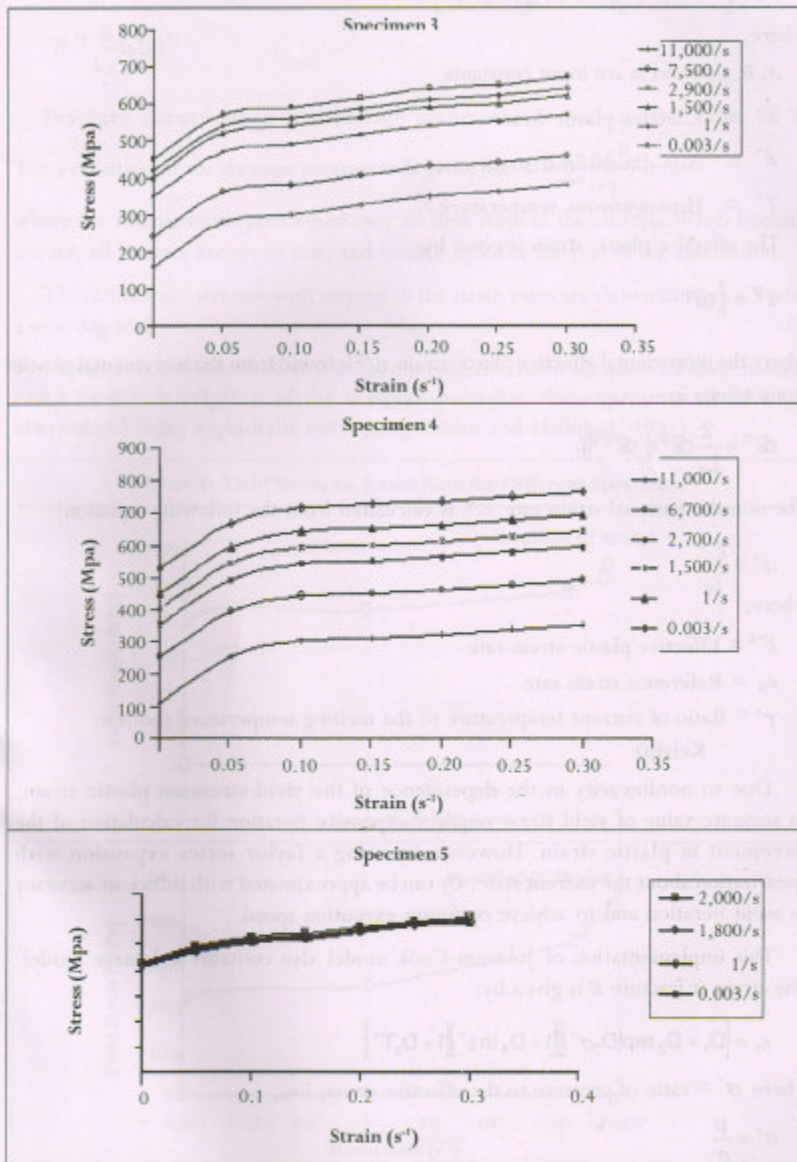


Figure 4 (Cont.)



$$\sigma_y = [A + B(\bar{\epsilon}^p)^n] [1 + \ln(\dot{\epsilon}^*)] [1 - (T^*)^m]$$

where,

A, B, C, n and m are input constants

$\bar{\epsilon}^p$ = Effective plastic strain

$\dot{\epsilon}^*$ = Non-dimensional strain rate

T^* = Homogeneous temperature.

The effective plastic strain is given by:

$$\bar{\epsilon}^p = \int d\bar{\epsilon}^p$$

where the incremental effective plastic strain $d\bar{\epsilon}^p$ is found from the incremental plastic strain tensor as:

$$d\bar{\epsilon}^p = \frac{2}{L_3} d\bar{\epsilon}^p_{ij} d\bar{\epsilon}^p_{ij}$$

The non-dimensional strain rate $\dot{\epsilon}^*$ is calculated from the following equation:

$$\dot{\epsilon}^* = \frac{\bar{\epsilon}^{*p}}{\dot{\epsilon}_0}$$

where,

$\bar{\epsilon}^{*p}$ = Effective plastic strain rate

$\dot{\epsilon}_0$ = Reference strain rate

T^* = Ratio of current temperature to the melting temperature (both in Kelvin).

