# DETERMINATION OF STRAIN RATE SENSITIVITY OF AL AND SA516 GR. 70 CS UPTO 400$^0$C USING SHPB

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## ABSTRACT

High strain rate tests of Al and SA516 Gr.70 CS are carried out using split Hopkinson pressure bar. These tests are performed to study the strain rate sensitivity of material at strain rates ranging from 500s$^{-1}$ to 3000s$^{-1}$ and temperature ranging from room temperature to 400$^o$C. Experimental results are reported in the form of stress-strain curves at different strain rate and temperature. It is observed that the strain rate sensitivity of aluminum is very low as compared to SA516 Gr.70 CS.

## INTRODUCTION

In present days there are numerous examples of engineering applications where material sees high strain rate loading. Such loading are dynamic in nature. Materials, to greater or lesser extent, show a change in mechanical response under increased strain rate and temperature condition. Change in response of material under dynamic loading condition and its application in modern engineering process such as high speed machining, military application, development of crashworthy vehicle, drop test of radioactive material shipping cask etc have made the study of subject important. Dynamic material property evaluation is necessary for safety analysis and structural integrity assessment of structures subjected to such loading.

Different test methods are available for high strain-rate material testing such as Split Hopkinson-Pressure-Bar or Kolsky bar [1-5], drop weight test [6], expanding ring technique [7,8], Taylor test [9,10]and plate impact test[10]. In the present work Split Hopkinson-Pressure-Bar (SHPB) is used to carryout the high strain rate test of aluminum and SA516 Gr.70 carbon steel samples. SHPB works on the principle of one dimensional wave propagation and are useful to test the material in strain rate range of $10^2$ to$10^4$ s$^{-1}$. Its main components are a gas gun, a striker bar, an incident bar and a transmission bar as shown in Fig. 1. The striker bar sits in the barrel at the gas gun chamber. The incident bar, transmission bar and striker bar are all made of same material and same cross-section area. The sample to be tested is sandwiched between the incident and transmission bar. The striker bar is propelled by gas pressure towards the incident bar. On impact, an elastic compression wave propagates down the incident bar toward the sample. On reaching the sample, repeated wave propagation within it deforms it plastically. Part of the wave goes through to the transmission bar (transmitted pulse) and part is reflected back into the incident bar (reflected pulse), each of which is picked up by the strain gauges mounted on the corresponding bars. Strain gauge in each bar is mounted in the half Wheatstone bridge configuration to eliminate the effects of bending and measuring only the axial strain. Elastic strain generated in incident and transmission bar are used to calculate the stress and strain in the specimen, respectively.

Equations to calculate the stress, strain and strain-rate induced in the specimen are based on continuity of motion and force between the incident/transmission bar and the specimen. At each of the two bar- specimen interfaces, the velocity of each material just to the left and right of the interface must be equal, since they are in intimate contact at all times. The forces just to the left and right of each interface must balance one another to satisfy equilibrium. Final expression for stress, strain and strain-rate are as follows

Stress
$$\sigma_s = \frac{A_0 E \varepsilon_t}{A_s} \quad (1)$$

Strain
$$\varepsilon_s = \frac{-2C_0}{L_s}\int_0^t \varepsilon_r dt \quad (2)$$

Strain rate
$$\dot{\varepsilon}_s = \frac{-2\varepsilon_r C_0}{L_s} \quad (3)$$

Where $A_o$ and $A_s$ are the cross-section area of bar and specimen, $C_0$ is stress wave velocity for a wave of infinite wavelength, E is young's modulus of bar, $L_s$ is length of specimen, $\sigma_s$, $\varepsilon_s$ and $\acute{\varepsilon}_s$ are specimen stress, strain and strain-rate respectively. $\varepsilon_r$ is the reflected strain in incident bar and , $\varepsilon_t$ is the transmitted strain in transmission bar.

