MECHANICAL PROPERTIES OF ALUMINIUM ALLOYS AT HIGH STRAIN RATE

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The split Hopkinson's pressure bar test is a part of a group of testing methods used to determine dynamic behavior of various materials in an interval of strain rate from 100 s^{-1} to 10^3 s^{-1}. The article describes the practical application of the testing method for aluminum alloy EN AW 6082. This alloy is used for cold-extruded parts (components of car airbags). Since the strain rate of cold forming technologies reaches up to 1000 s^{-1}, it is necessary to determine the material´s behavior at these strain rate values.

KEYWORDS
Split Hopkinson Bar test, aluminium alloy, EN AW 6082, high strain rate, dynamic load.

1 INTRODUCTION

An innovative research and development especially in sector of automotive industry aims to reduce the weight of certain car components which can be manufactured using the cold forming methods.

An advanced, high-precision technologies, which include cold forming technologies, are very popular, and are frequently used in various manufacturing sectors all around the world. Knowledge of the dynamic behavior of materials, especially aluminum alloys, forged under defined main and boundary conditions, is absolutely essential for a company which wants to successfully manufacture components using cold forming methods.

Most of the material models are based on quasi-static cold or hot compression or tensile tests. For different conditions, especially various temperatures and strain rates, a comprehensive database of many material models is missing nowadays.

The dependence between the stress-strain-strain rate is one of the essential material characteristics, especially with regard to its technological processing. The increase of the wear resistance of certain materials and onset of plastic deformation is related to the yield strength as the beginning of the strain hardening process. Quantification of these phenomena is particularly important for the mathematical description, especially with regard to material models in numerical simulation software's. Significant differences in the behavior of materials during processing on an automatic forming machines require verification of the deformation curves under the real strain rate conditions.

For medium strain rate values, experimental equipment, such as variously modified hammers, drop towers and other testing machines, is currently used. When using one of these devices, the interpretation of the obtained results in the form of material models under real conditions is a very complex process. This problem gradually led to the development of methods based on monitoring the spread of the stress waves in the material.

In order to test and monitor the behavior of materials under high strain rate conditions, different methods are used, for example the split Hopkinson pressure bar method. The basic arrangement of this method was first brought by Kolsky [Kolsky 1949]. Other variants of this test were developed later [Meyers 1994], [Slais 2016]. Today´s schematic arrangement for compression testing can be seen in Fig. 2.

At a high strain rate, for which the split Hopkinson pressure bar method is used, inertial forces, stress wave distribution, and mechanical resonance have an important effect. These effects are not observable in the case of quasi-static events and at a medium strain rate forming conditions.

2 EXPERIMENTAL FACILITY

The Laboratory of the high strain rate deformations (LHRD) was established at the Faculty of Mechanical Engineering of Brno University of Technology as part of the Institute of Manufacturing Engineering, Department of Metal and Plastics Forming Technology. The experimental equipment (pneumatic gun - see Fig. 1) allows to perform the split Hopkinson pressure bar test (SHPB). It´s a unique device, which can be rarely seen not only in Europe, and therefore very few institutions are able to perform this kind of testing.

Figure 1. The Hopkinson facility in LHRD

The Laboratory is equipped with capacitance sensors, non-contact temperature sensor, inductor and Tektronix digital oscilloscope with the Scope evaluation software.

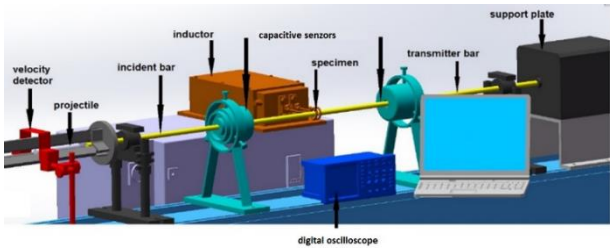

Figure 2. Schematics of the Hopkinson test arrangement

Measuring and evaluating components have been developed, manufactured and modified to meet the strict equipment requirements. The main part of the equipment consists of measuring bars, between which a test sample is placed. The bars are made of high-strength steel with the diameter of 15 mm and the length of 800 mm. The projectile (punch) is made out of the same material as the measuring bars and it gains its acceleration from air expansion in the air reservoir. The transformation of projectile´s kinetic energy into potential energy is provided by the axial point impact of the rounded front of projectile on the measuring bar.

