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Dynamic properties of 7000 - series aluminum alloys at large strain rates

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ABSTRACT

This paper presents test results of mechanical properties of EN AW-AlZn5Mg1Zr and EN AW-AlZn5Mg1,5CuZr aluminum alloys for various tensile strain rates. Static tests were conducted with the use of MTS 810.12 tension test machine, and dynamic tests - with RSO rotary impact test machine. The work was aimed at determination of effects of strain rate and notch geometry of specimens on their material mechanical properties and damage mechanisms.

Keywords: High resistance aluminum alloys; Dynamic characteristics; Analysis, RSO rotary impact

INTRODUCTION

The 7000 - series aluminum alloys have been commonly used in shipbuilding industry worldwide [1, 17]. Such properties as low specific weight, amagnetism, good corrosion resistance and high strength make ship designers and production engineers willing to apply the alloys as wide as possible [2, 15, 17]. Ships built of the alloys are subjected to dynamic (impact) loads during operation and therefore to know both static and dynamic properties of the alloys is necessary. Moreover, naval ships, due to their functions, are exposed to action of enemy dynamic weapons. Hence to properly select structural materials the designers and production engineers should know their properties in a wide range of strain rates.

Strain rate under dynamic load changes strength properties of structural materials [3, 4, 19, 20] including aluminum alloys [5, 15, 16, 18]. Static and dynamic characteristics of the tested materials have been determined to assess their properties at strain rates changing from quasistatic one to V_{max} = 40 m/s.

Many contemporary military engineering constructions contain local material discontinuities in the form of notches exposed to effects of intensive short-lasting loads during operation.

In this paper are presented dynamic characteristics of 7000 - series aluminum alloys commonly used in shipbuilding industry. The tests were aimed at determination of effects of strain rate and notch geometry of specimens on their mechanical properties and damage mechanisms in fracture zone. Geometrical notch effect is usually revealed under fatigue loads [17, 18]. The problem of behaviour of notched specimens under dynamic pulse loads at changeable strain rates has been left still open.

Strain rate is a crucial factor which affects value of material yield point. In Fig. 1 for example the curve 1 corresponds to tensile strength test of non-alloy steel of 0.2% C content at the static strain rate $\dot{\varepsilon} = 10^{-2}\ s^{-1}$, and the curve 2 – to tensile strength test of the specimen of the same material at the dynamic strain rate $\dot{\varepsilon} = 10^{-2}\ s^{-1}$.

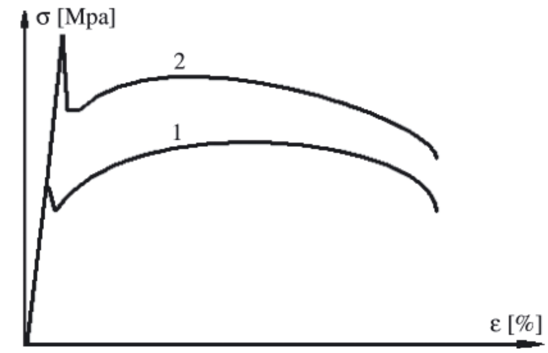

***Fig. 1.** Diagrams of the stress-strain relations: σ = f(ε):*
***1)** for static strain rate, and **2)** for dynamic strain rate, [6]*

Under dynamic load, value of acting force depends both on mass and speed of hiting body and specimen's strain rate [6, 7].

A way of action of blast energy to ship structures depends on distance and power of blast source, and the action may be direct (contact) or intermediate one (non-contact). In both the cases a shock wave is generated (shock wave pressure pulse), which affects both the above-water (in air) and under-water parts of ship hull. a way of propagation of shock wave in the two media, i.e. air and water, is different. In the presented investigations energy of rotary impact machine claw (Fig. 2) is deemed representative for action of air pressure pulse, and its short time to failure of specimen is most similar to action of explosion- generated shock wave pressure on to ship structure [3, 8].

