

COMPARISON OF MEASUREMENT OF ALUMINIUM ALLOY IN HIGH STRAIN RATE

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Abstract: This article describes the Split Hopkinson Pressure Bar test of aluminium alloy EN AW 7075-T6. This test is used for material testing at a high strain rate. Two approaches in measurement. In the first case was used one size of specimen and different initial pressure. In the second case was set one initial pressure and three different lengths of specimen. Based on measured data, constants of Johnson-Cook material model for FEM analysis were found.

KEYWORDS: Split Hopkinson Pressure Bar, Aluminium alloy 7075, Dynamic behaviour, High strain rate, Finite element analyses, Johnson-Cook material model

1 Introduction

The method of using thin bar for material testing in high strain rate was first described by B. Hopkinson in 1914. In this experiment was used only one bar. [1] In 1949 designed H. Kolsky apparatus with 2 bars with specimen sandwiched between them. [2] This test method is usable for experiment with a high strain rate in range $200 - 10^4 \text{ s}^{-1}$ [3]

The aluminium alloy 7075-T6 was chosen as the specimen material due to its frequent use in applications, where it can be part loaded by an impact or detonation, for example in aerospace, military, racing, etc. In our department were made analyses of cam [10] and crash test of rail wagon [11] which belongs to these applications. For accurate computational model is necessary to know material behaviour in specific strain rate.

The first research was carried out on same-size specimens with different initial pressure. [4] For lower pressure the measurement results showed deviations. For highest pressure the signals were more similar. It was the main reason to compare two methods of strain rate control.

2 Split Hopkinson Pressure Bar test

The apparatus for Split Hopkinson Pressure Bar test consists of incident and transmitter bar, gas gun and striker bar (Figure 1). The striker bar is accelerated by compressed air against the face of the incident bar. Impact to the bar generates the incident strain pulse $\varepsilon_i(t)$ in the incident bar. The pulse is propagated along the bar. When the pulse reaches the interface between the specimen and the incident bar, part is reflected $\varepsilon_r(t)$, and the rest is transmitted through the specimen to the transmitter bar. The specimen is loaded by uniaxial compression. There is evoked transmitted strain pulse $\varepsilon_t(t)$. The amplitude of the impact velocity of the pulse depends on the striker bar. The velocity is regulated by the air pressure in the gas gun. The pulses in the bars are measured by a strain gauges glued to the outer surface. The signal from the gauges is amplified and recorded in a digital oscilloscope.

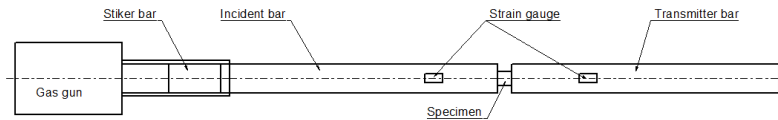


Fig. 1 Split Hopkinson Pressure Bar scheme [4]

The advantage of this method is the direct evaluation of stress $\sigma(t)$, strain $\varepsilon(t)$ and strain rate $\dot{\varepsilon}(t)$. The evaluation is made by these equations. [1]

$$\sigma(t) = \frac{A_b \cdot E}{A_s} \cdot \varepsilon_t(t), \quad (1)$$

$$\dot{\varepsilon}(t) = \frac{2 \cdot c_b}{l_s} \cdot \varepsilon_r(t), \quad (2)$$

$$\varepsilon(t) = \frac{2 \cdot c_b}{l_s} \cdot \int_0^t \varepsilon_r(t) dt. \quad (3)$$

Where A_b is cross section of incident and transmitter bar, E is Young's modulus of bars, A_s is cross-section of specimen, c_b is speed of the wave propagation, and l_s is length of the specimen.

For the measurement was used Split Hopkinson Pressure bar apparatus with incident bar and transmitter bar with diameter 24 mm and length 1700 mm. Also, the striker bar diameter is 24 mm and there were 3 possible lengths, 50, 100 and 200 mm. The length of the gun is 1000 mm. Apparatus is described in [6]. The scheme is in Figure 2.