Due to nonlinearity in the dependence of the yield stress on plastic strain, an accurate value of yield stress requires expensive iteration for calculation of the increment in plastic strain. However, by using a Taylor series expansion with linearization about the current state, σ_y can be approximated with sufficient accuracy to avoid iteration and to achieve optimum execution speed.

This implementation of Johnson-Cook model also contains a damage model. The strain at fracture ϵ_f is given by:

$$\epsilon_f = [D_1 + D_2 \exp(D_3 \sigma^*)] [1 + D_4 \ln \dot{\epsilon}^*] [1 + D_5 T^*]$$

where σ^* = ratio of pressure to the effective stress, i.e.,

$$\sigma^* = \frac{p}{\sigma}$$

and effective stress $\bar{\sigma}$ is found from:

$$\bar{\sigma} = \frac{3}{L_2} \xi_1 \xi_2^{1/2}$$

Fracture occurs when the damage parameter D exceeds the value of 1.

The evaluation of the damage parameter is given by: $D = \sum \frac{\Delta \bar{\epsilon} F}{\epsilon_f}$

where the summation is performed over all time steps in the analysis. When fracture occurs, all stresses are set to zero and remain zero for the rest of the calculation.

The initial yield stresses with respect to the strain rates are shown in Figure 5 with a semi-log scale.

Experimental results show that linear interpolation is not adequate for sheet metals. For a better description of the material behavior, the experimental data are interpolated using a quadratic curve (Engelmann and Hallquist, 1991).

