Bending fatigue behaviour of shot peened Al-Li 8090T3 thin plates

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Abstract

In this study, the effect of shot peening on fatigue life of Al-Li 8090T3 thin plates, which are used in the production of structural components of high-speed ships, is investigated. It is shown how various manufacturing procedures influence fatigue life of shot-peened material. Surface cleaning and protecting have a low impact on fatigue life Al-Li 8090, while cold rolling considerably improves the number of cycles that thin aluminium plates can endure. NC machining and surface polishing resulted in significant increase of the fatigue life. The experiment has shown that an adequately chosen shot peening parameters in a combination with favourable manufacturing procedures, like NC machining, may result in an increase of the fatigue life of more than 50 %. It can be concluded that shot peening improves fatigue life of Al-Li 8090T3 thin plates.

Key words: fatigue life, shot peening, Al-Li 8090T3, thin plates, surface condition

1. Introduction

Shipbuilding industry has recently started to consider production of some new types of high-speed ships, which utilize wing-in-ground (WIG) effect [1] for flying on low height above sea surface [2]. The reduction of vessels weight by using light-weight materials is one of the most promising ways to achieve this effect. It is known from the aircraft industry, that aluminium alloys have favourable strength-weight ratios [3]. Moreover, the fatigue properties and corrosion resistance are also very important requirements. Al-Li based aluminium alloys are being used by modern industries for complex structures since the addition of lithia decreases the density and increases the modulus of elasticity. These alloys on average have 10 % lower weight and 10 % higher strength [4, 5]. Al-Li alloys, which are not typical in shipbuilding industry, namely Al-Li 8090, are proposed for fabrication of different structural components of high-speed ships [6]. One of the major demands for this alloy is high fatigue strength because the considered parts of ship's hull will be exposed to significant dynamic loadings [7]. Therefore, it is important to investigate fatigue behaviour of above-mentioned Al-Li alloy and to find ways to improve the fatigue properties.

Today, modern technology offers numerous mechanical surface treatment processes for upgrading various properties of materials [8, 9]. Shot peening is well known as a low-cost process for improving fatigue resistance of many different materials, including high-strength steels, titanium alloys, aluminium alloys and other engineering materials [10–12]. Although the process of shot peening has evolved and become very specialized, it still employs the old principle of pre-stressing to create more durable material. It entails impacting a surface with small spherical shots with force sufficient to create dimples and with enough shots that those dimples overlap. The overlapping dimples from shot peening create a uniform layer of compressive stress at metal surfaces. It is known that nearly all fatigue failures originate at the material surface, but cracks will not initiate or propagate in a compressively stressed zone [13]. Thus, shot-peening

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treatment improves the fatigue strength of components and structure through the creation of compressive residual stresses in the material's surface layers. These residual stresses ensure that a structural component in a service, under alternating tensile loading, would be working at compressive stresses.

The results of shot peening process depend on various parameters: the peening intensity, peening coverage, saturation, shot material, shot size and velocity, shot hardness, type of peening machine and time of peening. Two most important parameters are the peening intensity and coverage [14, 15]. The peening intensity is governed by the velocity, hardness and size of the shots, and by an angle at which the stream of shots hit against the material surface. It is expressed in terms of Almen value [16] and shows the amount of impact energy delivered to the component by the shots. It is measured with special plates, called Almen strips. For different peening treatments, different thickness of the Almen strip is used; the letter accompanying the Almen value indicates this. For instance, Almen A and N values refer to thickness of 33 ± 0.5 and 20 ± 0.5 mm, respectively.

The extent of peening coverage is also very important [17]. Coverage is defined as the uniform and complete dimpling or obliteration of the original surface of the part. Generally, peening to obtain complete coverage or even redundant coverage is preferred to partial coverage. Tests should always be conducted in order to determine the proper intensity and the degree of coverage for each particular part to be peened.