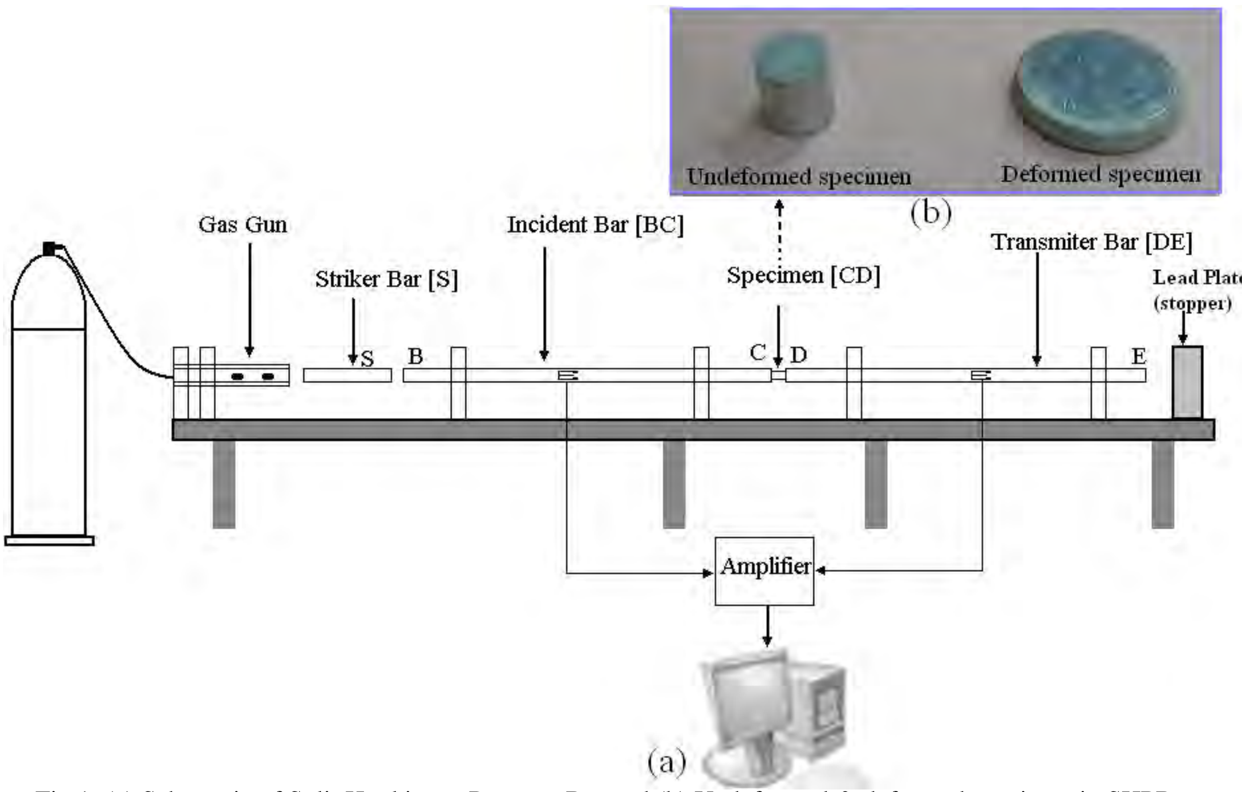



Fig.1: (a) Schematic of Split Hopkinson Pressure Bar and (b) Undeformed & deformed specimen in SHPB test

## HIGH STRAIN RATE TESTS

High strain rate flow behavior of aluminum and SA516 Gr.70 carbon steel sample is evaluated experimentally. The test is carried out at strain rates ranging from $500s^{-1}$ to $3000s^{-1}$ and temperature ranging from $30^oC$ to $400^oC$. Cylindrical samples of 5mm diameter and 5mm length were used for the compression tests. Molybdenum disulphide powder was used as lubricant for high temperature tests and Molybdenum disulphide grease was used as lubricant for room temperature tests to reduce friction at bar-specimen interfaces.

