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DYNAMIC TENSION TESTING OF DP600, DP800 STEEL AND AL 6061 T4 ALLOY SHEETS BY MEANS OF ROTARY HAMMER

DYNAMICZNE PRÓBY ROZCIĄGANIA BLACH ZE STALI DP600, DP800 ORAZ STOPU AL 6061 T4 ZA POMOCĄ MŁOTA ROTACYJNEGO

The aim of this research was to apply a rotary hammer to dynamic tension testing and to determine the effect of deformation velocity (ranging from 300 to 1000 s^{-1}) on the stress-strain curves for sheets made from steel DP600, DP800 and alloy Al 6061T4. The costs and the lack of uniform standards, which makes the choice of specimens and deformation conditions and the interpretation of the results affected by the waviness of the elastic wave and its dissipation and reflection difficult, are a serious problem in dynamic testing. Thanks to an upgraded measuring system and fixtures minimizing the slip of the sheet replicable results were obtained for a wide range of deformation velocities, with relatively small oscillations at the start of deformation. The above materials were subjected to tension tests in a testing machine at strain rates of 0.0001 and 0.01 s^{-1} and to rotary hammer tests at strain rates of 300, 500 and 1000 s^{-1}. On this basis the effect of deformation velocity on stress was assessed for the tested materials. Owing to the application of a high-speed digital camera the deformations of the specimen measuring base can be precisely determined.
Keywords: dynamic testing, sheet metal, rotary hammer, dual-phase steel, aluminium alloy

Celem prezentowanych badań było zastosowanie zmodernizowanego młota rotacyjnego do dynamicznych prób rozciągania oraz wyznaczenie wpływu prędkości odkształcenia na krzywe rozciągania blach ze stali DP 600, DP800 i stopu Al 6061T4 z prędkościami odkształcenia 300 – 1000 s^{-1}. Poważnym problemem badań dynamicznych, są ich koszty, oraz brak jednolitych standardów, co utrudnia dobór próbek, warunków odkształcania oraz interpretacji wyników zakłóconych falowym charakterem fali sprężystej oraz jej rozpraszaniem i odbiciem. Zmodernizowany układ pomiarowy oraz uchwyty minimalizujące poślizg blachy pozwoliły na uzyskanie powtarzalnych wyników dla szerokiego zakresu prędkości odkształcania ze stosunkowo niewielkimi oscylacjami na początku odkształcania. Dla badanych materiałów przeprowadzono próby rozciągania na maszynie wytrzymałościowej z prędkościami 0,0001 i 0,01 s^{-1} oraz próby na młocie rotacyjnym z prędkościami odkształcenia 250, 500 i 1000 s. Na tej podstawie dokonano oceny wpływu prędkości odkształcenia na naprężenia dla badanych materiałów. Zastosowanie szybkiej kamery cyfrowej pozwala na wyznaczenie dokładnych odkształceń bazy pomiarowej próbki.

1. Introduction

The growing demand for precise material characteristics in a wide range of deformation conditions, including elevated and high deformation velocities, has been generated by the advances in the techniques of investigating and analyzing processes with a high percentage of plastic deformation (forming, impact tests, machining) and by the frequent introduction of new materials [1-3].

In order to able to quickly and accurately design forming tools and processes and optimize them one needs modern support systems, such as expert systems or mathematical modelling (FEM), which in turn require access to accurate and reliable data on the properties of the materials researched [3,4].

Because of the increasing importance of car safety, the regulations concerning the requirements which automotive vehicles must meet are made more stringent and new more rigorous testing standards are introduced. In order to reduce vehicle weight, ever lighter materials are sought. The latter are also to improve the properties of the controlled crushing zones and so greatly contribute to passive car safety. Besides the car body's weight, also its strength significantly determines the extent of the impact affected area. Therefore new high-strength materials, such as HSLA, DP, CP and TRIP steels, are used for the load-bearing structures of modern vehicles [1,5,6].

The average deformation velocity in the considered processes is usually not high but the local conditions may

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vary greatly. For example, in impact tests carried out on structural elements average strain rate is considerably below 100 s^{-1}, whereas local strain rates considerably exceed 1000 s^{-1} [6]. Forming processes are conducted ever faster but also in this case the average deformation velocities are relatively low while locally very high deformation velocities occur. Cutting, die shearing and machining are typical examples of processes conducted at very high strain rates [2].

In the course of sheet metal forming (stamping and impact tests) relatively small areas with large deformations and large areas being in an elastic state or subjected to small deformations occur. When a material model which departs from reality as regards the initial deformations is used for mathematical modelling, considerable deviations in the shape of the surfaces unsupported by tools and large differences in reverse elastic deformations result [7]. This is of particular consequence for the above new materials whose yield point is very high.

