STUDIES ON DYNAMIC BEHAVIOUR OF TI-6AL-4V ALLOY SHEETS IN AIRCRAFTS

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

Key words: Stress, Strain, Strain-rate, Dynamic behaviour & Hopkinson bar

1.0 Introduction

Aircrafts structures are generally constructed from sheet metals of deep-drawing quality. The dynamic behaviour of the materials is different from the static one because of inertia effect and the propagation of stress waves, an adequate experimental techniques has to be developed for the corresponding strain rate level. A high strain rate testing apparatus was devised by Kolsky [1] in 1949, which is known as Split Hopkinson Pressure bar [2]. The stress - strain curves for the high strain rate ranging from 1000 to 10,000S^{-1}, can be acquired from the stress waves propagating through the introduced 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 but this grips are not considered for simplicity of the work. 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 [3]. Hence it is very important that the geometry of a specimen used in high strain rate tensile test is important acquiring uniform deformation.

Nicholas[4] used threaded bar type tensile specimens to obtain high strain rate stress-strain curves for different materials near about 15 to 20. Lindholm and Yeakley[5] 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 complicated and expensive. In these experiments, wave distortion occurs at the clearance of the threaded region of a specimen. Staab and Gilat [6], investigated the effect of the bar type specimen geometry in direct tension split Hopkinson bar tests. When the length to diameter ratio of specimen is large than about 1.50, the experimental results showed that the dynamic tensile strength was consistent. Compression tests for Ti-6Al-4V alloy plates for the Aircrafts structure are performed by compression split Hopkins pressure bar apparatus by the Zhao and Gary [7]. The above said methods gives results for different material models which are used in numerical analysis of crashes. The material behaviour can not be described in a general way, hence, it is necessary to describe the various types of constitutive relations have been proposed to describe the dynamic behaviour of materials. Johnson and Cook [8] given a constitutive model and find five material constants in the constitutive relation for materials subjected to large strains, high strains rates and high temperatures. And these constants of Johnson and Cook model material models are obtained from Hopkinson pressure bar apparatus.

This paper exposes the high strain-rate tensile tests have been carried out with a split Hopkinson pressure bar apparatus, which is specifically designed for sheet metals. Tensile tests were 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 Aircrafts structures made up of sheet metals.

2.0 Split Hopkinson Bar - Tension

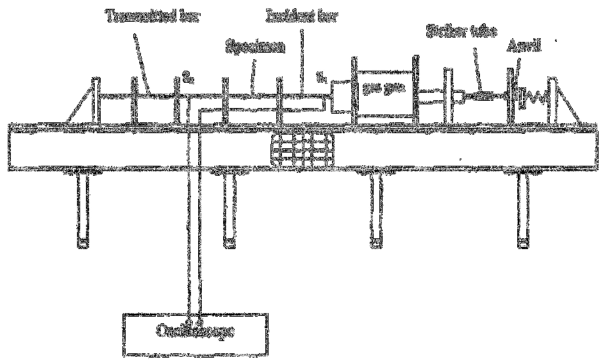

Fig.(1) – Tension split Hopkinson bar apparatus schematic diagram

A striker tube is fired from a gas gun and impacts an Anvil as shown in Fig.(1). From the impact, a tensile pulse is generated in an incident bar and propagates into a specimen. Some part of the incident pulse is transmitted into a specimen and propagates through a transmitted bar as the tensile pulse. The rest of the pulse is reflects into the incident bar as a 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 on two bars at equal distances from each end of the bars. The signals from the strain gauges are monitored and acquired by an oscilloscope.

Fig.(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

$$\varepsilon(t) = 2\,\frac{C}{Ls}\,\varepsilon_R(t) \qquad (1)$$

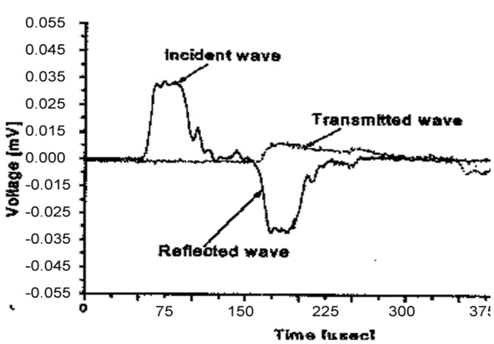

Fig.(2) – Typical forms of waves obtained of specimen I from an Oscilloscope

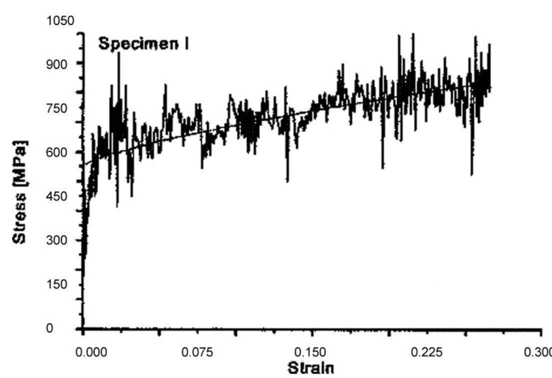

Fig.(3) – Stress – Strain curve

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

$$\varepsilon(t) = \int_{o} \varepsilon(\tau)\, d\tau \qquad \text{———} \qquad (2)$$