The speed of projectile´s impact on the measuring bar is calculated from measuring a uniform flight motion between two photodiodes.

In addition to room temperature testing, it is possible to test and evaluate the material model using the experimental equipment at a higher temperatures with the help of an induction heating devices. [Rihacek 2019].

Throughout the application of this method, the material of the bar and its heat treatment must ensure elastic behavior of the bars. The compression tension pulse, which is generated inside the incident bar, spreads through the **t**ransmitter bar at a sonic speed to the area between the bar and the sample, and it is time-dependent on the strain. In the area between the incident bar and the test sample, a part of the compression wave is reflected, second part is absorbed in the test sample, and the third part passes into the transmitting bar. Deformation of the bars is measured by capacitance sensors mounted on the bars [Dohnal 2013]. The reflected wave travels back through the incident bar in the form of a compression wave, which causes its elastic deformation in an inversed direction. This deformation is again measured by the capacitance sensors. A compression deformation is observed and measured on the sample. It´s caused by energy transformation, which occurs when the sample transmits the compression wave and absorbs a part of its energy, which results a plastic deformation of the test sample.

Tension pulses are measured using the radial capacitance sensors. Radial deformations of the sample are measured and recorded on a separate channels of the TEKTRONIX digital oscilloscope, gained data are then transferred to a notebook and evaluated by the special SCOPE software. [Jopek 2000]

3 PROCEDURE OF EXPERIMENTAL EVALUATION

The tested sample has a cylindrical shape with a diameter of d_0 and length of l_0. Sample is placed between two steel bars of circular cross-section. Due to the interaction between the loading tension pulse $\sigma_1(t)$ at the end of the incident bar and the sample, this pulse is a partially reflected $\sigma_R(t)$ and partially transmitted $\sigma_T(t)$. The tension pulse time λ_I must meet the following requirement:

$$\frac{d}{\lambda} = \frac{c_{el}}{2\pi} \qquad (1)$$

where:

c_{el} is the propagation rate of elastic wave [m/s]

d is the bar diameter [mm].

The time behavior and magnitudes of tension pulses can be used to determine the dynamic mechanical properties of materials. The subjects of evaluation are engineering strains, strain rate, and stress in the sample. The course of the tension pulse $\sigma_I(t)$ in plastic materials is characterized by the final engineering plastic strain ε_p:

$$\varepsilon_p = \frac{(b_o - b)}{b_o} \qquad [-] \qquad (2)$$

where:

$\boldsymbol{b_0}$ is the initial length of sample, $\boldsymbol{b}$ is the length after deformation.

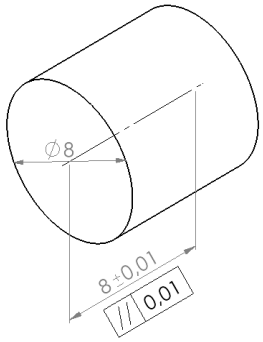

Figure 3. The SHPBT sample

It is important to determine the parameters of the functions σ_T, σ_R and σ_I . Parameters are directly related to the magnitude of the engineering strain ε_p.

Based on the acoustic assumptions about propagation of waves speed to the relation of the bar dimensions, it holds that $\lambda > d_0/2$. The wave can be considered as one-dimensional, and the measurement of the surface deformation of the bar can be also considered as indicator of the axial deformation of the measuring bar according to Poisson ratio of the bar material. It makes possible to determine the axial engineering deformations ε_R, ε_R and ε_I , for example using with a radial capacitive sensor**.**