TESTING METHOD

The tests were performed on plate specimens made of EN AW-AlZn5Mg1Zr (7108, PA47) [21] and EN AW-AlZn5Mg1,5CuZr (7015) [21] alloys obtained from two heats of different chemical composition. The chemical compositions of the materials are given in Tab. 1 and 2. From the plates the following specimens were prepared for static and dynamic tensile tests:

- plain specimens;
- „V"- notched specimens
- „U"- notched specimens.

From the tested materials were made the specimens of the forms presented in Fig. 2, intended for static and dynamic tensile tests. The direction of cutting from plates the specimens for testing the static and dynamic properties of EN AW-AlZn5Mg1Zr and EN AW-AlZn5Mg1,5CuZr aluminum alloy of heat No.507, was in line with that of plate rolling. To assess the influence of rolling direction on dynamic properties of the tested alloy the specimens of EN AW-AlZn5Mg1,5CuZr alloy of heat No. 635 were cut in perpendicular to plate rolling direction and marked "p".

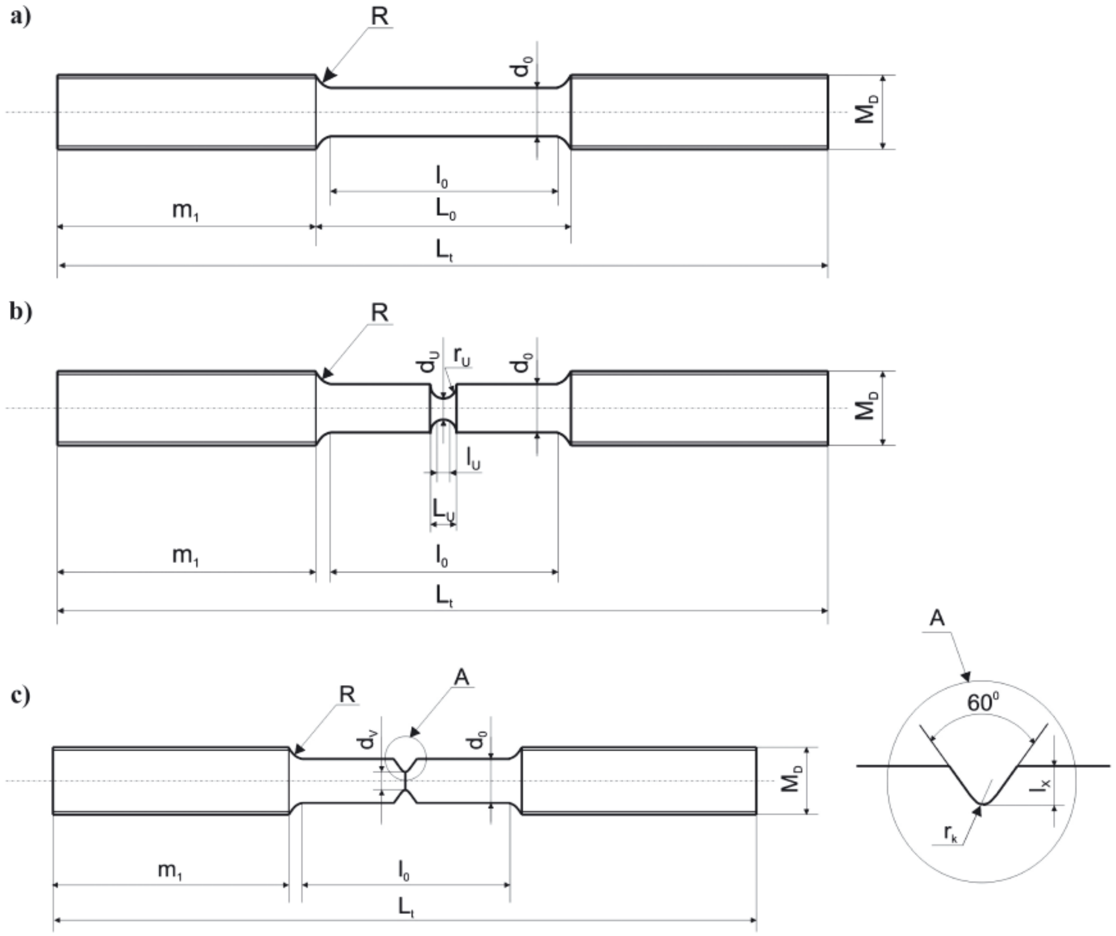

***Fig. 2.** Forms and dimension symbols of specimens made of the tested Al- alloys:*
***a)** plain specimen of circular cross-section, **b)** „V" notched specimens, **c)** „U"notched specimens*