Fig. 2 Split Hopkinson Pressure Bar apparatus [12]

3 Experiment with different pressures

For experiment a set of 9 circular specimens with length 10 mm and diameter 10 mm was used. Specimens were made by turning. In the gas gun 3 pressures, 5, 10 and 15 bars were set. The longest striker bar with length 200 mm was chosen because for longer strikers are longer strain pulses in bars and higher reachable strain in the specimen. From the initial pressure we calculated the impact velocity, which is shown in Table 1.

Table 1 Impact velocity for each pressure

Pressure [bar]	Impact velocity [m/s]
5	18.5
10	26.1
15	31.9

With the use of the strain gauge, the strain was measured in incident and transmitter bar (Figure 3). The incident, reflected and transmitted waves were separated from the signal (Figure 4). The signal was amplified 257 times. In this case, where variable pressure is necessary before the measurement beginning, set right measurement window in the oscilloscope.

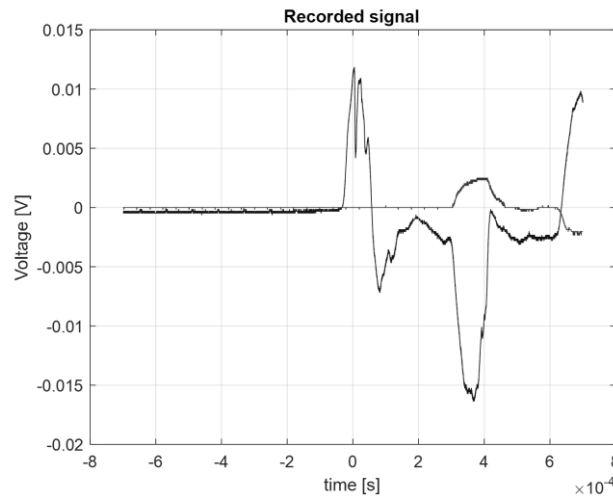


Fig. 3 Recorded signal

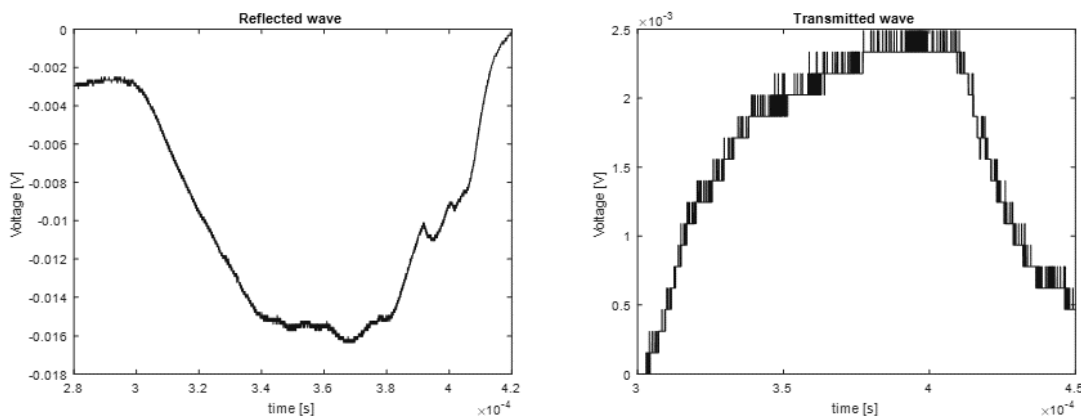


Fig. 4 Separated reflected and transmitted waves for pressure 15 bars

The reflected and transmitted waves were evaluated using equation (1), (2), (3) evaluated stress, strain and strain rate for each specimen. The stress strain curves are in Figure 5. The values of the mean yield strength and the mean strain rate for each pressure are in Table 2. Because of the noise in signal and measurement accuracy were stress strain curves smoothed, the third order Savitzky-Golay filter with window length 499 was used. [3]