The elevated temperature tests were carried out by heating the sample using a small resistance coil furnace of 30 mm thickness (a disc shaped furnace). During heating the sample is held using a thermocouple wire by a brass sleeve such that it does not touch either bar; the gap being about 10 mm on each side of the sample. This reduces the heating of the bars. The furnace slides over the bars at a position where the sample is at the furnace center. After reaching the desired temperature the sample is held for a minimum of 3 to 4 minutes before testing. The bars and sample are brought together within a second prior to firing the striker bar. Thermocouple on sample gives the temperature of the sample and the temperature is controlled using a variac

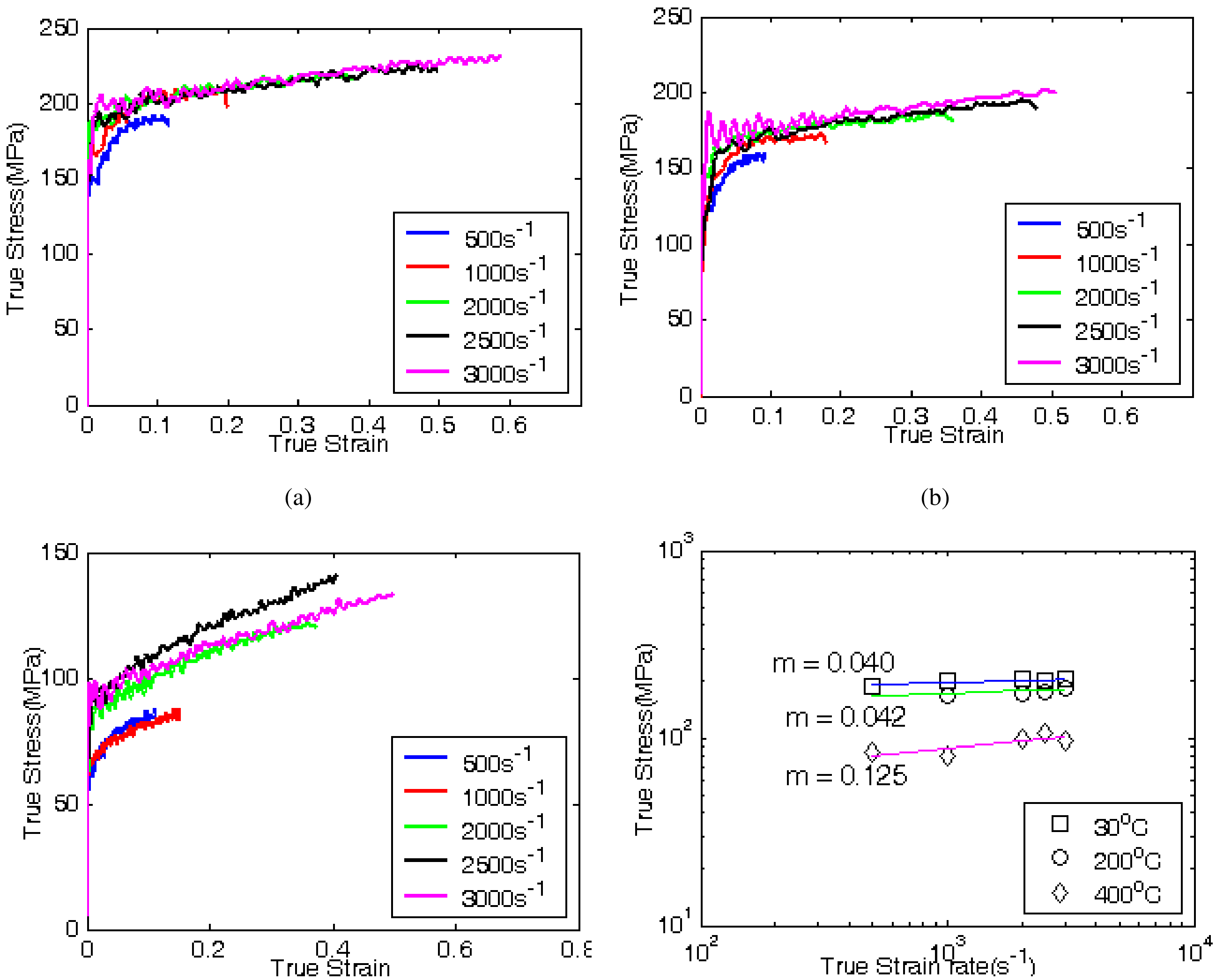
### Stress-Strain Response of Aluminum under High Strain Rate