***Tab. 1.** Chemical composition of the tested EN AW-AlZn5Mg1Zr (7108, PA47) aluminium alloy [21, 22]*

Heat treatment state	Plate thickness [mm]	Chemical composition [mass percentage]									No. of batch and certificate
		Mg	Mn	Ti	Zn	Cr	Si	Fe	Cu	Al	
tb	12	1.25	0.18	0.034	5.3	0.14	0.16	0.32	0.05	rest /Zr = 0.04/	2945/485/4 ZN 81 MH-MN-190-06

tb: Solutioning - heating up to 480°C for 50 min, cooling down with hot water to min. 70°C, natural ageing for 0 ÷ 4 days at 20°C, two-stage artificial ageing at - two-stage artificial ageing: 95°C for 8h and at 150°C for 8h

***Tab. 2.** Chemical composition of plates made of EN AW-AlZn5Mg1,5CuZr (7015) aluminium alloy [9, 21, 22]*

No. of heat	Chemical composition [mass percentage]											No. of batch and certificate
	Zn	Mg	Cr	Zr	Ti	Fe	Si	Cu	Mn	Ni	Al	
507	5.13	1.9	0.16	0.15	0.071	0.27	0.15	0.08	0.057	0.006	rest	1086
635	4.81	1.9	0.17	0.12	0.016	0.31	0.21	0.09	0.06	0.006	rest	1085

tb: Solutioning - heating up to 480°C for 50 min, cooling down with hot water to min. 70°C, natural ageing for 0 ÷ 4 days at 20°C, two-stage artificial ageing at two-stage artificial ageing: 95°C for 8h and at 150°C for 8h

The static tensile tests were conducted with the aim of the MTS 810.12 electro-hydrodynamic tension test machine fitted with computer-aided control and recording system, and the dynamic tensile tests - by means of the RSO rotary impact test machine presented in Fig. 3, which has been specially instrumented and used by the Institute of Machine Construction Fundamentals, Polish Naval University.

Owing to the fitting of the rotary impact machine with the original measuring system it was possible to perform measurements of tensile force and displacement rate with simultaneous recording the data by means of the digital oscilloscope. The force was recorded by using a resistance dynamometer and the displacement - by means of an opto-electronic sensor of displacement rate of the traverse fixed to the specimen. The force F and the displacement W was recorded by using the LS-140 digital oscilloscope. The tests were performed for four selected displacement rates: 10, 20, 30 oraz 40 ms^{-1}, which were measured with the use of the opto-electronic measuring system [5].

For the analyzing of microstructure of the tested specimens and their fracture mechanisms was used the Neophot-2 microscope, SSC-DC88P SONY digital camera, and a PC computer fitted with MultiScan v.14 CSS software of MultiScanBase.