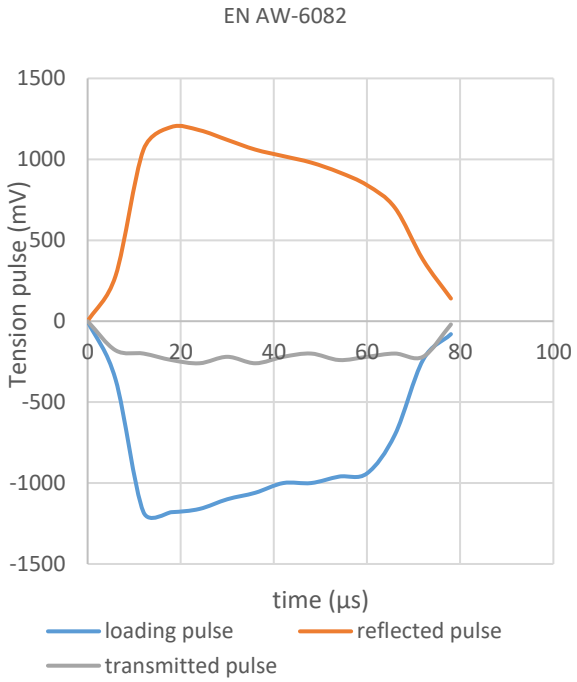

Figure 4. Plot of tension pulses in millivolts by sample in delivered condition

As can be seen from Fig. 4, the impact pulse, which is generated in the incident bar by the projectile, is more pronounced than the reflected pulse.

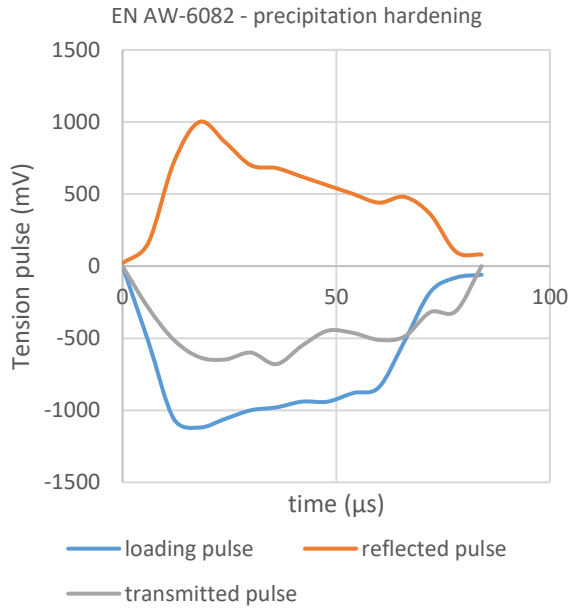

Figure 5. Process of the tension pulses (in millivolts) by precipitation hardening

From the Fig 5 it can be seen bigger differences of transmitted pulse by precipitation hardening condition in compare with the sample in delivered condition. The difference is then even bigger compared to soft annealing condition, see Fig.6

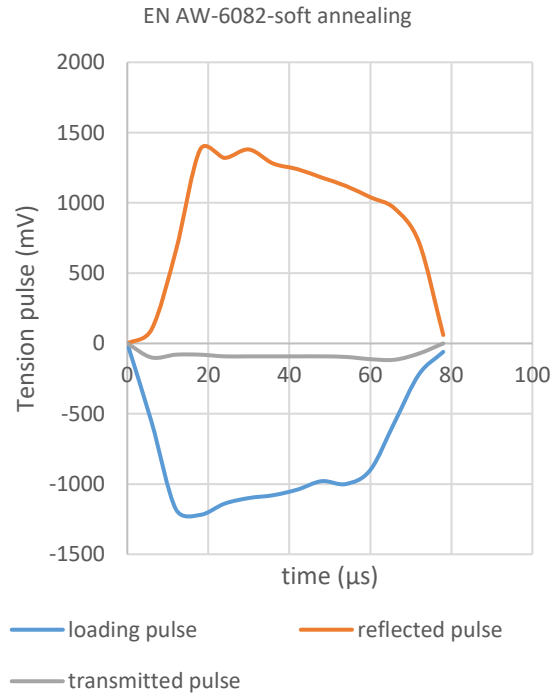

Figure 6. Progress of the tension pulses in millivolts by soft annealing

The stress wave propagation is a general prerequisite for evaluating an experiment. Both, the sample and the bars are in a state of uniaxial stress. The stress σ and engineering strain ε are homogeneous along the sample axis. The value of strain and stress can be calculated according to the following equations

A formulas below are used for calculating the mathematical model.