The results of high strain-rate tests and their comparison are shown Fig. 2. The comparisons of the test results are shown as. stress-strain curve at constant temperature with varying strain-rates. Flow stress is found to increase very slightly with increase in strain-rate. As the strain-rate increases, the specimen strain also increases in SHPB test as strain generated during the test is also proportional to strain-rate of test. Form these plots it is clearly observed that flow stress of the material decreases with increase in test temperature. The effect of thermal softening seems to be more prominent as compared to strain-rate sensitivity. The oscillations seen in the curves are due to wave dispersion effects and not due to material property. Chemical composition of the material is shown below in table 1.

Table 1: Chemical composition of aluminum sample tested on SHPB (Wt %)

| Al | Cu | Mg | Si | Fe | Ni | Mn |
|---|---|---|---|---|---|---|
| 98.62 | 0.063 | 0.415 | 0.319 | 0.40 | 0.002 | 0.058 |
| Zn | Pb | Sn | Ti | Cr | Vd | |
| 0.078 | 0.015 | 0.006 | 0.003 | 0.011 | 0.004 | |

Fig. 2(d) shows the strain rate sensitivity of the material at different temperature. Mathematically strain rate sensitivity is expressed as $m = \Delta \ln \sigma / \Delta \ln \dot{\varepsilon}$ , where $\sigma$ and $\dot{\varepsilon}$ are true stress and true strain rate respectively. Strain rate sensitivity is equal to slope of true stress vs. true strain rate curve if plotted on log-log axis. It is observed through the test result that the strain rate sensitivity at different temperature is different




(a) (b) (c) (d)

Fig. 2: Stress-strain curve for Al: (a) room temperature, (b) 200°C, (c) 400°C and (d) strain rate sensitivity of Al at 0.1 strain

**Stress-Strain Response of SA516 Gr.70 Carbon Steel under High Strain Rate**

The results of high strain-rate tests for SA516 Gr. 70 and their comparison are shown in Fig. 3. Here also the comparisons of the test results are shown as stress-strain curve at constant temperature with varying strain-rates. Flow stress is found to increase with increase in strain-rate. As the strain-rate increases, the specimen strain also increasing. The flow stress of the material decreases with increase in test temperature. The oscillations seen in the curves are due to wave dispersion effects. Fig. 3(d) shows the strain rate sensitivity of the material at different temperature. Chemical composition of the material is shown below in table 2.

Table 2: Chemical composition SA516 Gr. 70 carbon steel sample tested on SHPB (Wt %)

| C | Mn | Si | P | S | Ni | Cr | Cu |
|---|---|---|---|---|---|---|---|
| 0.24 | 1.14 | 0.2 | 0.016 | 0.022 | 47 ppm | 30 ppm | 180 ppm |