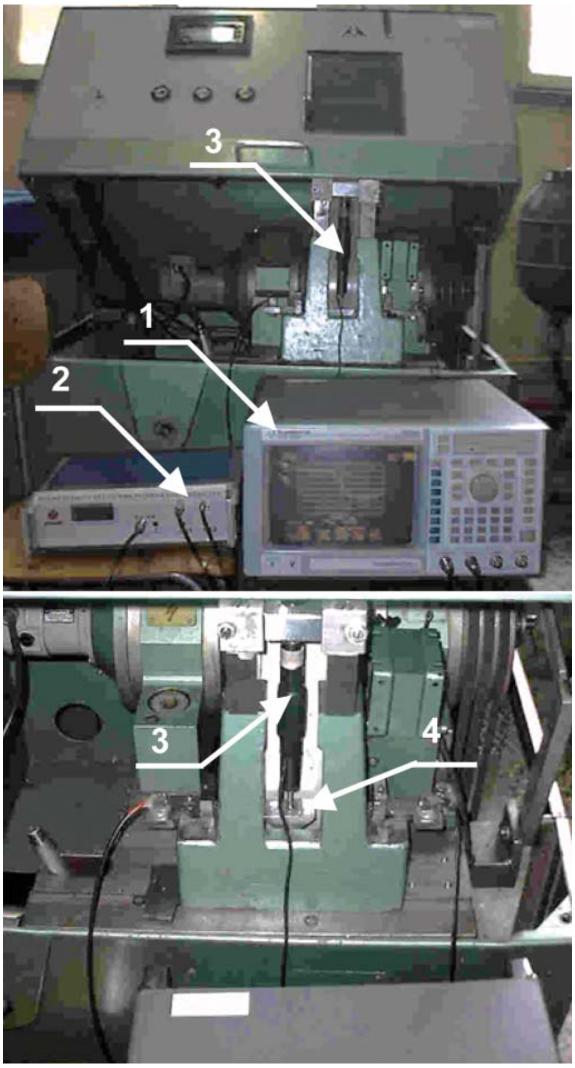

Fig. 3. The RSO rotary impact test machine: traverse– specimen– dynamometer system. The instrumentation of the machine was consisted of: 3) the extensometric dynamometer, 2) the system's amplifier, 1) the LS-140 LeCroy digital oscilloscope. In advance of the measurements calibration was performed of the extensometric dynamometer by using the MTS, and calibration of rotational speed indications of the drum to which the ram claw (4) was fixed

TEST RESULTS

The performed static and dynamic strength tests made it possible to determine characteristic strength properties of the tested alloys. Each of the measurement points in the diagram stands for the arithmetic mean value obtained from three specimens. In Fig. 4 and 5 are presented example time runs of force and traverse displacement recorded during dynamic tension test of the specimens made of the investigated alloys, performed by using the rotary impact test machine. Detailed test results of the tested Al - alloys are given in [10].

The results obtained from the static and dynamic tension tests of the investigated Al - alloys are presented in function of the displacement rate in Fig. 5 through 7.

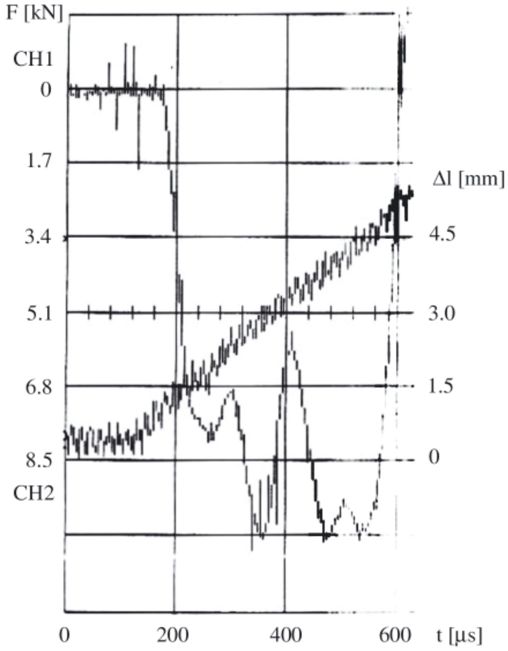

Fig. 4. Time runs of the force F(t), (marked CH1), and the traverse displacement Δl(t), (marked CH2), recorded during the dynamic tension test of a plain alloy specimen of EN AW-AlZn5Mg1Zr, performed with the use of the RSO rotary impact test machine at the tension displacement rate V = 10 ms^{-1}