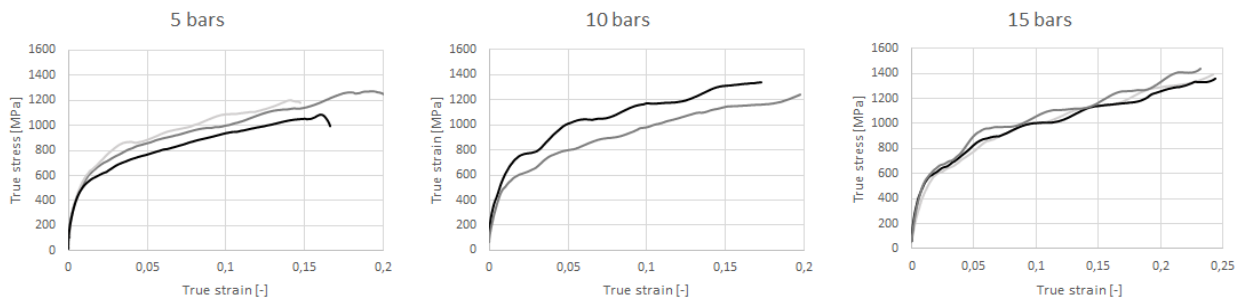


Fig. 5 Stress strain curves for each pressure

Table 2 Mean values of plastic strain rate and yield strength

Pressure [bar]	Plastic strain rate [s^{-1}]	Yield strength [MPa]	Yield strength standard deviation [MPa]
5	1740	548	24.5
10	3000	552	61
15	3430	573	10.3

In this method is advantage high range of strain rate, where strain rate for 15 bars is about two times higher than for 5 bars. But for the lower pressures there is a higher deviation of the results. For 10 bars one measurement was not recorded because of damaged strain gauge on incident bar.

4 Experiment with different specimen length

In this variant of experiment, variable specimen length and constant pressure 15 bars were used for all measurements. This was because of the smallest deviation in the results with this pressure in a previous experiment. Circular specimens with diameter 15 mm and length 5 mm, 10 mm and 15 mm were used. 9 specimens were prepared in total. The striker with length 200 mm was used again.

Recorded signal (Figure 6) was separated to the reflected and the transmitted wave (Figure 7). From these waves, the stress strain curves and strain rate for each specimen length were evaluated. The plastic strain rate and yield strength with standard deviation were also evaluated; see Table 3.

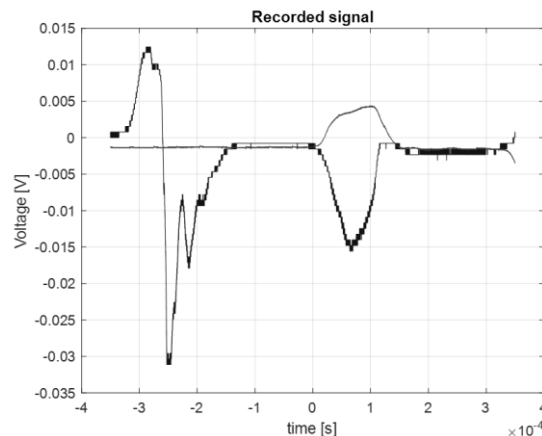


Fig. 6 Recorded signal for specimen length 5 mm

In this case there are similar results for plastic part of stress strain curves for all specimens except one measurement for length 10 mm. The reachable strain rate range is not as high as in case with variable air pressure but is possible to reach higher plastic strain rate by shorter specimen.