Evaluation of the measured pulses ΔU [V]

$\mathbf{U_I}$ [mV], – loading pulse (tension pulse $\boldsymbol{\sigma_I}$)

$\mathbf{U_R}$ [mV], – reflected pulse (tension pulse $\boldsymbol{\sigma_R}$)

$\mathbf{U_T}$ [mV], – transmitted pulse (tension pulse $\boldsymbol{\sigma_T}$)

Capacitor capacitance in quiescent state

$$C_0 = \frac{2\cdot\pi\cdot\xi_0\cdot l_0}{ln\frac{R_2}{R_1}} \quad [pF] \quad (3)$$

Change in bar radius (radial deviation)

$$\Delta R_1 = R_2 \cdot exp\left\{\frac{2\cdot\pi\cdot l_0\cdot\xi_0\cdot(U_0+\Delta U)}{C_p\cdot\Delta U - C_0\cdot U_0}\right\} - R_1 \quad [m] \quad (4)$$

where:

R_1 is the bar radius, R_2 is the radius of the capacitor ring, ξ_0 is the permittivity of vacuum, C_p is the parasitic capacitance, U_0 is the initial stress, ΔU are the measured stresses (established from the readings), l_0 is the height of sensor (length on the axis)

Engineering bar deformation (where μ is the Poisson number)

$$\varepsilon_r = \frac{\Delta R_1}{R_1} \qquad \varepsilon_z = -\frac{\varepsilon_r}{\mu} \quad [-] \quad (5)$$

Waveforms of axial stresses $\sigma_T(t)$, $\sigma_R(t)$ and $\sigma_I(t)$ from the Hooke´s law

$$\sigma = E \cdot \varepsilon_z \quad [MPa] \quad (6)$$

True stress:

$$\sigma_d = \sigma_T = \sigma_{I(t)} + \sigma_{R(t)} = \frac{1}{2}\left[\sigma_{I(t)} + \sigma_{R(t)} + \sigma_{T(t)}\right] \text{[MPa]} \quad (7)$$

where:

$\sigma_I(t)$.. Loading tension pulse [MPa]

$\sigma_R(t)$.. Reflected tension pulse [MPa]

$\sigma_T(t)$.. Transmitted tension pulse [MPa]

Strain rate:

$$\dot{\varepsilon}_{(t)} = \frac{[\sigma_{I(t)} - \sigma_{R(t)} - \sigma_{T(t)}]}{z_b\cdot l_0} \quad [s^{-1}] \quad (8)$$

where:

$\mathbf{z_b = \rho c_0}$ is the specific acoustic impedance of the bar.

4 DISCUSSION OF RESULTS

The samples cannot have a larger diameter than the diameter of the measuring bars in order to achieve axial impact stress in the sample. Conversely, the sample cannot have to small diameter, because it would be difficult to ensure aligning the sample between the measuring bars.

Asymmetric deformation of the sample could occur. Thus the sample would not meet the conditions of the test validity. Another reason is the impossibility of a clear reading pulses or, in extreme cases, the transient stress can be absorbed by the sample deformation. The ideal ratio seems to be b_o/d_o = 0.5, however, not more than b_o/d_o =1. In our case we used ratio b_o/d_o =1. The reason was a practical comparison with the same ratio (geometric parameters) in a dynamic test with real upsetting process on a forming machine.

Another important factor is the friction at the interface of the end of bar faces and the sample.