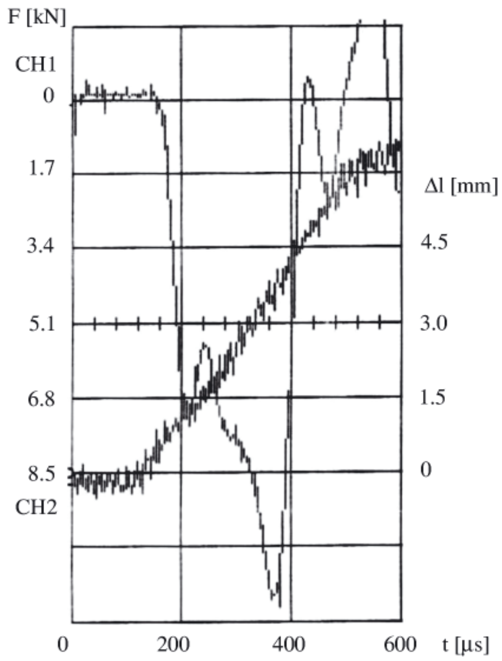

Fig. 5. Time runs of the force F(t), (marked CH1), and the traverse displacement Δl(t), (marked CH2), recorded during the dynamic tension test of a plain specimen of EN AW-AlZn5Mg1Zr alloy, performed with the use of the RSO rotary impact test machine at the tension displacement rate V = 30 ms^{-1}

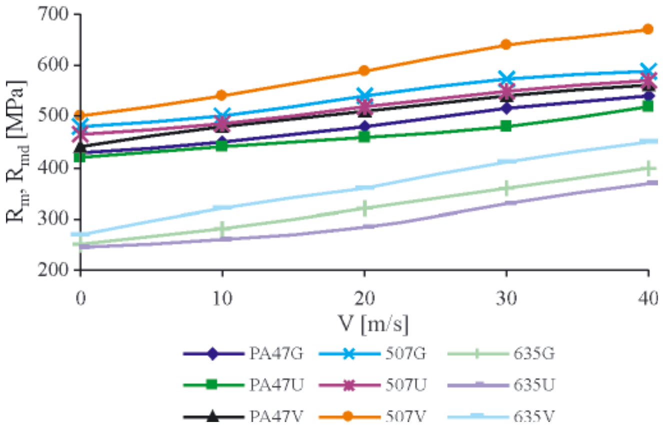

***Fig. 6.** Relation of the dynamic tensile strength R_{md} of EN AW-AlZn5Mg1Zr and EN AW-AlZn5Mg1,5CuZr aluminium alloys in function of the displacement rate V for plain and notched specimens. **Notation:** **PA47** – EN AW-AlZn5Mg1Zr alloy, **507** - heat number of EN AW-AlZn5Mg1,5CuZr alloy, **635** – heat number of EN AW-AlZn5Mg1,5CuZr alloy, and: **G** – plain specimen, **U** – „U"notched specimen, **V** – „V"notched specimen*

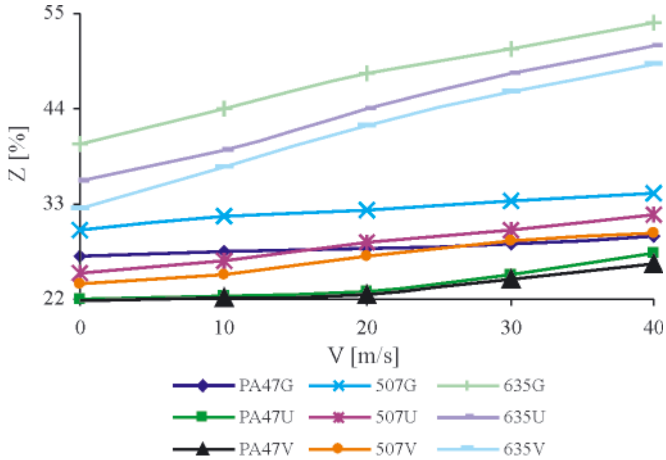

***Fig. 8.** Relation of the percentage reduction of area Z of EN AW-AlZn5Mg1Zr and EN AW-AlZn5Mg1,5CuZr aluminum alloys of heat No. 507 and 635 in function of the displacement rate V for plain and notched specimens. **Notation**: **PA47** – EN AW-AlZn5Mg1Zr alloy, **507** - heat number of EN AW-AlZn5Mg1,5CuZr alloy, **635** – heat number of EN AW-AlZn5Mg1,5CuZr alloy, and: **G** – plain specimen, **U** – „U"notched specimen, **V** – „V"notched specimen*