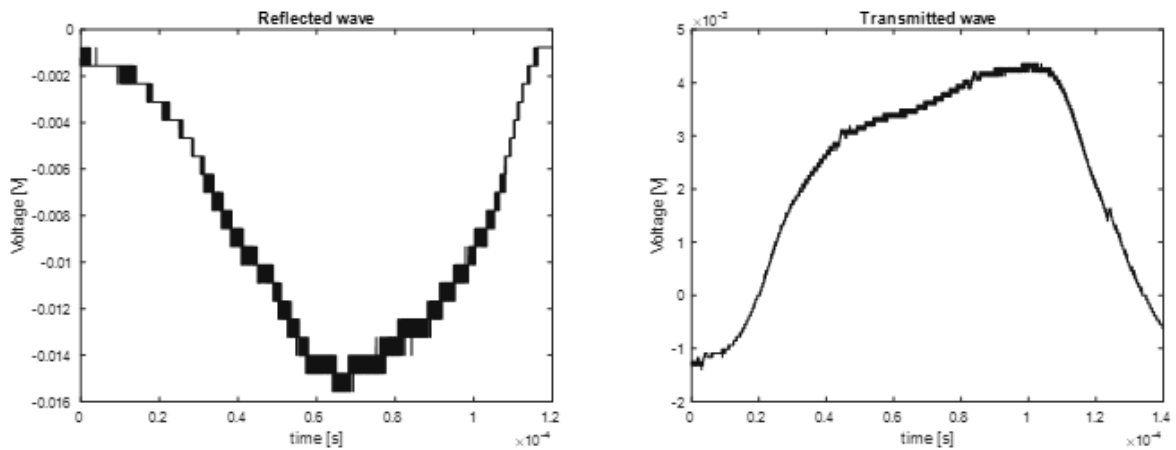


Fig. 7 Separated reflected and transmitted signal for specimen length 5 mm

Stress-strain curves for each specimen dimension were evaluated from the recorded signal. The curves are in Figure 8.

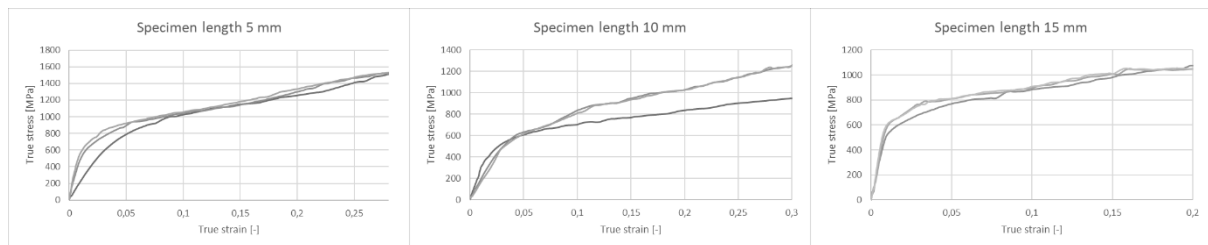


Fig. 8 Stress strain curves for each specimen length

Table 3 Mean values of plastic strain rate and yield strength

Specimen length [mm]	Plastic strain rate [s^{-1}]	Yield strength [MPa]	Yield strength standard deviation [MPa]
5	3806	575	11.6
10	3557	545	24
15	2863	560	25

5 Johnson-Cook material model parameters

The Johnson-Cook strength model is one of the widely used constitutive models in explicit analyses. It is suitable for applications where it is possible to have high strain rate loading or temperature changes during the deformation process. The model consists of strain hardening, strain rate hardening and temperature influence part. [7] Each part can be fitted separately. For strain hardening are suitable stress strain curves, for strain rate hardening yield stress in specific strain rate to reference strain rate ratio and for temperature part data at different temperature. Because there was no measurement of the temperature during the experiment and the temperature change after the experiment was not significant, the temperature part was neglected. For fit of the model the data for low strain rate 0.001 , 0.01 and $0.1 s^{-1}$ were found. [9] As the reference strain rate value $0.1 s^{-1}$ were chosen. The model defines stress as: [8]

$$Y = [A + B\varepsilon_p^n] \left[1 + C \ln \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_{ref}} \right] [1 - T_H^m]. \quad (4)$$

Where A is the reference yield stress for the reference strain rate. B and n represent the effect of strain hardening, ε_p is the effective plastic strain, $\dot{\varepsilon}_p$ is effective plastic strain rate, $\dot{\varepsilon}_{ref}$

is reference strain rate, C is the constant of strain rate hardening, T_H is the homologous temperature and m is the temperature exponent [8].

It is obvious from the stress strain curves that the slope of hardening in the plastic part is significantly higher for the high strain rate than for the low strain rate. Also, the yield strength increased with strain rate but not so significantly and for measured range is similar for all cases, see Figure 9. Because of that, strain hardening constants fitted on all results separately and for the final model were used mean values of coefficients B and n . For evaluation of strain rate hardening constants were used ratios of yield strengths for each strain rate to reference yield strength, see Figure 10. The constants of the material model are in Table 4.