One of the most used aluminum alloys in automotive industry is EN AW 6082. This alloy is used for cold-extruded parts (part of Airbags). Since the strain rate of these technologies reaches up to 1000 s^{-1}, it was necessary to determine the material properties at these strain rate. The chemical structure of the supplied alloy is shown in Tab. 1

Si		Fe	Cu	Mn		Mg		Cr
Min	Max	Max	Max	Min	Max	Min	Max	Max
0,7	1,3	0,5	0,1	0,4	1	0,6	1,2	0,25

Table 1. Chemical structure of EN-AW 6082

The aluminium alloy EN AW 6082 was tested in delivered condition. From rod in delivered state, an additional heat treatment- (precipitation hardening and soft annealing) was performed. The results of stress in depending on strain are shown in Fig.7, 8 and 9. The resulting dependence of the stress in the sample on the strain was obtained after recalculating the impact, reflected and transient tension pulses. Results show the occurrence of an unstable yield strength and its sharp decrease to a stable yield strength. In the case of precipitation hardening state, an internal collapse of the material structure is evident, which is characterized by a reduction in the stress correlating around the value of 20-50 MPa, see Fig.8

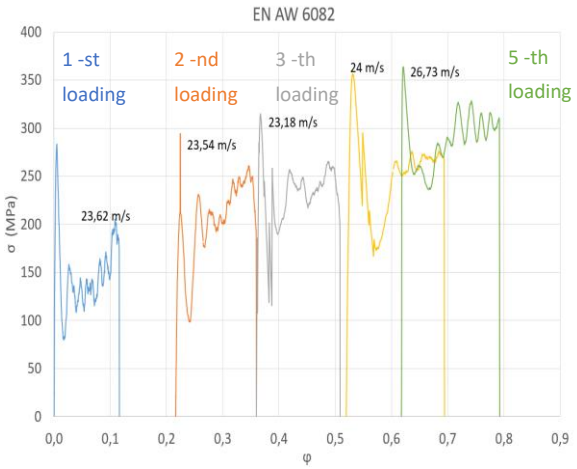

Figure 7. Dependence of stress on a true strain.

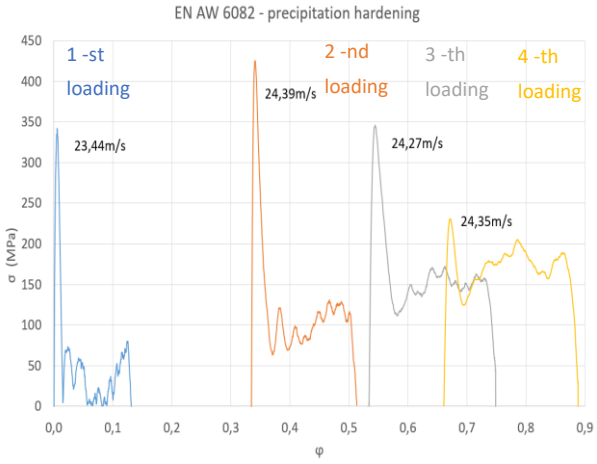

Figure 8. Dependence of stress on true strain by hardening state

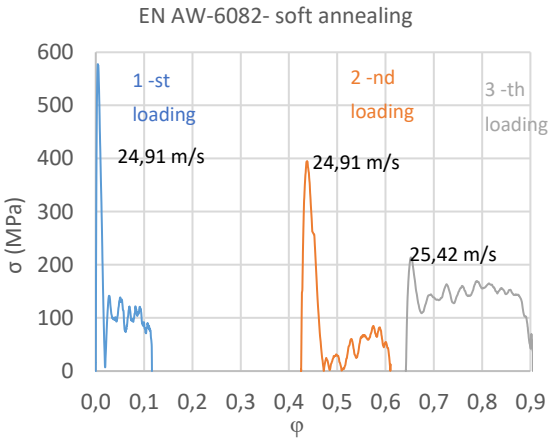

Figure 9. Dependence of stress on true strain by soft annealing

At strain rates between 1000 and 6000 s^{-1} is the strain of sample between 0.05 and 0.9 after repeated loading, as can be seen in Fig 10. In practice, this means, that the sample was upset after 1-st loading to a thickness 5,12mm, after 2-nd loading to a thickness 3,19mm and after 3-th loading to a thickness 2,14mm. Such a plastic deformation have a big influence of sample shape. With regard to the speed of the process, the coefficient of friction at the interface between the rod surfaces and the sample is very small, close to the hydrodynamic values.

The fact has also been proven by previous research or research projects of renowned laboratories for high strain rate deformations [Kobayashi 2014].