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

$$\sigma(t) = E \frac{Ao}{A} \varepsilon_T(t) \qquad \text{———} \qquad (3)$$

where C = Speed of an Elastic wave in a bar
Ls = Effective gage length of a specimen.
Ao & A = are the area of bar and specimen
E = Young's modulus for a bar.

The subscripts R and T indicates the reflected and the transmitted pulses in equations (1) & (3) respectively.

Incident and transmitted bars are made up 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 gages S_1 & 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 time of the incident pulse, as expressed by

$$\Delta t = \frac{2\,Lt}{C} \qquad \text{———} \qquad (4)$$

where Lt = Length of the striker tube.

3.0 Experimental results and constitutive relations of sheet Metals

The sheet metals used in experiments are shown in the following Table (1)

Table(1) : The sheet Metals used in Experiments

Description	Name	Thickness (mm)	Quality
Specimen I	60 TRIP	1.3	TRIP 60
Specimen II	B 42904	1.3	CQ
Specimen III	B 43786	1.3	DQ
Specimen IV	B 96821	1.5	CHSP35R
Specimen V	CP 800	1.7	DQ

The quasi static tensile tests were carried out at strain rates of 0.03/s and 1/s with the Instron 5500 and 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 were ranged from 1500 to 10,000/s. The stress strain curve of specimen I is shown in Fig.(3). Since high frequency component of incident wave is attenuated in the bar the dynamic stress - strain curve from the Hopkinson bar test is oscillatory. And the experimental results are shown in Fig.(4) for several materials and used to construct constitutive relations of sheet metals.