In the present research, the fatigue behaviour of Al-Li 8090 alloy in state T3 is experimentally evaluated according to the shot peening treatment process. Up to date, little or no information is available on the fatigue strength of shot peened Al-Li based alloy 8090 [18]. These results cannot be adopted for thin plates (less than 4 mm) since it is known that the compressive residual stress field (CRSF) of metal surfaces layers is strongly dependent on material thickness [19]. Here, a new investigation was carried out to determine the influence of shot peening on fatigue behaviour of Al-Li 8090 plates with thickness ranging from 1.2 to 4 mm, which are commonly used for production of structural components of fast ships. Hence, this study presents the original experimental results of fatigue behaviour investigation of thin, shot peened, Al-Li 8090 plates. Additionally, an extensive analysis of the most common fabrication methods used in shipbuilding practice on fatigue behaviour is presented.

2. Experiment

The experiment was accomplished through five test series, with specimens in each series prepared in a way to include various actual fabrication conditions of plates, as used in the industry. The first two test series included specimens cut from flat metal plates as they were delivered. Fatigue results of these series were compared for shot-peened conditions for different plate thickness. Subsequent tests included specimens cut parallel and orthogonal to the rolling direction of the plates, in order to investigate the influence of material anisotropy. Polished specimens and specimens with grinded bevelled edges were also tested. Investigation was carried out to determine the effect of deformed plates, bent to radiuses of $R = 1410$ mm and $R = 2820$ mm. Tests were also done on specimens cut from plates of thickness 2.0 mm and then milled with NC milling machine to achieve requested thickness of 1.6 mm.

The primary aim of the first four test series was to investigate influence of various procedure parameters, namely air pressure, nozzle angle and nozzle distance in combination with different surface conditions and plate thicknesses, in order to establish adequate peening parameters for the fifth series. In the fifth series only the 1.6 mm plates were investigated, since they are mostly used in the actual ship structures. Here, fatigue life was compared for peened and unpeened specimens in order to investigate expected benefits of shot peening treatment of thin Al-Li plates.

This study produced comparative data of fatigue life of thin plates regarding different surface conditions (cold rolled, milled, polished, etc.) and different fabrication methods of actual plates (cutting and machining direction). In all tests the influence on fatigue life was determined by measuring number of cycles that specimens have endured.

2.1. Material and mechanical testing

The material tested was Al-Li 8090 in T3 state. The chemical composition of the alloy is given in Table 1. The material was supplied in the form of plates in cold rolled condition with thickness ranging from 1.2 to 4 mm. Mechanical properties of the alloy for different thicknesses, t, are given in Table 2. $R_p0.2$ is yield stress and R_M is the ultimate strength. A is the cross section area of the specimen.

2.2. Specimens

Specimens were cut from plates of size $77 \times 45 \times t$ cm (Fig. 1), using bar saw for light weight alloys on ap-

Table 1. Chemical composition of Al-Li 8090 alloy (wt.%)

Cu	Mg	Mn	Si	Fe	Li	Zr
1.32	0.65	0.001	0.02	0.05	2.37	0.11

T a b l e 2. Mechanical properties of Al-Li 8090 alloy

t (mm)	A (mm^2)	$R_p0.2$ (N mm^{-2})	R_M (N mm^{-2})	Elongation (%)
1.2	24.4 (24.3)	276 (280)	326 (333)	7.2 (9)
1.6	32.4 (32.7)	260 (263)	327 (320)	7 (6)
2	40.3	282	332	9
4	80.6	465	517	12

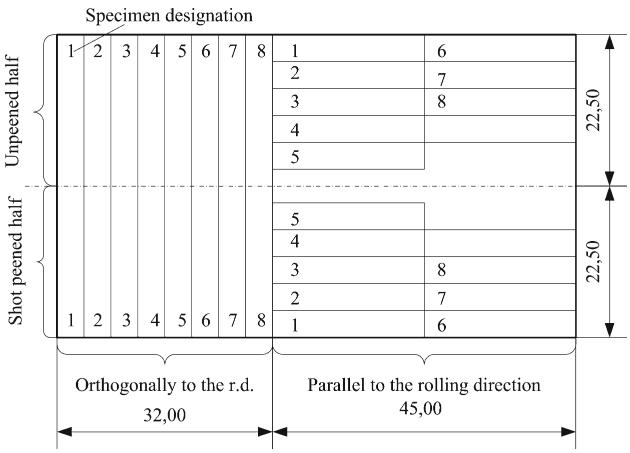

Fig. 1. Plate dimensions (in cm).