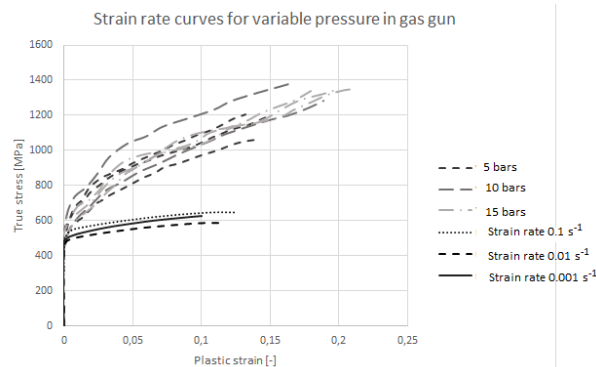


Fig. 9 Strain rate curves for low and high strain rate

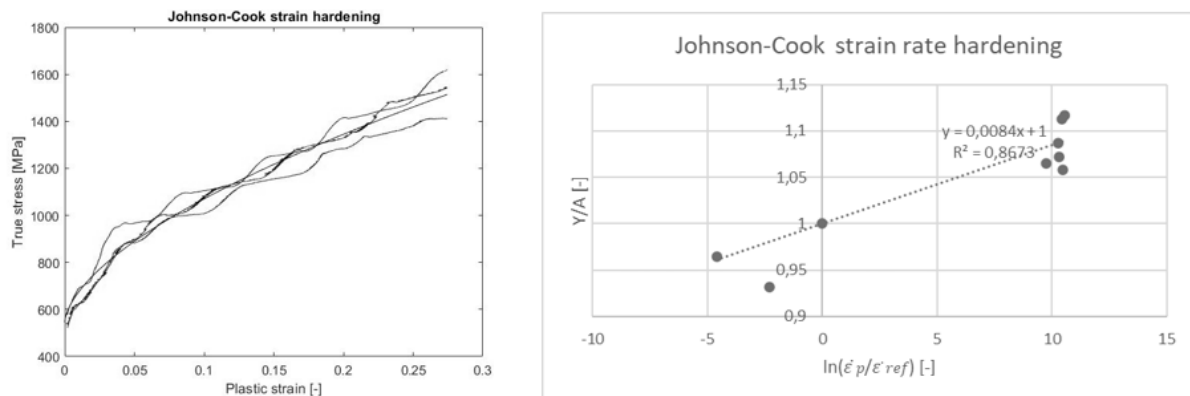


Fig.10 Fitting of material model parameters

Table 4 Constants of the material model

A [MPa]	B [MPa]	n [-]	C [-]	$\dot{\epsilon}_{ref}$ [s⁻¹]
515	1819	0,58	0,0084	0,1

6 Finite element analyses

The experiment with set material model was performed using Ansys Explicit solver. [8] The model was created according to the real testing apparatus. There were prepared striker bar, incident and transmitter bar and specimen between them. The diameter of the bars was 24 mm and length of incident and transmitter bars was 1700 mm. The length of the striker bar was 200 mm. Both variants of the experiment were simulated. In the first case was prepared specimen with diameter 10 mm and length 10 mm. Striker bar velocity was established for each pressure according to Table 1. In the second case were prepared specimens with diameter 15 mm and lengths 5, 10 and 15 mm. Two symmetry planes were used. The strike velocity was set from

Table 1 for the pressure of 15 bars. Influence of damping was neglected. The end time of the simulation was set at 0.0004 s. The basic element size was 2.5 mm and in the sample the mesh was refined to 0.75 mm (Figure 11). Contact friction was neglected.

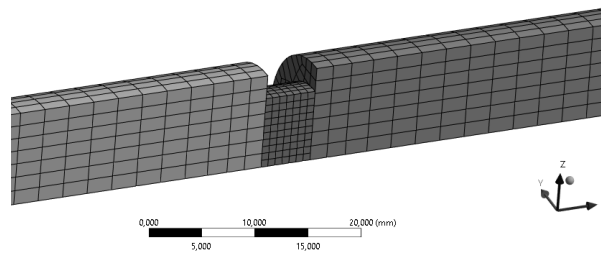


Fig. 11 Prepared mesh

From the results were created stress strain curves, which were compared with experimental curves. It is obvious from the comparison that the computational model corresponds with the experimental data in the yield stress and slope of the plastic part. However, there is a significant difference in the total plastic strain, which is about twice higher in the experiment, see Figure 12.