The availability of material data for dynamic conditions is limited and the available data are not highly accurate. The reported data from comparative tests on steel DP590 have a stress value scatter of 350-650 MPa at a deformation of 1% and a strain rate 500 s^{-1}. As the defor-mation increases, the scatter of the results becomes considerably smaller [8]. The differences in the results of dynamic tests carried out on the same materials produced in different research laboratories are due to the complexity of such tests, the large number of loading, measuring and result interpreting methods and the lack of standards relating to the test methods, the shape and dimensions of the specimens and the measuring equipment. This means that the reported data cannot be uncritically used [5,9].

The aim of this research was to develop a methodology for dynamic rotary hammer tension tests and to determine the effect of deformation velocity on the properties of metal sheets made of steel DP600, DP800 and aluminium alloy 6061 T4.

2. Dynamic tension tests

Hopkinson bar system as the most popular dynamic testing method

The determination of stress-strain curves for elevated and high strain rate, particularly for metal sheets, has two main limitations: the high strain rate excitation and the problems with recording and interpreting the results [9,10]. The measurement problem can be illustrated by an example of the tension of a steel specimen with a base of 10 mm at a strain rate of 1000 s^{-1}. For the latter deformation velocity the rate of strain excitation is 10 m/s. Then the wave front takes 2 μ s to pass through the specimen, which corresponds to 0.2 % of the nominal specimen elongation, assuming that the passage of the one-dimensional wave is undisturbed. During this time the distribution of elastic deformations in the specimen is inhomogeneous, but the plastic deformations (delayed relative to the elastic wave) show even greater non-homogeneity.

The assumption about the undisturbed one-dimensional wave is a simplification dependent on the structure of the excitation-fixtures-specimen-measuring circuit system. As a result of elastic wave dissipation, reflections, interferences and the (usually direct) measurement, the measured quantities are shifted in time and loaded with disturbing factors. Therefore correct interpretation of the results and filtering out the disturbing signals play a critical role [9].

Conventional mechanical testing machines (deformation velocities below 0.5 s^{-1}), servo-hydraulic testing machines (strain rates up to 500 s^{-1}) and testing systems based on the Hopkinson bar principle (strain rates up to 10000 s^{-1}) are used to investigate the effect of strain rate on the properties of metals [5].

The modified Hopkinson split pressure bar (HSPB) distinguishes itself by not only its strain excitation system, but mainly by its measuring system which attempts to eliminate elastic wave interference [11]. Originally the HSPB system was used for compression tests (Fig. 1). A striker brought to speed by a launcher strikes a transmitting bar, imparting its kinetic energy in the form of a nearly rectangular elastic wave impulse. The impulse is registered by a system of strain gauges, reaches the bar's end face and some of it is transmitted onto the specimen while some of it is reflected. The reflected signal is again registered by the strain gauges. The impulse transmitted onto the specimen causes its deformation and subsequently is transmitted onto a receiving bar and registered by another bank of strain gauges. The lengths of the bars are such that the registered signals do not overlap each other and multiple reflections occur only when deformation ends.

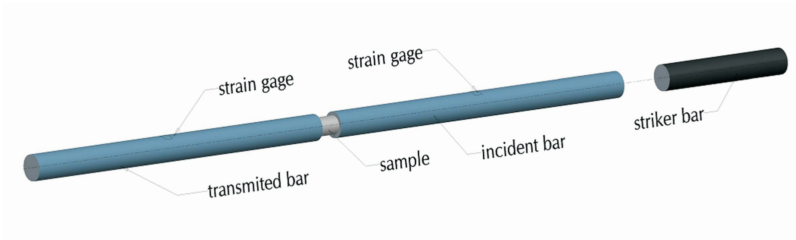

Fig. 1. General idea of splitting Hopkinson bar measurement system (SHPB) for compression tests

Even though excitation sleeves or excitation direction reversers are used for the tension tests, the principle of the test does not significantly change. Nevertheless, the necessary specimen fixtures are an additional source of disturbances causing the dissipation and reflection of the elastic wave [10,12].

The strain gauge sets measure only the strains in the places where the particular gauges are located. On the basis of the measured strains one can determine the stresses in the bar, the force and the displacements of the ends of the bars during specimen deformation, provided that the signals are not disturbed. Due to wave interference on the specimen fixtures, usually oscillatory waveforms are obtained in tensile tests. In such cases, the calculated specimen end displacements and velocity are loaded with a considerable error.

In bar systems, excitation rate is one of the less effectively controlled parameters and as a result, bar end or fixture displacements have to be directly measured and recorded.

Application of a rotary hammer

The aim of using the rotary hammer for dynamic tests is to load a specimen not by an impulse, but a displacement at a nearly constant velocity. A rotary disc with high kinetic energy allows one to easily control and measure rotational speed, set the strike release time and brake the disc to a stop with no difficulty after the test [10].