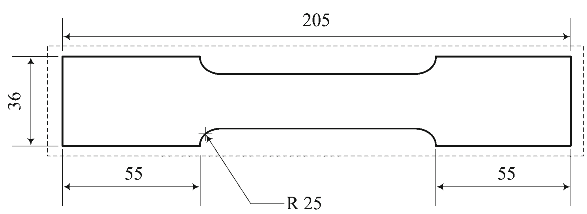

Fig. 2. Dimensions of fatigue test specimens (in mm).

proximate dimensions, shown on Fig. 2 as dashed lines, and then sized to the required measures by milling. The specimen's shape is rectangular with parallel lateral edges and rounded transition area to reduced surface (Fig. 2).

In several testing series, before the peening process was applied, the specimens had been milled on the top and the bottom surface, thus removing 0.2 mm of material on each side. All specimens were examined with fluorescent penetrant in order to find out the possible cracks. Surface roughness of specimens was measured by a profilometer, and it was found to be below 5 μm in longitudinal direction, which was satisfactory for the experiment. All specimens (except in the first series) were degreased in acetone prior to fatigue testing and protected by anticorrosion coating.

2.3. Shot peening parameters

Shot peening was conducted in a closed cabinet designed to safely confine the media and provide proper aiming of the shot blast stream. It was accomplished by using special injector-type system unit for drying treatment. The shots were propelled by an air blast nozzle, made of special carbon steel with diameter of 9.52 mm. Air blast peening is usually used for smaller quantities of parts and when tight tolerances are required, especially in the aerospace sector. Air was supplied to the processing unit at pressure ranging from $p = 0.6$ to 2 bars. The distance between nozzle and work piece was $H = 200$ mm. Velocity along y-axis, i.e. jet travel rate, was $V_y = 400$ mm min^{-1} and velocity of specimens along x-axis was $V_x = 2000$ mm min^{-1}. Average specimen treatment time was 2.5 s cm^{-2}. Jet angle between the shot path and surface being peened ranged from $\alpha = 45°$ to $75°$. The shots were fired to the surface of the specimens at an angle in order to avoid collision with the rebounding balls. Shots with size of $d = 0.6$ mm (S230) were used. Peening intensity was measured using an A2 Almen strip and then recalculated to N2 Almen strip using the relation 1 : 2.5. Coverage rate was chosen to be $P_r = 200$ %. Saturation velocity was $v_s = 1600$ mm min^{-1} and coverage velocity was $v_c = 800$ mm min^{-1}. Average shot flow was 9 kp min^{-1}.

Granulometry analysis was done according to the MIL-S-13165 standard and the shot satisfied all the requirements. Micro hardness of shots was HV 514. Chemical composition of the shot material is given in Table 3.

T a b l e 3. Shot material (wt.%)

C	Si	Mn	S	P	Fe
1.082	0.72	0.6	0.024	0.019	rem.

The effectiveness of shot peening depends in large measure on various factors. Except peening intensity, other factors have been extensively investigated and optimised for various materials including aluminium alloys [20]. Based on probationary made tests and in agreement with CEN and MIL-S-13165 standards, the following peening intensities were used in this study: 0.22 to 0.39 (measured by Almen strips).

2.4. Experimental procedure

The fatigue characterization was performed on specimens cut and machined from the either flat or

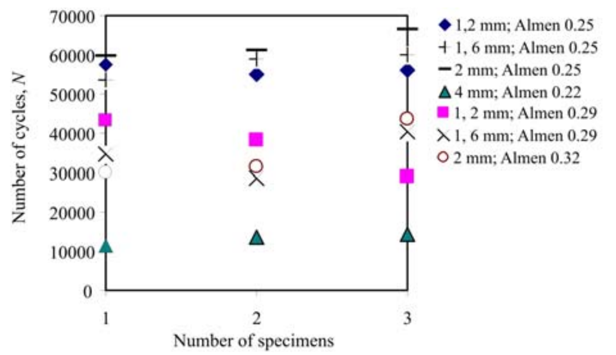

Fig. 3. Results of the 1st test series (A stands for Almen intensity).