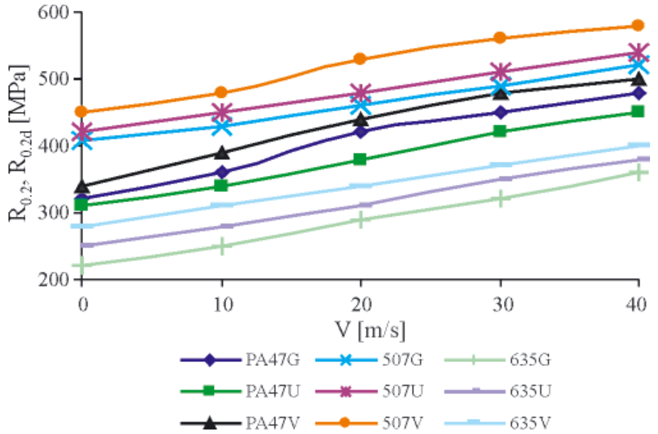

***Fig. 7.** Relation of the tensile yield point $R_{0.2d}$ of EN AW-AlZn5Mg1Zr and EN AW-AlZn5Mg1,5CuZr aluminum alloys in function of the displacement rate V for plain and notched specimens. **Notation:** **PA47** – EN AW-AlZn5Mg1Zr alloy, **507** - heat number of EN AW-AlZn5Mg1,5CuZr alloy, **635** – heat number of EN AW-AlZn5Mg1,5CuZr alloy, and: **G** – plain specimen, **U** – „U"notched specimen, **V** – „V"notched specimen*

ANALYSIS OF THE TEST RESULTS

Static properties of the tested Al- alloys

The static strength tests performed on plain specimens showed that the highest values were obtained for the EN AW-AlZn5Mg1,5CuZr alloy of heat No. 507 for the load direction in line with rolling direction. The smallest values were obtained for the specimens of EN AW-AlZn5Mg1,5CuZr alloy of heat No. 635p, loaded in perpendicular to the rolling direction. The tests confirmed the earlier strength test results of Al-alloys as regards relation of loading and rolling direction. Data from literature sources indicate that values of strength properties of the alloys of the heats No. 507 and 635, obtained from the specimens of the same heat treatment, subjected to loading in line with rolling direction, are close to each other. This results from that the heats are of the similar chemical composition [2] and somewhat higher strength properties, as regards the EN AW-AlZn5Mg1Zr alloy, due to a lower summary content of Zn + Mg [2]. The strength tests confirmed - on the example of the heat No. 635p - the effect of rolling direction on strength

***Tab. 2.** Relative maximum values of the dynamic yield point $R_{0.2d}$ and the dynamic tensile strength R_{md} (at V = 40 m/s) against respective values of the static yield point $R_{0.2}$ and tensile strength R_m for the alloys: EN AW-AlZn5Mg1Zr and EN AW-AlZn5Mg1,5CuZr– heat No.507, EN AW-AlZn5Mg1,5CuZr – heat No.635p, based on tests for plain and notched specimens*

Alloy	Type of specimen	Diameter	R_{md} / R_m	R_{ed} / $R_{0.2}$
EN AW-AlZn5Mg1Zr	plain cylindrical	$5.0^{+0.1}$	1.25	1.50
	with U – notch of 1.9 mm radius	$5.0/ 4.3^{+/-0.1}$	1.24	1.45
	with V – notch of 0.2 mm radius	$5.0/ 4.3^{+/-0.1}$	1.27	1.47
EN AW-AlZn5Mg1,5CuZr -507	plain cylindrical	$5.0^{+0.1}$	1.23	1.27
	with U – notch of 1.9 mm radius	$5.0/ 4.3^{+/-0.1}$	1.23	1.28
	with V – notch of 0.2 mm radius	$5.0/ 4.3^{+/-0.1}$	1.34	1.28
EN AW-AlZn5Mg1,5CuZr - 635p	plain cylindrical	$5.0^{+0.1}$	1.60	1.63
	with U – notch of 1.9 mm radius	$5.0/ 4.3^{+/-0.1}$	1.51	1.52
	with V – notch of 0.2 mm radius	$5.0/ 4.3^{+/-0.1}$	1.66	1.47

properties of Al-alloys. The specimens subjected to tension load perpendicular to rolling direction showed almost two times smaller strength as compared with those loaded in line with rolling direction. Hence a way of arranging the sheet made of the tested alloy on plating of ship hull or its superstructure should take into account direction of operational stresses.