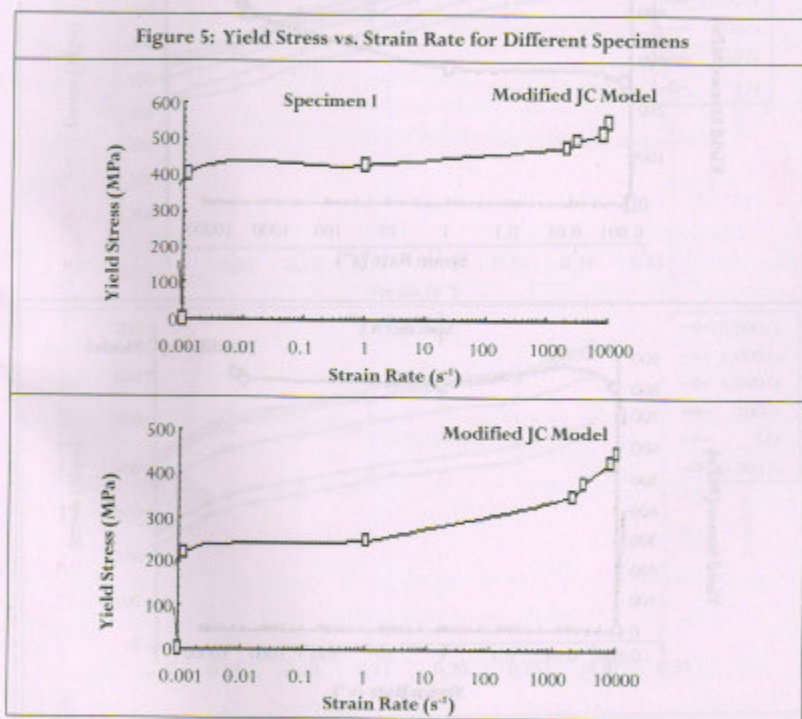
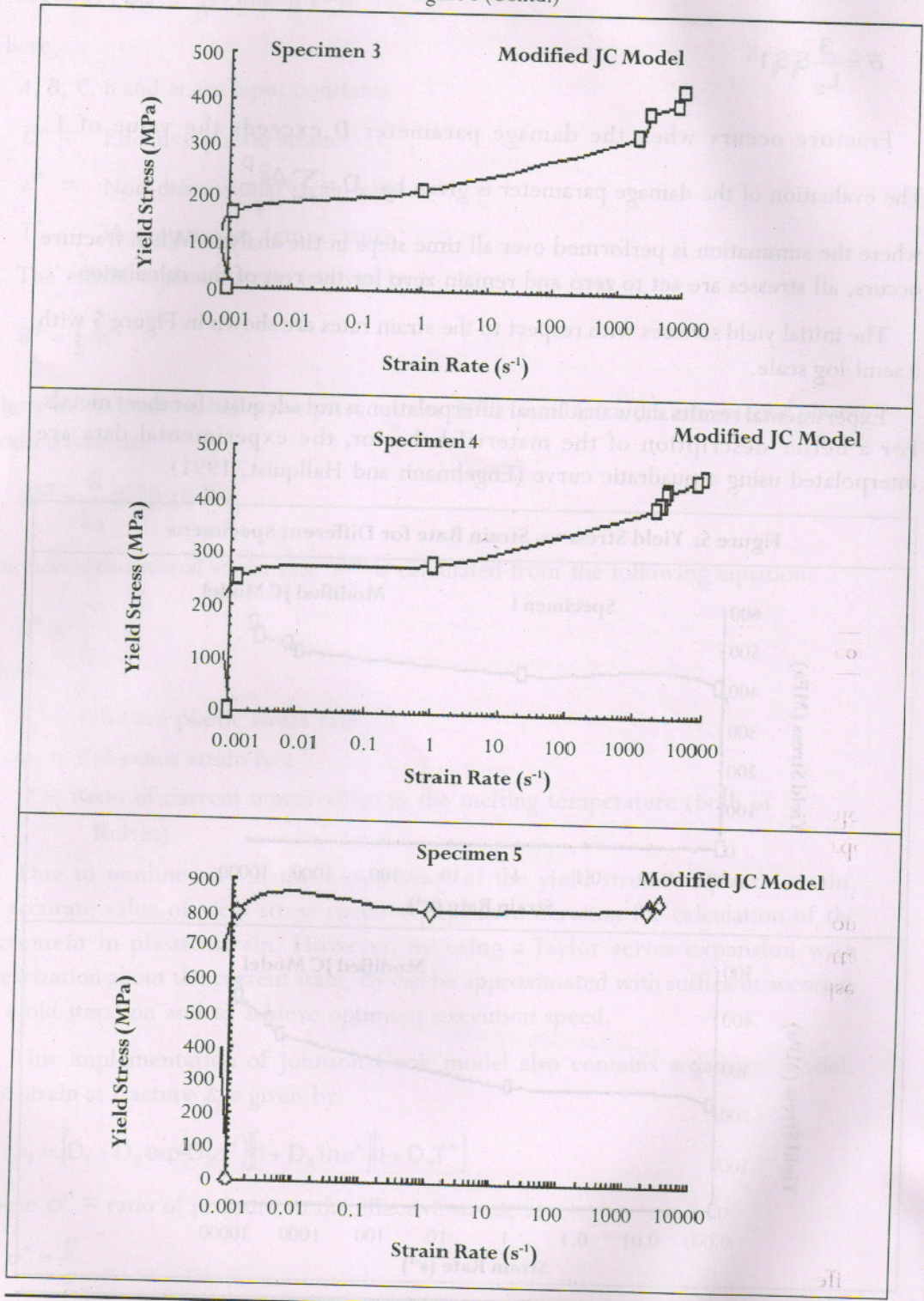


Figure 5 (Contd.)



$$\bar{\sigma} = [A + B(\bar{\epsilon}^p)^n] [1 + C_1 \ln(\dot{\epsilon}^*)^2 + C_2 \ln(\dot{\epsilon}^*)^2] [1 - (T^*)^m]$$

The quadratic interpolation of the strain rate hardening effect reduced deviation from the experimental data. In some sheet metals, a cubic interpolation of the strain rate hardening effect described the dynamic behavior better than the quadratic interpolation, although it is less effective in application. Figure 6 shows the stress-strain curves estimated with the original and modified Johnson-Cook models for sheet metals.

The stress-strain curves presented here are obtained from the adiabatic condition, which would well describe the dynamic behavior of sheet metals at high strain rates.