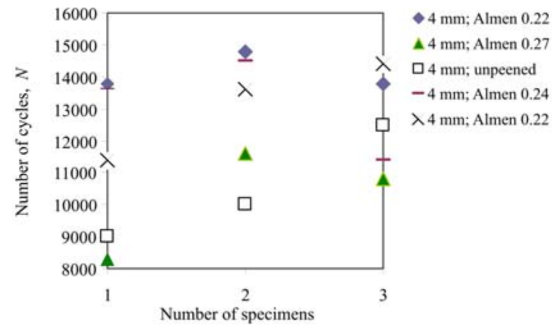

Fig. 4. Influence of peening intensity (2nd series).

deformed metal plates, oriented parallel and orthogonal to the rolling direction. Fatigue tests were performed in a bending loading fatigue machine using servo hydraulic automatic loading system. The range of fatigue machine dynamic loads was 0 to 250 kN with frequency of 60 Hz. Testing environment included standard laboratory conditions at room temperature. Breaking of a specimen was used as a testing criterion. Three or four specimens of each thickness were used for each of investigated peening intensities.

In the first two series, specimens had been cut from flat plates parallel to the rolling direction before the shot peening was applied. The specimens in the first series were made from a 'raw' material, while specimens in the second series were additionally washed over in acid solution and protected by grease coating (tectane). Fatigue testing was accomplished with applied force ratio: $F_{\max}/F_{\min} = 10$. Maximum applied force was taken to be $F_{\max} = 0.8\ F_{\mathrm{M}}$, where F_{M} is the force at the ultimate strength.

In the third series, specimens were prepared and tested in the same way as in the second series with addition of bevelled unpolished edges with $r = 0.5$ mm on each specimen.

In the fourth series, specimens were cut from previously shot peened plates. The plates were firstly deformed to radius $R = 2820$ mm, by cold bending treatment in several passes, using the machine with three rollers. This process additionally hardened the material surface. Prior to peening treatment, the plates were divided in two equal sections of which one was masked (protected from peening) and the other was shot peened. The specimens were cut parallel and orthogonal to the rolling direction. The edges were bevelled (as in the third series) and additionally polished. This resulted in comparison of influence of cutting direction to previously peened and cold bended plates. The fourth test series also included testing of 1.6 mm thick specimens that were made by NC milling from 2.0 mm thick plates. The required thickness of 1.6 mm was achieved by removing 0.2 mm of surface layer on the top and the bottom surface of the plates, i.e. using the milling procedure the cold rolled layer was removed. This resulted in a comparative data for shot peened specimens that had differently machined surfaces.

In the fifth series the specimens were prepared as in the fourth series but they were cold rolled to radius $R = 1410$ mm. The fatigue testing was accomplished with maximum applied force $F_{\max} = 0.6\ F_{\mathrm{M}}$ to investigate low cycle fatigue behaviour of peened specimens. Here, the fatigue life of shot-peened material was compared with unpeened material.

3. Results and discussion

The results of the first and second test series are presented on Fig. 3 and Fig. 4.

The peening intensity has significant influence on peening results (Fig. 3). However, this influence decreases with increased plate thickness (Fig. 4). In case of inadequately chosen peening parameters (high intensity), fatigue life of peened specimens can be lower than fatigue life of unpeened specimens (Fig. 4). This effect is known as overpeening, which results in larger surface roughness and tiny cracks. This can be critical for aluminium plates of small thickness, as it was the case here. The preparation of specimens (cleaning, coating) has very small influence on peening results (Fig. 4). These tests indicated that peening intensity (Almen) should be 0.22 for thin aluminium plates.

Statistical analysis for the first two series was done on a computer. Analysis of variance and regression analysis resulted in definition of all necessary parameters (peening pressure, peening angle and coverage rate) for the following test series.