The RSO-type rotary hammer used in the tests and its schematic are shown in respectively Fig. 2 and Fig. 3. The disc, 600 mm in diameter, is brought up to a tangential velocity of 50 m/s (on the disc surface) by a motor. The originally used rate generator has been replaced with a rotary encoder ensuring the precise measurement of rotational speed. The electromagnetically released claw (retractable into the disc) once it reaches the set rotational speed is ejected by the centrifugal force and strikes the anvil which constitutes the lower specimen fixture. The piezoelectric measuring system has been replaced with a dynamometer in the form of a 6 m long bar 16 mm in diameter, independently attached to the hammer body, with electric resistance wire strain gauges (forming a full bridge circuit) stuck on in the lower part of the bar. The bar is sufficiently long to ensure the passage of the elastic wave in 2.3 ms whereby test signal interference with the returning wave is eliminated. The bridge works with a specially designed wide-band amplifier. The measuring-control system has the form a PC with a USB module of analogue and digital inputs/outputs, with a sampling frequency of 1 MHz, connected to the amplifier, the rotary encoder and the claw release system.

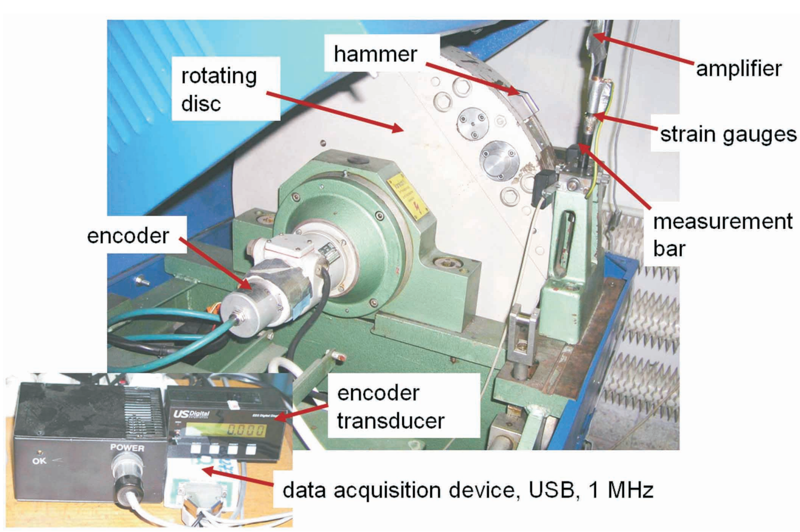

Fig. 2. Rotating hammer with a measurement system

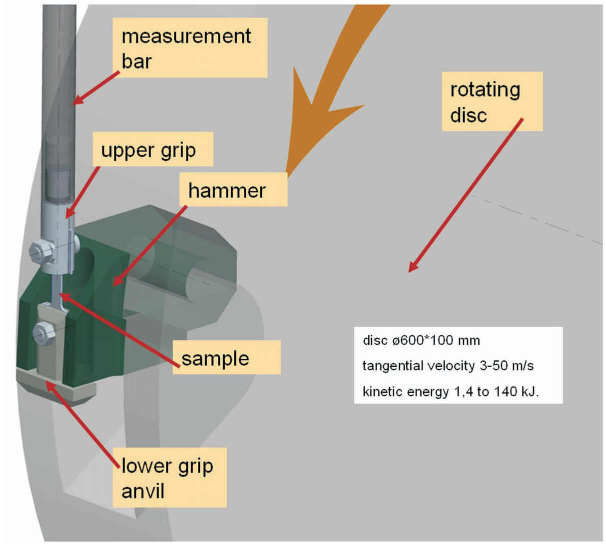

Fig. 3. Rotating disc as a hammer

The rotary hammer operating software allows one to set the speed, automatically release the claw once the set speed is reached and record the results.

Much attention was given to the design of the fixtures for tensioning metal sheet specimens. The lack of rotational symmetry imposes considerable lateral extension of the fixtures and major changes in the cross sections, which may result in severe elastic wave dissipation and deterioration of the recorded results. A preliminary analysis of the upper fixture's reaction to impulsive loading showed (as intuitively predicted) that the best solution would be a fixture in the form of a fork clamping the specimen (Fig. 4a). Such a 125 mm long fixture was made from a bar 16 mm in diameter, identical as that of the measuring bar to minimize changes in the cross section. The drawback of this solution is that it is necessary to make separate fixtures for each metal sheet thickness.

The lower fixture serves also as the anvil which the hammer's claw strikes and in this case major changes in the cross sections are unavoidable. Two types of anvil were designed: a solid one with the fork clampable on the specimen (Fig. 4a), suitable for one metal sheet thickness, and a universal, split one (with minimum weight) also with the fork clampable on the specimen (Fig. 4b,c). The two fixtures were made of steel and titanium alloy TiA16V4, so matched (with regard to tensile tests) as to reduce the difference in Young's moduli between the specimen and the fixture.