Dynamic properties of AlZn5Mg2CrZr alloy in function of strain rate

In order to assess real impact strength of ship structure it is necessary to know impact mechanical properties of its material.

In Tab. 2 are given values of the dynamic yield point $R_{0.2d}$ and the dynamic tensile strength R_{md} related to respective values of the static yield point $R_{0.2}$ and the tensile strength R_m.

As results from the performed analysis of results of the tests on plain specimens of the alloys in question, the greatest increase of the dynamic tensile strength and yield point at V = 40 m/s, as compared with the static strength, was revealed by the EN AW-AlZn5Mg1,5CuZr - 635p. However, as already mentioned, the alloy showed low strength properties as a result of cutting the specimens from the sheets in perpendicular to rolling direction. The absolutely greatest increase of the $R_{0.2d}$ was revealed by the EN AW-AlZn5Mg1,5CuZr alloy – heat No. 507. The results of the tests are illustrated in Fig. 9.

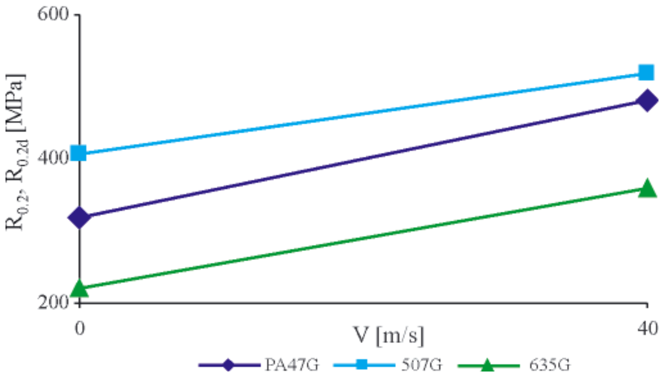

Fig. 9. *The dynamic tensile yield point $R_{0.2d}$ of EN AW-AlZn5Mg1Zr and AlZn5Mg1,5CuZr of the heats 507 and 635 in function of the displacement rate V.* ***Notation****:* ***PA47*** *– EN AW-AlZn5Mg1Zr alloy,* ***507*** *- heat number of AlZn5Mg1,5CuZr alloy,* ***635*** *– heat number of AlZn5Mg1,5CuZr alloy,* ***G*** *– plain specimen,* ***U*** *– „U"notched specimen,* ***V*** *– „V"notched specimen*

Along with increasing strain rate values the plastic properties of the tested Al-alloys reach greater values in contrast to such properties of steel which are as a rule dropping. The tests aimed at determination of effects of notch form and strain rate demonstrated that the greatest increase of the strength properties was revealed by the „V" – notched specimens of the EN AW-AlZn5Mg1,5CuZr alloy – heat No. 507. Moreover, the remaining Al-alloys, of which the notched specimens were made, showed the greatest increase of strength properties. The test results are illustrated in Fig. 10.

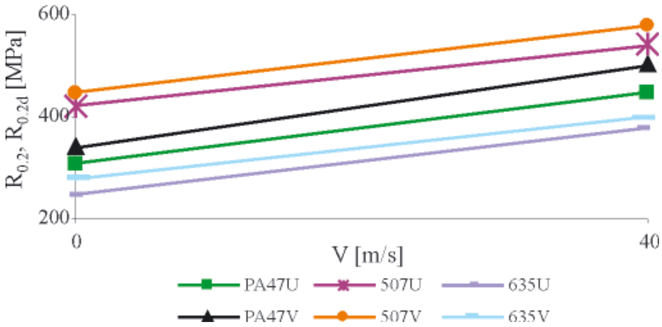

Fig. 10. *The dynamic tensile yield point $R_{0.2d}$ of EN AW-AlZn5Mg1Zr and AlZn5Mg1,5CuZr PA47 alloy – heat No. 507 and 635 in function of the displacement rate and notch form.* ***Notation****:* ***PA47*** *– EN AW-AlZn5Mg1Zr alloy,* ***507*** *- heat number of AlZn5Mg1,5CuZr alloy,* ***635*** *– heat number of AlZn5Mg1,5CuZr alloy,* ***G*** *– plain specimen,* ***U*** *– „U"notched specimen,* ***V*** *– „V"notched specimen*