Fig. 9 clearly shows a steep linear increase in stress (which characterizes elastic deformation according to the Hooke´s law) practically until a stable dynamic yield strength is reached. Fig. 9 also shows the reduction of the yield strength, which is caused by the release of dislocations and the start of plastic deformation, until the lower stable yield strength is reached. As can be seen, at higher value of strain, plastic strain develops more significantly. At higher strain rate of projectile impact on the bar, the yield strength changed, see Fig.8. It can be seen from the Fig. 8 , that the steepness of reduction is similar nature, as is the subsequent increase in resistance to deformation due to hardening mechanism. There is also a noticeable change in the size of the upper and lower yield strengths depending on the strain rate.

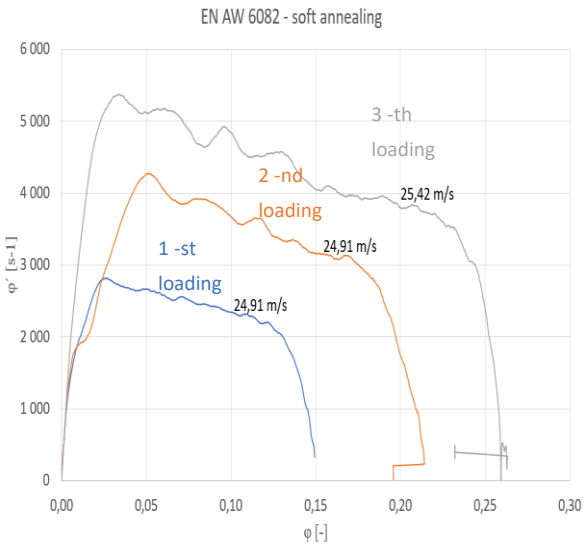

Figure 10. Dependence of the strain rate on a true strain

Even with such a low strain, the decrease from the upper to the lower yield strength is considerable, up to over 250 MPa.

However, at different strain rate, the lower yield strength in the tested sample shows minimal differences.

The shape of the samples after dynamic loading can be seen from Fig. 11, 12 and 13.

Figure 11. SHPBT sample in a delivered condition state after 5-th impact

Fig. 11 show the sample after impact loading with the delivered states. Max. diameter of sample after 5-th impact was 12.65 mm. The figure shows development of plastic deformation and especially the movement of dislocations. The movement of the dislocation is mainly reflected on the surface of the sample.

Figure 12. SHPBT sample in a precipitation hardening state after 4-th impact

On the dynamic test by SHBT with the sample, which was additional precipitation hardened, the depletion of plasticity is evident. The Fig.12 shows a crack in the sample. From Fig 8 it can be predicted, that plasticity has already been depleted during 1-th impact at the true strain value of 0.07. To compare the dynamic test with a practically manufactured part, we therefore loaded the sample repeatedly. Max. diameter of sample after 4-th impact need to be smaller as rods. In this case it was 13.39 mm.

Sample that has been additional soft annealed condition shows much better plasticity. There is a clear internal collapse of the material structure at the true strain value 0.48, which is manifested by a large stress drop – see Fig 9. Sample after impact shows Fig 13. Max. diameter of sample after 3-th impact was 13.55 mm. This fact of internal collapse of the material structure must be verified by subsequent microstructure research of sample.

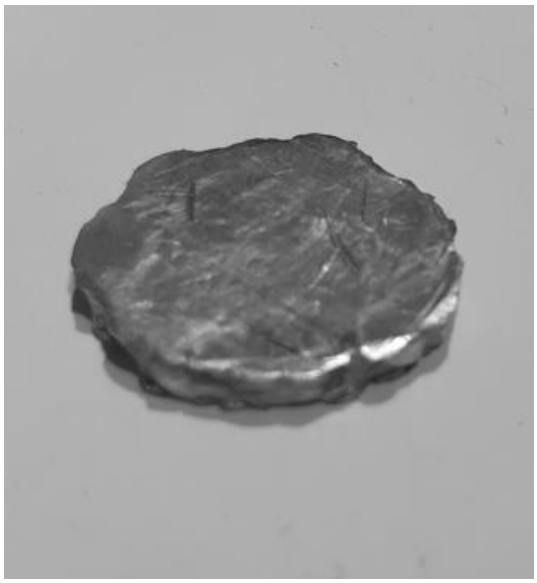

Figure 13. SHPBT sample in soft annealing state after 3-th impact

In order to be able to insert the experimentally obtained data of the material model into standard simulation software, it is necessary to compare the experiment with the simulation. In this case it was compared with ANSYS – Explicit Dynamic.