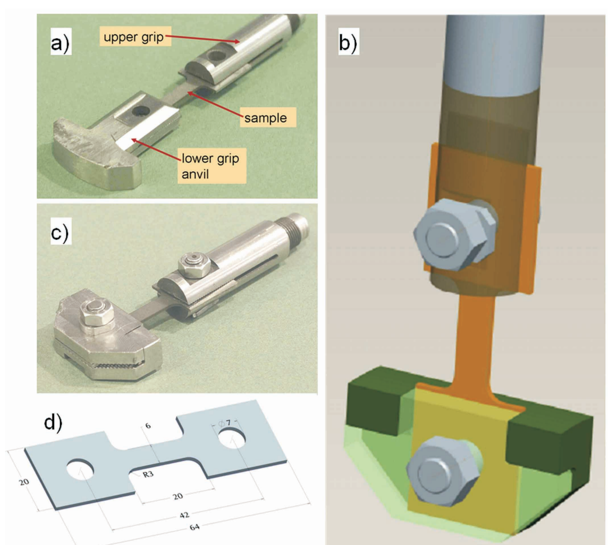

Fig. 4. Grips and a sample used during testing: a – upper grip and long lower grip, b and c – short, universal grip, d – sample

The shape and dimensions of the specimens are shown in Fig. 4d. The dimensions were selected according to the tentative Klepaczko standard [13]. They are well justified since the width is 3-4 times larger than the thickness and the gauge length should ensure uniform distribution of plastic strains. Thanks to these specimen dimensions the rotary hammer is capable of strain rates in the order of 250-3000 s^{-1}. If a shorter measuring base is selected one can expect strain rate higher than 8000 s^{-1}. The lower deformation velocity is determined by the level of rotating disc kinetic energy (Fig. 3). For typical stamping materials the reduction in disc speed (and so in strain rate) during the test at a tangential velocity of 3 m/s amounts to less than 5%, which is considered to be allowable.

3. Results

A 1.25 mm thick sheet made of steel DP600, a 1 mm thick DP800 steel sheet and a 1mm thick sheet made of aluminium alloy 6061T4 were chosen for the tests. The chemical compo-sition of the tested materials is given in Table 1.

The tension tests by means of the rotary hammer were carried out at strain rates of 300, 500 and 1000 s^{-1}. In addition, tests at velocities of 0.001 and 0.01 s^{-1} were carried out using an Instron 5056 testing machine. At least 5 specimens were tested at each of the velocities.

TABLE 1

Chemical composition of tested materials

Material	Chemical composition mass %								
	C	Si	Mn	P	S	Al	Cr	Ni	V
Dp600	0.11	0.41	0.90	0.009	0.005	0.039	0.03	0.05	0.01
Dp800	0.12	0.19	1.5	0.013	0.005	0.045	0.04	0.04	0.01
	Si	Cu	Mg	Fe	Cr	Mn			
6061T4	0.67	0.21	1.01	0.19	0.13	0.09			

The results of the rotary hammer tension tests on steel DP600 at a strain rate of 500 s-1 in the engineering stress-time system are shown in Fig. 5. The high replicability of the results in the whole range of strains, including the total specimen elongation, is noticeable. Characteristic oscillations with two frequencies are visible in the diagram. The higher frequency with small amplitude represents measuring circuit and high gain amplifier noise present throughout the test. The lower frequency represents the stress peak at the start of deformation and the accompanying decaying oscillations.

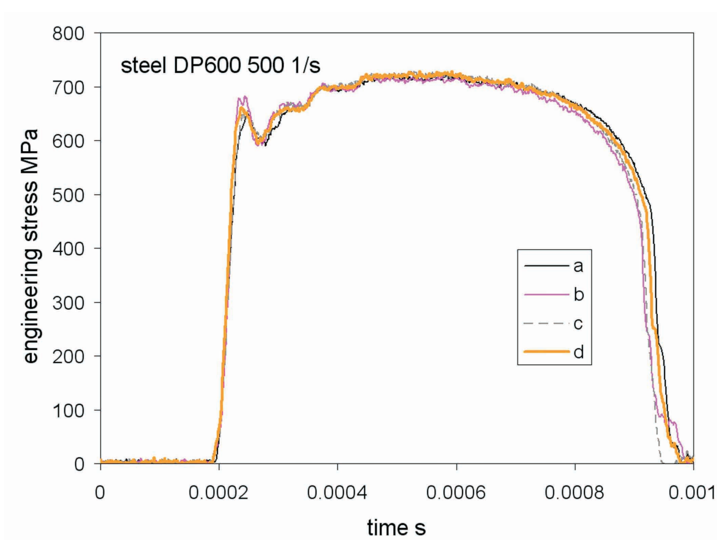

Fig. 5. Tensile curves of steel DP600, strain rate – 500 1/s

The dynamic tensile curves for used strain rates for the DP600 sheet and the 6061 alloy are shown in respectively Figs 6 and 7 and for all the materials – in Fig. 8. It appears from the figures that the character of the stress changes is similar for the tested materials: the original peak and the decaying oscillations become ever more distinct as the velocity increases and their frequency does not depend on the strain rate or the type of material. The wavelength is comparable with the length of the upper fixture, which might suggest that the latter contributes significantly to the generation of interference. Performed tests with different lower grips showed that there are no observable differences between curves for long solid grip and short split one. This observation is consistent with the earlier presumption.