Character of phenomena which occur under dynamic loads is very complex because of influence of many factors such as: stress wave propagation, stress concentration, temperature, strain rate distribution etc. Increasing strain rate results in increasing resistance to plastic deformation of metals, which leads to yield point, strength and hardness increasing. Notch form influences very much fatigue strength of materials [17, 18]. Under the assumption that plastic flow of metals is based on a thermally activated process which determines motion of dislocations through crystal network containing point defects, tensile strain rate can be usually described in the form of Arhenius equation as follows:

$$\varepsilon = \varepsilon_0 \exp[-\Delta G(\sigma)/kT]$$

where:
$\Delta G(\sigma)$ – activation energy dependent on the stress σ,
k – Boltzman constant,
T – temperature,
ε_0 – material constant.

Making use of the above given relations one can relate the obtained values of yield point and tensile strength to the activation energy ΔG(σ).

Microscopic examinations of non-etched microsections taken from the area reveal occurrence of voids in the microstructure, hence a loss of material continuity, Fig. 11.

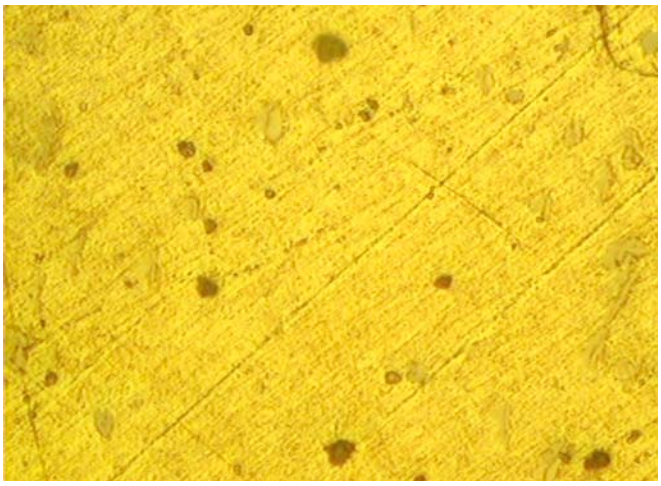

Fig. 11. *Non-etched micro section of a EN AW-AlZn5Mg1Zr alloy specimen under tension; maximum void diameter: 5 µm, mean void diameter: 4 µm*

Material plastic flow is not usually accompanied with a change in material volume. Therefore occurrence of voids may be deemed equivalent to material deterioration or damage process. Such damage may be defined by means of a function dependent on stresses, plastic strain energy, pressure, strain rate and temperature [11].

In the dynamic modelling of damages proper models of process of voids nucleation and grow are necessary. On the basis of metallographic observations of plastically damaged areas, models of spherical voids are assumed for description of plastic damage processes both in neck of tension specimens and specimen of colliding plates, [12, 13, 14].

FINAL CONCLUSIONS

From the performed static and dynamic tests on plain and notched specimens made of EN AW-AlZn5Mg1Zr and EN AW-AlZn5Mg1,5CuZr alloys, as well as the performed analysis of the test results, the following conclusions can be drawn:

1 Rolling direction is of essential influence on static and dynamic mechanical properties of the tested materials.
2. The lowest susceptibility to dynamic loading, this way also to strain rate, was found for the „V"- notched specimens. The „V" notched specimens both of EN AW-AlZn5Mg1Zr and EN AW-AlZn5Mg1,5CuZr alloy revealed higher increase of strength properties than the plain specimens and the „U"- notched ones at increasing strain rate.
3. As a result of dynamic loading an increase of strength indices of the tested Al-alloys was observed as compared with those obtained from static tension test.

The conclusions drawn from the performed static and dynamic tests may be applied to the modelling of dynamic deformation of Al-alloys considered elastic – visco-plastic materials.

Financing

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