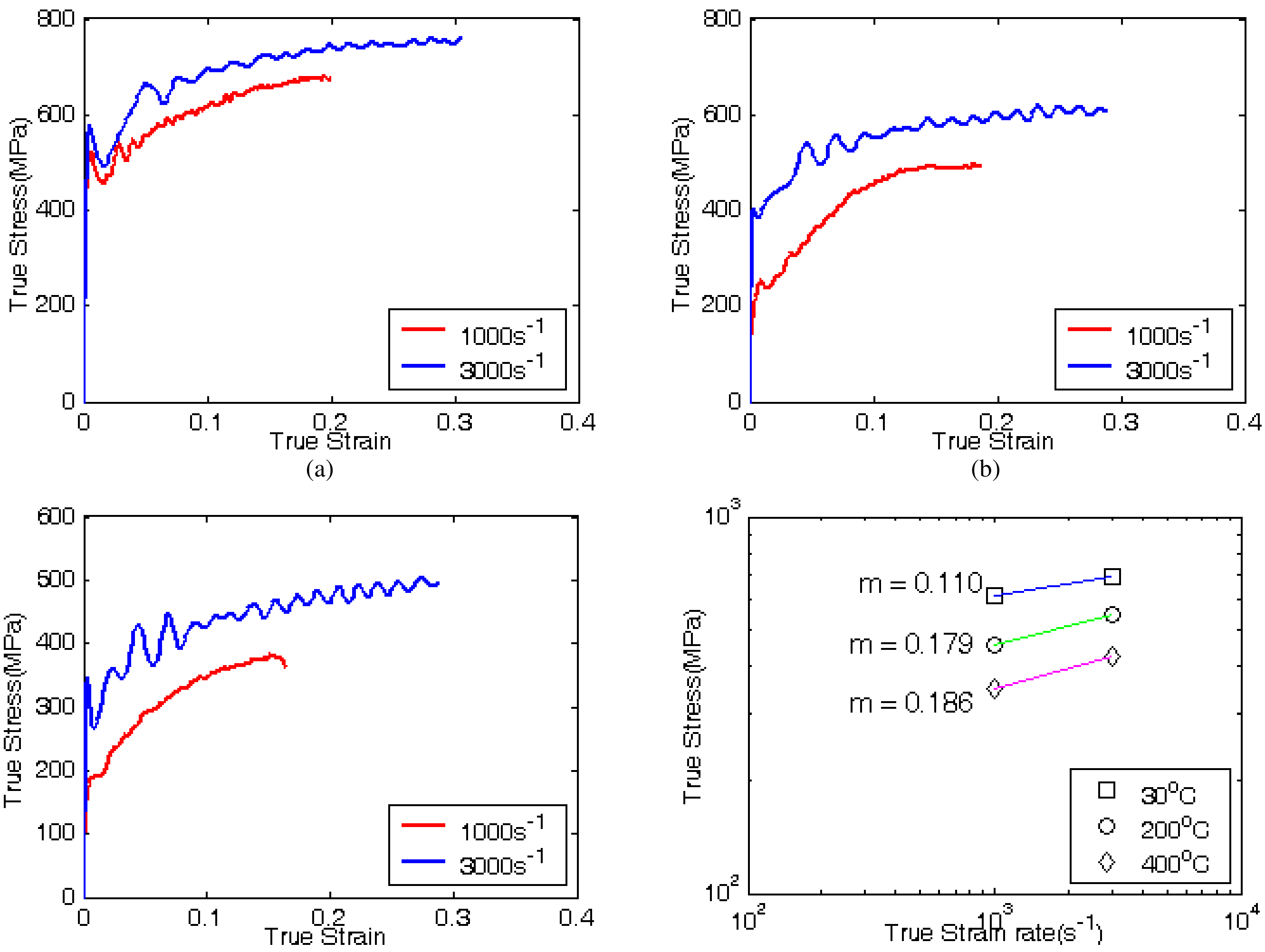



Fig. 3: Stress-strain curve for SA516 Gr.70 steel: (a) room temperature, (b) 200°C, (c) 400°C and (d) strain rate sensitivity of SA516 Gr.70 at 0.1 strain

## CONCLUSION

High strain rate test have been carried out to understand the effect of loading rate and temperature on aluminum and SA516 Gr.70 carbon steel. The results obtained through the test shows that the strain rate sensitivity of Aluminum specimen is very low and temperature sensitive high. Strain rate sensitivity (slope m) for the aluminum material at a 0.1strain at different temperature is different as obtained through the test results. However for the SA516 Gr.70 steel the strain rate and temperature sensitivity both are high and strain rate sensitivity at different temperature are nearly same.

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