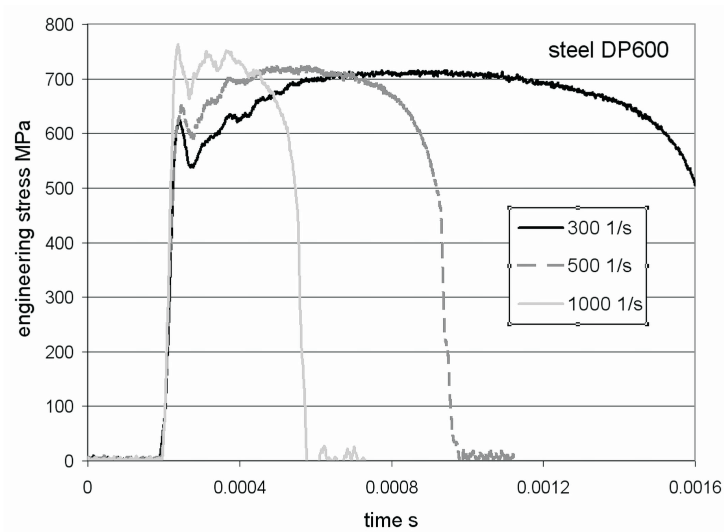

Fig. 6. Tensile curves of steel DP600 for testing strain rates

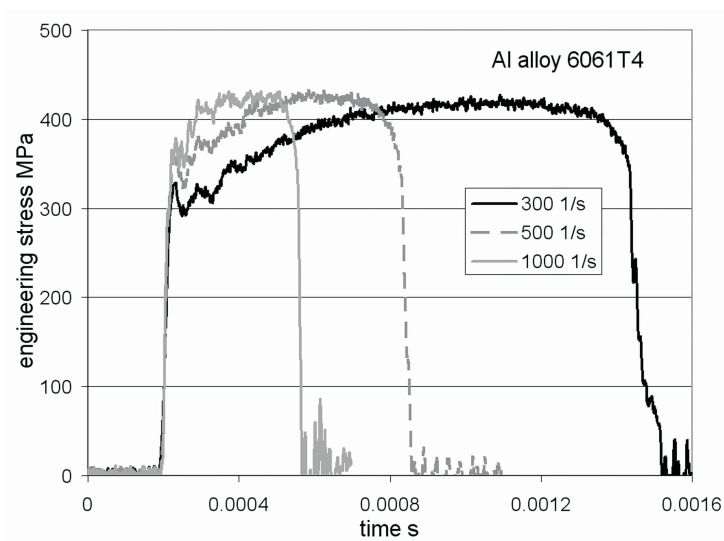

Fig. 7. Tensile curves of aluminum alloy 6061T4 for testing strain rates

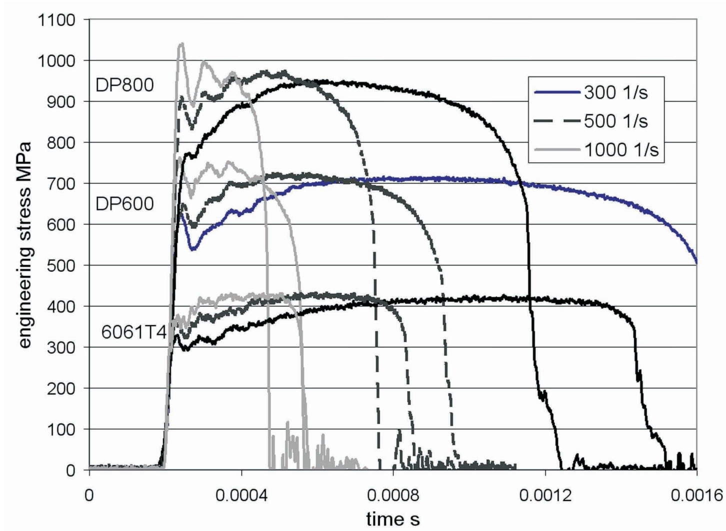

Fig. 8. Tensile curves of tested materials for testing strain rates

The influence of the strain rate on the engineering stress- engineering strain curves is shown in Figs 9-11. The engineering strain for the dynamic curves is calculated from the elongation assumed as the nominal distance covered by the claw, calculated from the latter's nominal velocity. This means that the displacement is not only that of the specimen, but also of the whole excitation and measuring system (the problem will be discussed later in the paper).