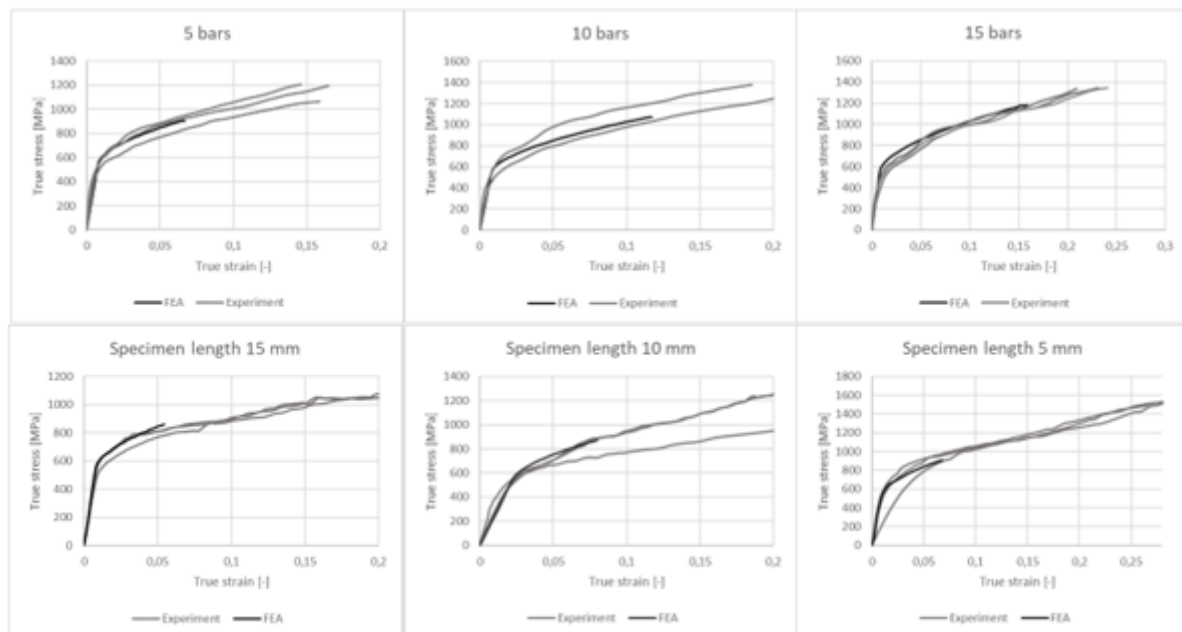


Fig. 12 FEA and experiment comparison

CONCLUSION

In the paper, the Split Hopkinson Pressure Bar test of aluminium alloy EN AW 7075-T6 is shown. In the first part, there is the measurement, which was made by two different methods. In the first case, the air pressure in the gas gun was used to control the strain rate. In the second case, variable length of the specimen. Both cases were compared according to the achievable strain rate and the standard deviation of the yield strength standard deviation. From the perspective of the yield strength deviation, both methods are equivalent. There was higher standard deviation only for the test with initial pressure of 10 bars, so it can be considered by a measurement issue. From the other perspective, the strain rate range is higher for variable initial pressure, but it is more difficult because of the set-up of measure window in oscilloscope for each pressure. With the use of the variable specimen length is less strain rate range, but it can be reached higher strain rate and the measure window in the oscilloscope is the same for all specimens.

After measurement evaluation, constants of Johnson-Cook material model were fitted, and this model was used for numerical validation. It is obvious that the yield strength and hardening slope in the plastic part correspond to experiment. However, the total plastic strain is significantly less than in the experiment. The causes of this can be clarified using the high-speed camera and the image correlation of the experiment with simulation. A 3D printed specimens and testing apparatus for tensile loading will follow.

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