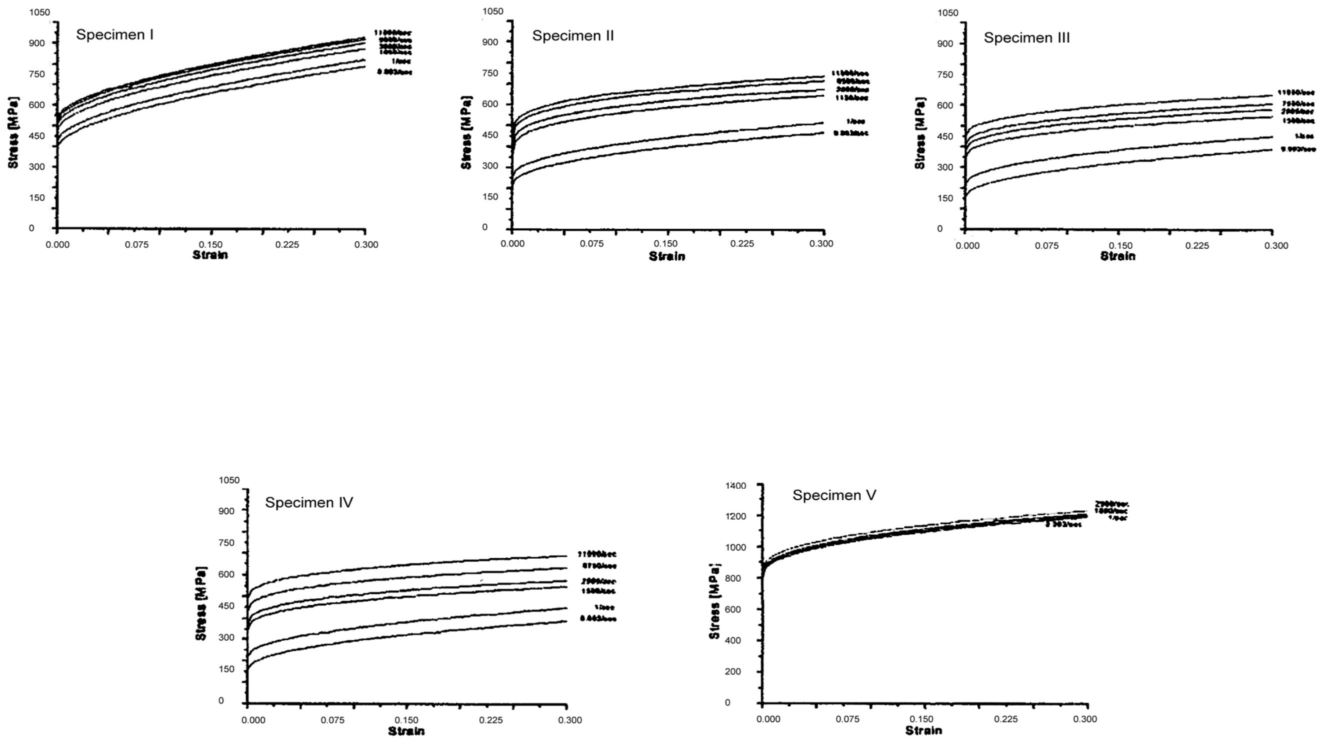

Fig.(4) – Stress - Strain curves obtained from different specimens at various Strain rates.

In this work ,the Johnson-cook constitutive relation is applied to sheet metals.
The conventional Johnson-Cook model [9] for the yield stress is -

$$\sigma y \quad = \quad [\, A+B\,(\bar{\varepsilon}^{p})^{\,n}\,] + [\,1 + C \ln (\overset{\bigstar}{\varepsilon}{}^{*})]\,[1-(T^{*})^{m}\,]$$

where A = Yield stress constant
B = Strain hardening coefficient
C = Strain rate dependence coefficient
n = strain hardening exponent
m = Temperature dependence exponent
Tm = Melting Temperature, in degree Kelvin
Tr = Room Temperature, in degree Kelvin
$\overset{\bigstar}{\varepsilon}o$ = Reference strain rate
Cv = Specific Heat
Pcut = Pressure cut off or failure stress, σ_m

The above said A, B, C, n and m are the input constants ε^{-p} is the effective plastic strain, $\overset{\bigstar}{\varepsilon}{}^{*}$ is the non dimensional strain rate and T* is the homogeneous Temperature.

The effective plastic strain ε^{-p} is given by

$$\bar{\varepsilon}^{p} = \int_{o}^{t} d\,\bar{\varepsilon}^{p}$$

where the incremental effective plastic strain $d\bar{\varepsilon}^p$ is found from the incremental plastic strain tensor $d\varepsilon_{ij}$ as

$$d\,\bar{\varepsilon}^p = \left[\frac{2}{3}\, d\,\bar{\varepsilon}^p_{ij}\, d\,\bar{\varepsilon}^p_{ij}\right]^{1/2}$$

The non dimensional strain rate $\dot{\varepsilon}^*$ is calculated from $\dot{\varepsilon}^* = \dot{\bar{\varepsilon}}^p / \dot{\varepsilon}_o$

Where $\dot{\bar{\varepsilon}}^p$ is the effective plastic strain rate and $\dot{\varepsilon}_o$ is the reference strain rate defined in the input. The homogeneous temperature T* is the ratio of the current temperature to the melting temperature when both expressed in degree Kelvin. Temperature change in this model is completed assuming adiabatic conditions i.e., no heat transfer between elements.

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 achieve optimum execution speed.

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

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

where σ^* is the ratio of pressure to the effective stress. i.e.,$\sigma^* = P / \bar{\sigma}$

and the effective stress $\bar{\sigma}$ is found from $\bar{\sigma} = \left[\frac{3}{2} S_{ij} S_{ij}\right]^{1/2}$

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

And the evolution of the damage parameter is $\bar{D} = \sum \Delta\bar{\varepsilon}^p / \varepsilon_f$

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

The initial yield stresses with respect to the strain rates are displayed in Fig. (5) with a semi log scale.