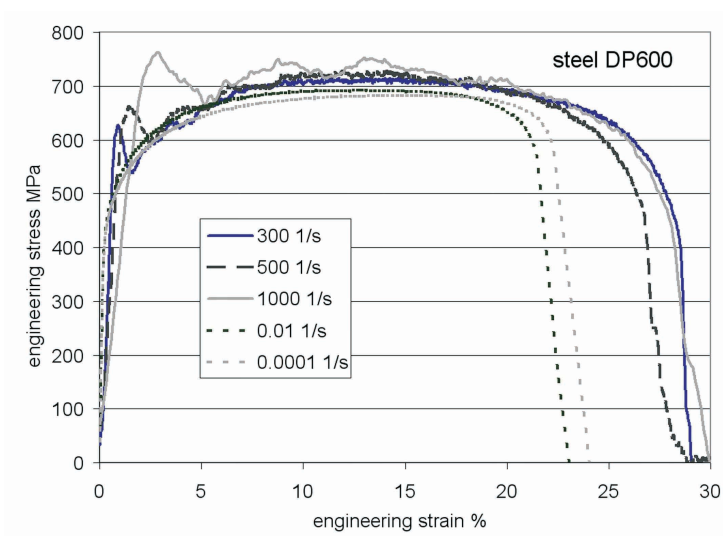

Fig. 9. Stress strain curves of steel DP600 for quasi-static and dynamic strain rates

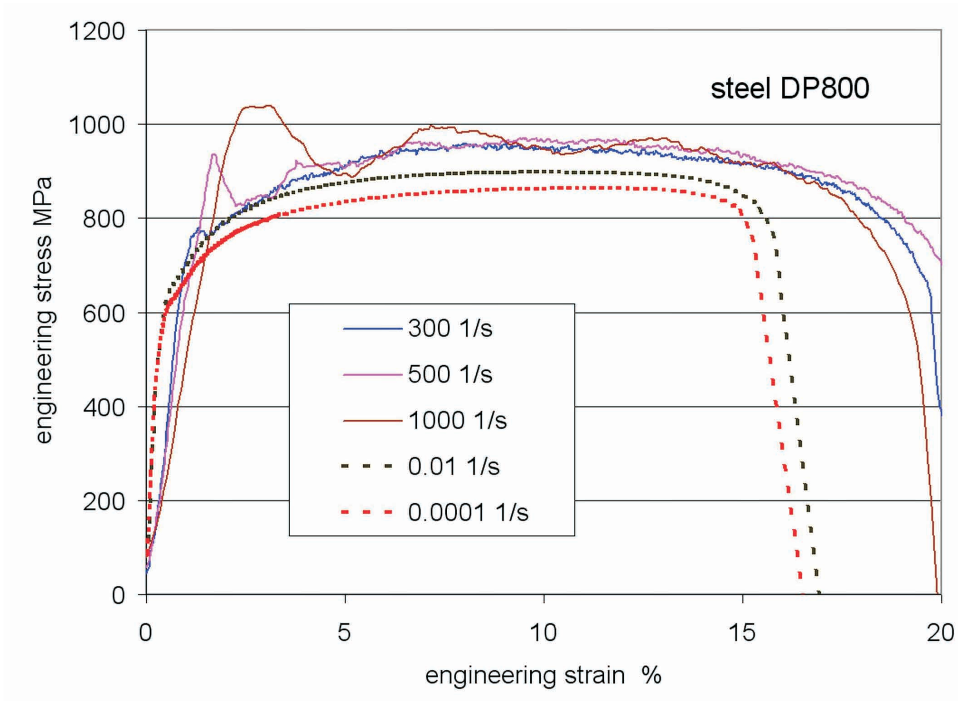

Fig. 10. Stress strain curves of steel DP800 for quasi-static and dynamic strain rates