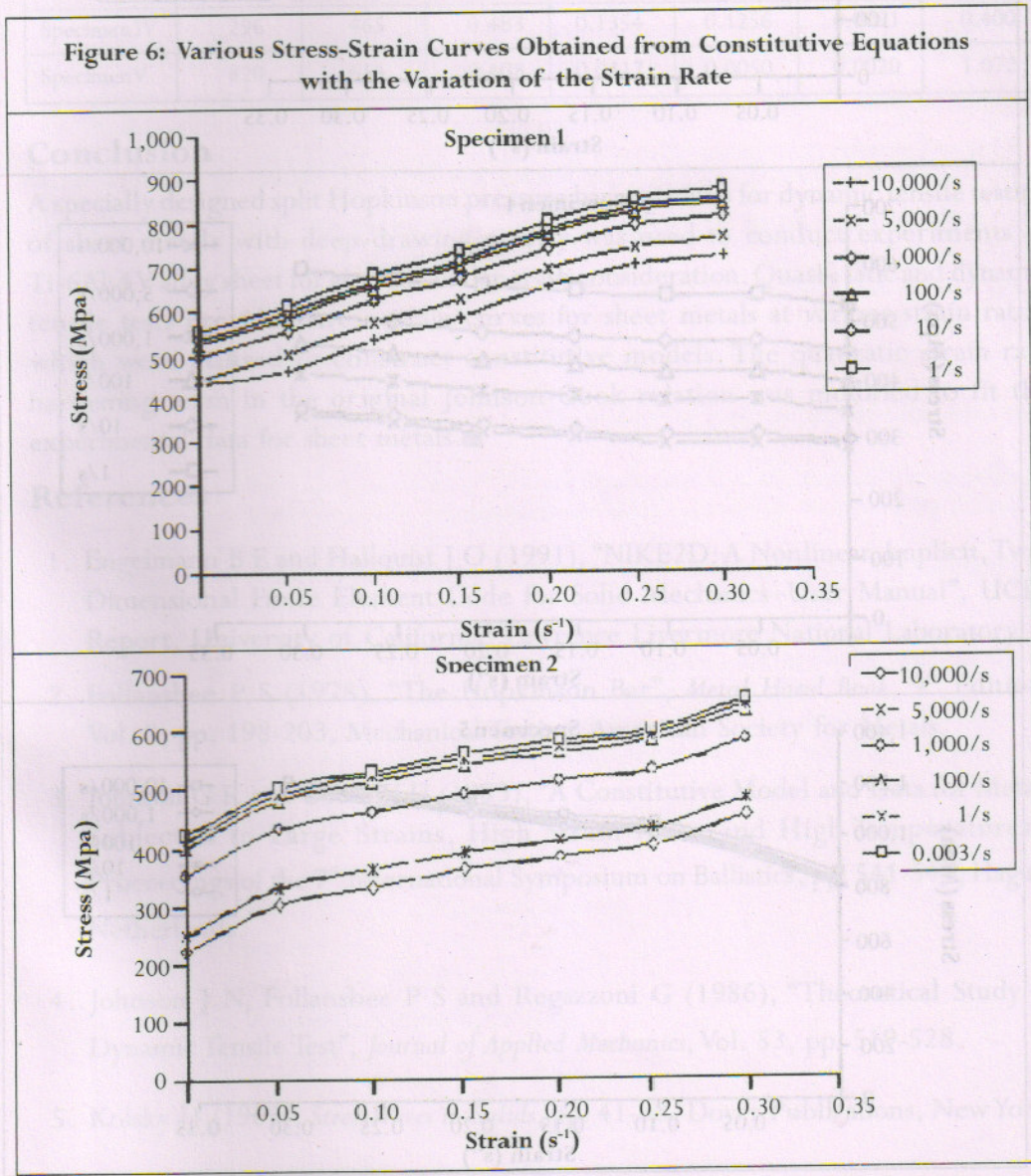
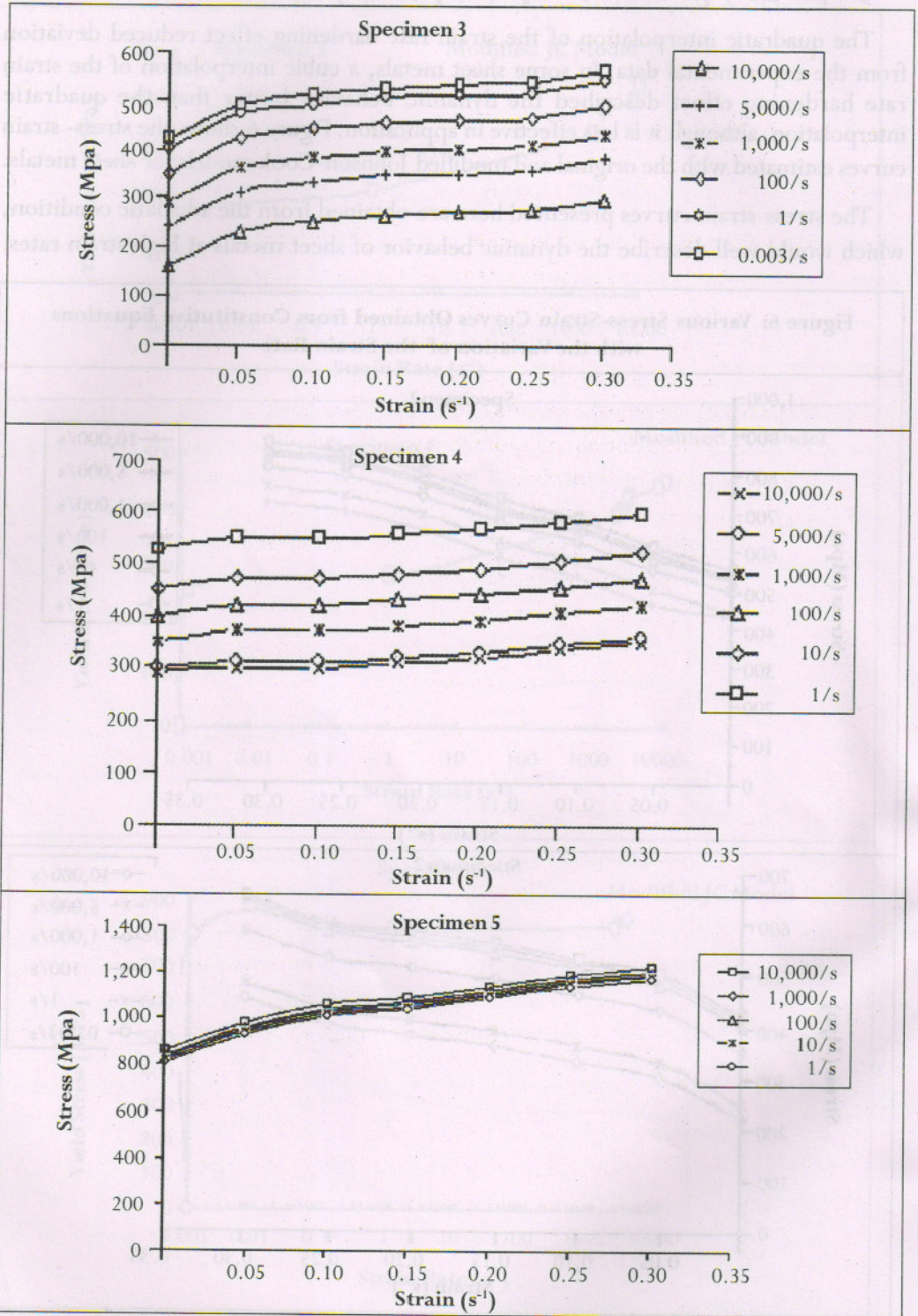


Figure 6 (Cont.)



The material constants in constitutive relations for various sheet metals are shown in Table 2.

Description	A (MPa)	B (MPa)	n	C	C ₁	C ₂	m
Specimen I	433	820	0.592	0.0766	0.0450	0.0043	0.709
Specimen II	265	470	0.490	0.1880	0.1080	0.0212	0.465
Specimen III	230	419	0.496	0.2240	0.1573	0.0274	0.380
Specimen IV	296	465	0.483	0.1354	0.1256	0.0091	0.400
Specimen V	820	654	0.408	0.0117	0.0050	0.0020	1.072

Conclusion

A specially designed split Hopkinson pressure bar apparatus for dynamic tensile testing of sheet metals with deep-drawing quality was used to conduct experiments of Ti-6Al-4V alloy sheet for aircrafts under crash consideration. Quasi-static and dynamic tensile tests provided stress-strain curves for sheet metals at various strain rates, which were utilized to construct constitutive models. The quadratic strain rate hardening term in the original Johnson-Cook relation was modified to fit the experimental data for sheet metals.

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