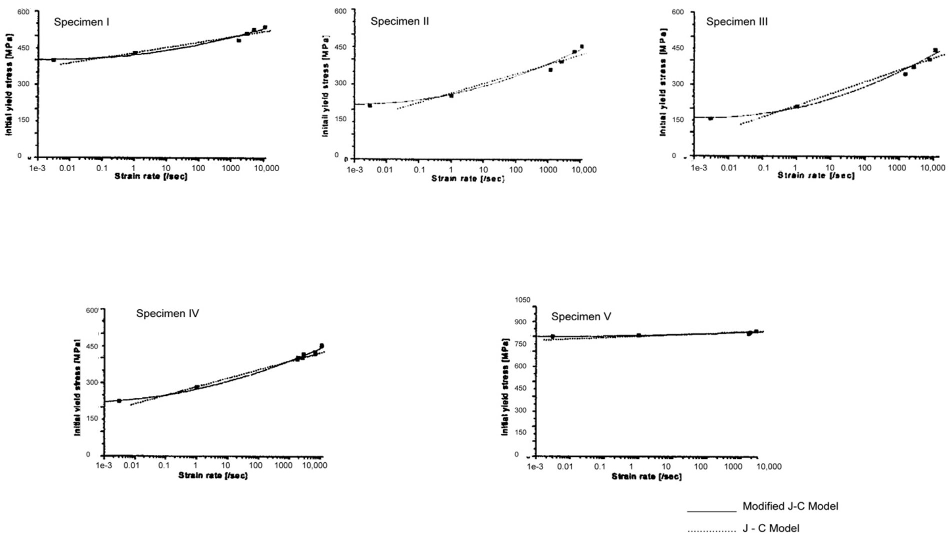

Fig.(5) – Initial Yield Stress Vs Strain rate for different specimens

Experimental results show that linear interpolation is not adequate for sheet metals. For a better description of the material behaviour, the experimental data are interpolated using a quadratic curve [10]

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

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 behaviour better than the quadratic interpolation although it is less effective in application. Fig.(6) shows the stress - strain curves estimated with the original and modified JC models for sheet metals.

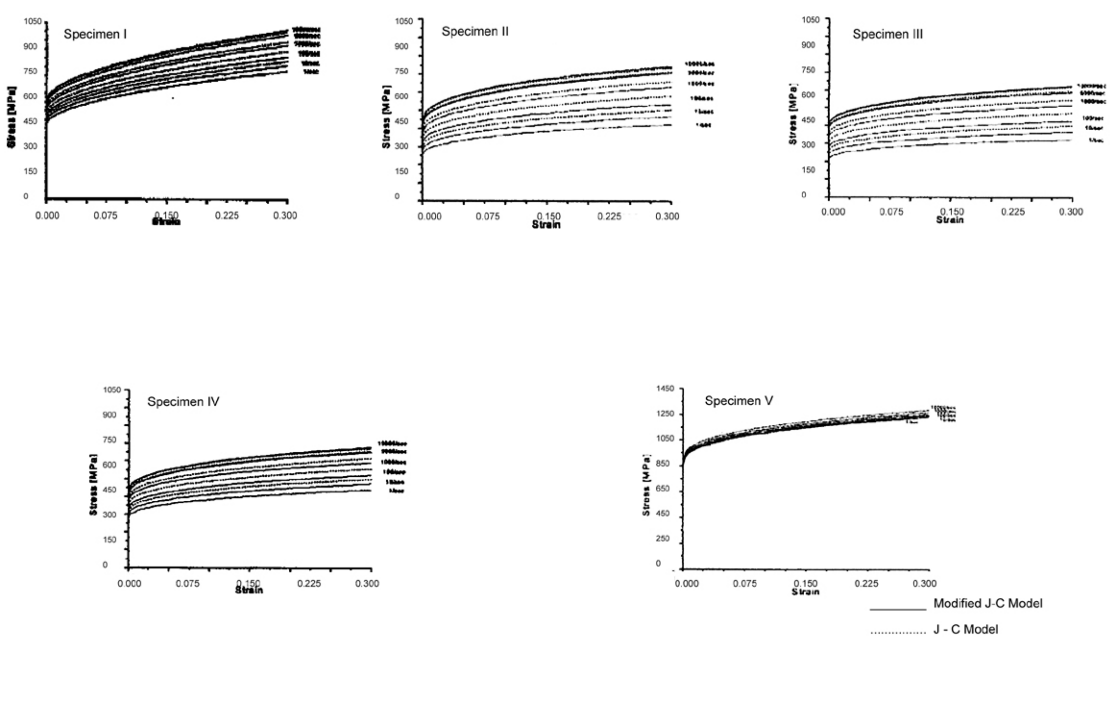

Fig. (6) – Various Stress Strain curves obtained from constitutive equations with the variation of the strain rate

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

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

Table (2): Material constants in the original & modified JC constitutive relation for the sheet metal

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	260	465	0.480	0.1840	0.1050	0.0202	0.455
Specimen III	220	417	0.490	0.2230	0.1569	0.0264	0.372
Specimen IV	290	461	0.480	0.1324	0.1240	0.0095	0.399
Specimen V	815	638	0.400	0.0107	0.0046	0.0018	1.060

4.0 Conclusion :

By using a specially designed split Hopkinson pressure bar apparatus for dynamic tensile testing of sheet metals, with deep drawing quality, conducted the experimental of Ti - 6Al - 4V alloy sheet for Aircrafts under crash consideration. Quasi- static and dynamic tensile tests have provided stress strain curves for sheet metals at various strain rates and have been utilised to construct constitutive models. Introducing of quadratic strain rate hardening term in the original Johnson - Cook relation has been modified which fits the experimental data for sheet metals.

5.0 References

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