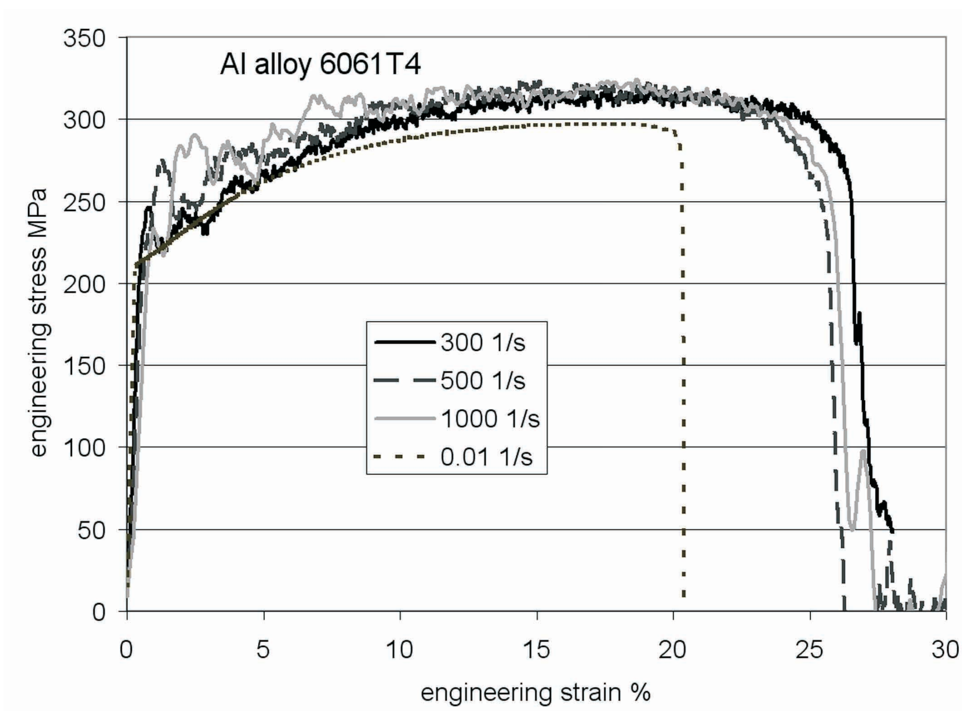

Fig. 11. Stress strain curves of aluminum alloy 6061T4 for quasi-static and dynamic strain rates

Since the sensitivity to the strain rate is different for different strain values, the influence of strain rate on only the maximum engineering stress was determined. The results for the tested materials are shown in the logarithmic system in Fig. 12. The regression line slope values represent the sensitivity to deformation velocity. It is apparent that the strain rate sensitivity m of steel DP600 is low in comparison with that of steel DP800 and that of alloy Al 6061 T4.

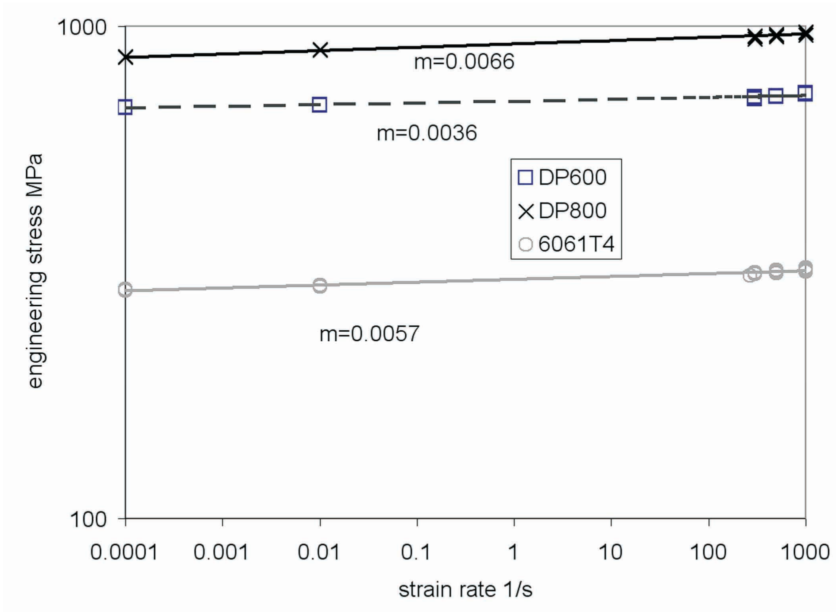

Fig. 12. The effect of strain rate on the engineering stress

In figures 9-11 one notices the differences in the slope of the curves for the initial deformations, a distinct stress peak (suggesting a sharp yield point) and elongations considerably larger than in quasi-static conditions. But for this type of steel no sharp yield point should occur in dynamic conditions, the change in the slope of the curve is not caused by a change in the modulus of elasticity and the curve is much longer than the specimen elongation measured after deformation. This suggests the occurrence of considerable disturbances which should be identified and corrected so that the obtained curves could be accepted as the stress-strain curve. The averaging of oscillations, proposed in some papers [12], could be applied except for the first peak, but also here if the disturbances are not identified, the smoothing of the diagrams can produce incorrect results.

Because of the complexity of the measuring system it is difficult to analyze the elastic wave curve and determine the precise percentages of the particular elements in the total elongation. The disturbing factors can be first approximated by directly measuring the displacements and using the finite element method [10].

Thanks to the collaboration with The Department of Computer-Aided Design in the Institute of Machines Design & Operation at Wrocław University of Technology a high-speed digital camera was employed to film the dynamic tensile test. Three frames from the film of the test in which the lower split grip was used are shown in Fig. 13. Owing to the high camera frequency and proper lighting the images are of very good quality whereby detailed analyses and precise measurements can be made. Although the image resolution is not very high (the specimen is merely 40 pixels wide), thanks to the good contrast it will be possible in the future to use advanced image analysis techniques to determine true strain values [15]. The results of preliminary measurements of the change in the intergrip distance and the gage length elongation are shown in fig. 14, which also shows the nominal distance covered by the claw. The difference in displacement between the claw and the fixtures represents the elastic displacements of the fixtures. The difference between the specimen base and the fixtures shows the percentage of the specimen transitional parts and interfixture specimen displacement in the nominal claw displacement. The result is quite surprising since the specimens were clamped in the fixtures (with incised surfaces) using a large controlled force. The figure explains the observed large difference between the length of the curves and the measured elongation (figs 9-11) and demonstrates that in metal sheet tension tests, displacement correction made solely for the elastic displacements of the fixtures is insufficient. Only the direct measurement of specimen displacements should be the basis for calculating specimen deformations.