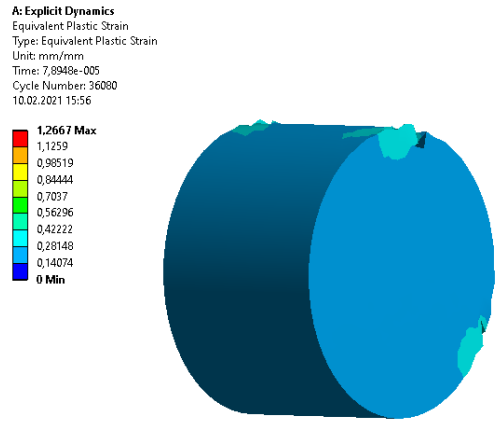

Figure 14. SHPBT sample at a delivered condition in the time of 80 µs after the impact

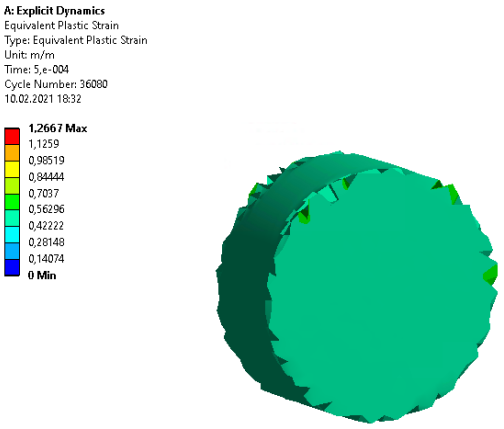

Figure 15. SHPBT sample at delivered condition in the time of 500 µs after the impact

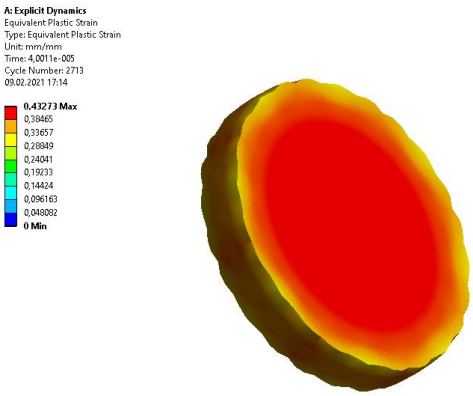

Figure 16. SHPBT sample at a soft annealing state after the impact

The obtained data from the simulations confirm the results of the experiment tests. The Fig. 14, 15 and 16 shows the unevenness of the surface. It might seem that this is due to the inappropriate size of the elements. Similar simulation results were obtained with the smaller elements.

5 CONLUSIONS

The method of split Hopkinson pressure bar test is suitable for higher strain rate (100 to approx. 6000 s^{-1}). In the case of this method, inertial forces, progress of the stress waves and mechanical resonance have an important effect, unlike in the case of the quasi-static tests, where these influences reach negligible values.

SHPBT test was performed with aluminium alloy EN AW 6082 samples under three types' conditions: delivered state, an additional precipitation hardened state and an additional soft annealed state. Both additional heat treatments were performed with a semi-finished aluminium alloy rod in a delivered condition. The results of the experiment show an internal collapse of the material of the sample (depletion of plasticity) at the additional precipitation hardening state at a true strain value of 0.07. In the case of an additional soft-annealed state, the plastic depletion limit occurs at a true strain value of 0.48. If the semi-finished product is additionally heat treated, effects of the additional heat treatment must be taken in mind, as there is a risk of internal cracks, which could have fatal consequences for the endurance of the manufactured parts. Possible unwanted occurrence of these microscopic cracks must be verified by research of the microstructure of the sample.

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