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 \( V_{\text{max}} = 40 \text{ m/s} \).

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.

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 \( \dot{\varepsilon} = 10^{-2} \text{ s}^{-1} \), and the curve 2 – to tensile strength test of the specimen of the same material at the dynamic strain rate \( \dot{\varepsilon} = 10^{-2} \text{ s}^{-1} \).

Under dynamic load, value of acting force depends both on mass and speed of hitting 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".

![Diagram showing the forms and dimension symbols of specimens made of the tested Al-alloys:](image)

**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

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

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<thead>
<tr>
<th>Heat treatment state</th>
<th>Plate thickness [mm]</th>
<th>Chemical composition [mass percentage]</th>
<th>No. of batch and certificate</th>
</tr>
</thead>
<tbody>
<tr>
<td>tb</td>
<td>12</td>
<td>Mg 0.16 Mn 0.15 Zr 0.071 Ti 0.27 Cr 0.15 Fe 0.08 Si 0.21 Cu 0.057 Mn 0.006 Ni Al rest</td>
<td>1086</td>
</tr>
</tbody>
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<thead>
<tr>
<th>Heat treatment state</th>
<th>Plate thickness [mm]</th>
<th>Chemical composition [mass percentage]</th>
<th>No. of batch and certificate</th>
</tr>
</thead>
<tbody>
<tr>
<td>tb</td>
<td>12</td>
<td>Mg 0.16 Mn 0.15 Zr 0.071 Ti 0.27 Cr 0.15 Fe 0.08 Si 0.21 Cu 0.057 Mn 0.006 Ni Al rest</td>
<td>1085</td>
</tr>
</tbody>
</table>

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

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

**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 alloy, 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. 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.
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-AlZn5Mg1Zr 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 \(V = 40\ \text{m/s}\)) 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

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Type of specimen</th>
<th>Diameter</th>
<th>(R_{md} / R_{m})</th>
<th>(R_{nd} / R_{s,2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN AW-AlZn5Mg1Zr</td>
<td>plain cylindrical</td>
<td>5.0°/0.1</td>
<td>1.25</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>with U – notch of 1.9 mm radius</td>
<td>5.0/ 4.3°/0.1</td>
<td>1.24</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>with V – notch of 0.2 mm radius</td>
<td>5.0/ 4.3°/0.1</td>
<td>1.27</td>
<td>1.47</td>
</tr>
<tr>
<td>EN AW-AlZn5Mg1,5CuZr -507</td>
<td>plain cylindrical</td>
<td>5.0°/0.1</td>
<td>1.23</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>with U – notch of 1.9 mm radius</td>
<td>5.0/ 4.3°/0.1</td>
<td>1.23</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>with V – notch of 0.2 mm radius</td>
<td>5.0/ 4.3°/0.1</td>
<td>1.34</td>
<td>1.28</td>
</tr>
<tr>
<td>EN AW-AlZn5Mg1,5CuZr -635p</td>
<td>plain cylindrical</td>
<td>5.0°/0.1</td>
<td>1.60</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>with U – notch of 1.9 mm radius</td>
<td>5.0/ 4.3°/0.1</td>
<td>1.51</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>with V – notch of 0.2 mm radius</td>
<td>5.0/ 4.3°/0.1</td>
<td>1.66</td>
<td>1.47</td>
</tr>
</tbody>
</table>
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.

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.

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 \( \sigma \),
- \( k \) – Boltzman constant,
- \( T \) – temperature,
- \( \varepsilon_0 \) – 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 \( AG(\sigma) \).

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.

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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9. Material certificate of AlZn5Mg2CrZr alloy, IMN-OML Skawina nr 4550/91, 336 OML/91.

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