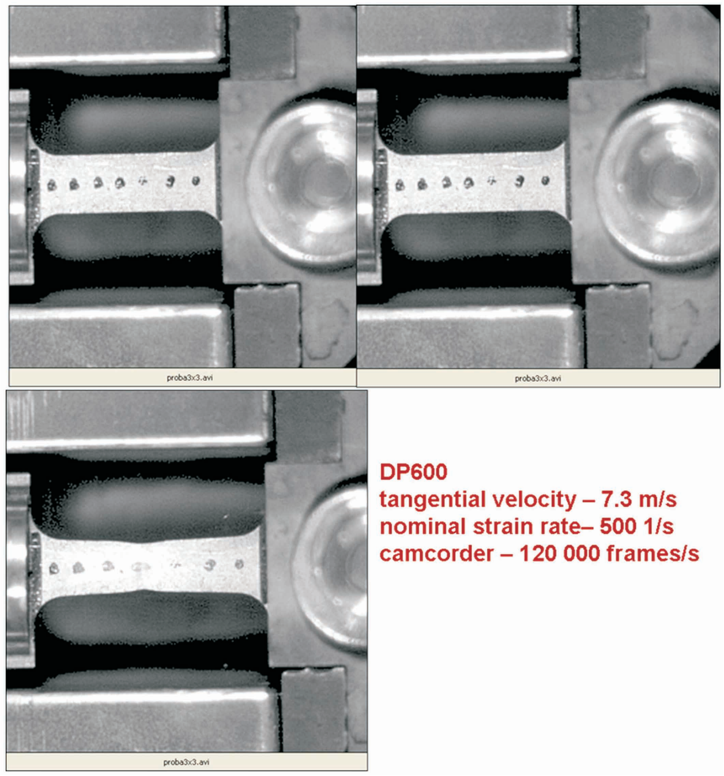

Fig. 13. Example of frames recorded by the fast camcorder

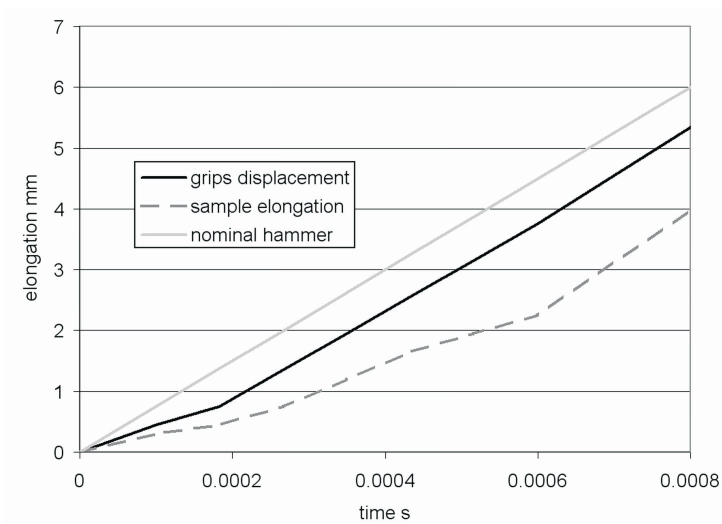

Fig. 14. The nominal hammer displacement, relative grips displacement and elongation of the sample gage length

The film showing in slow motion the course of tension revealed the successive stages of the tension process: the contact of the claw with the anvil, the deformation of the lower fixture, the beginning of deformation of the specimen and the initiation of deformation of the upper fixture. One can also observe the slipping of the specimen out of the fixtures. By applying image analysis (DIC) to such photographs it will be possible to replace the quality assessment with the precise measurement of averaged elongation and to determine the strain pattern on the specimen's surface as well as the local strains.

Thanks to the use of the upgraded rotary hammer combined with image recording by a high-speed camera one can obtain dynamic stress-strain curves and accurately determine the distribution of strains on the specimen's surface. The corrected, accurate strain values are the basis for determining work-hardening curves. The tensile forces are determined quite accurately, except for the initial range of strains. The tensile force for this range will be corrected using the finite element method.

4. Conclusions

The rotary hammer enables dynamic tension at a velocity of 3-50 m/s (250-3000 s^{-1}). Because of the disturbances due to the wave nature of the excitation, the stress-strain curves need correction as regards both the elongation and the force. The mode and reproducibility of specimen fixing in the fixtures have a significant bear-ing on the course of the tension test. Thanks to the application of the high-speed digital camera the deformations of the specimen can be precisely measured and the strain pattern on its surface can be determined.

The directly recorded stress-strain curves allow one to assess the effect of deformation velocity on stress for only larger deformations.

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