For a number of degrees of freedom of 16 and adopted confidence interval of 95 %, the table value according to Student's t-distribution is $t_{\mathrm{t}} = 1.75$. Fisher's criterion was used for evaluation of the model. Calculated value of Fisher's number was $F_{\mathrm{r}} = 2.1834$, while table value was $F_{\mathrm{t}} = 3.01$. Since $F_{\mathrm{r}} < F_{\mathrm{t}}$, the mathematical model is correct.

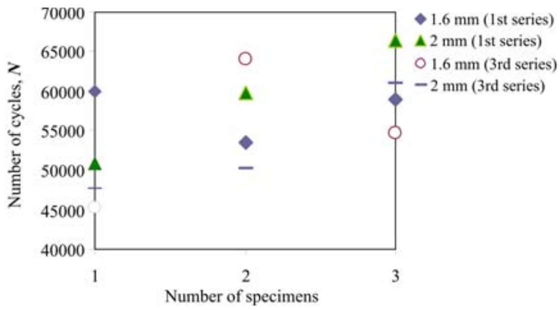

Fig. 5. Results of 3rd test series.

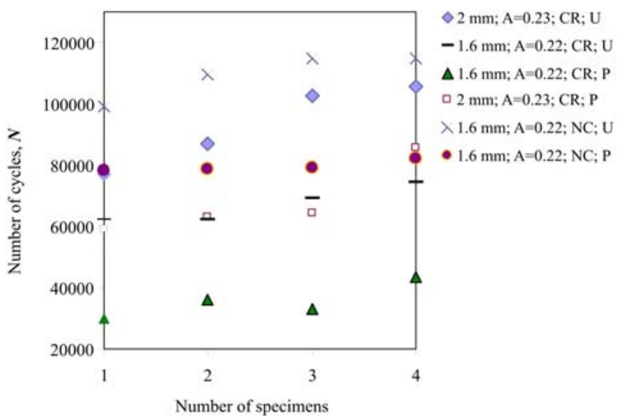

Fig. 6. Comparative data for the 4th experiment series.

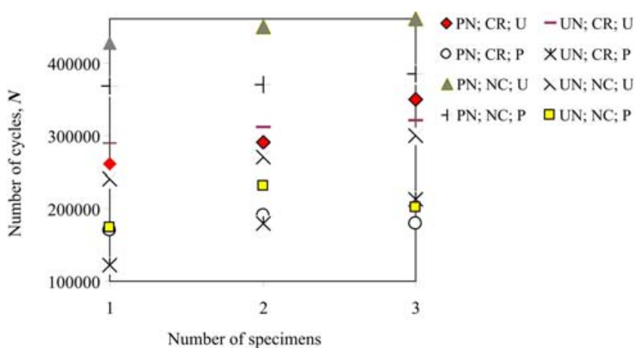

Fig. 7. Comparative data for the 5th experiment series.

No important difference in the results of the 3rd test series was discovered (Fig. 5), compared to previous two test series. Test results from the first three series pointed out adequate shot peening parameters for thin Al-Li plates: Almen 0.22, pressure 0.6 bar, nozzle angle 75° and nozzle distance 200 mm. These peening parameters were applied in fourth and fifth series.

Test results from the first three series pointed out adequate shot peening parameters for thin Al-Li plates: Almen 0.22, pressure 0.6 bar, nozzle angle 75°

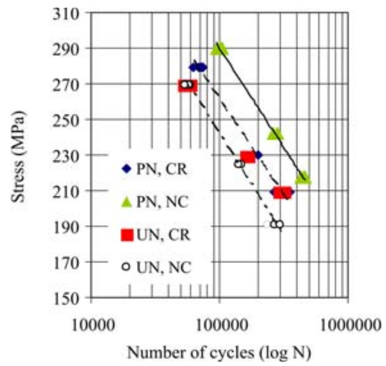

Fig. 8. *S-N* curves for shot peened and unpeened Al-Li 8090.

and nozzle distance 200 mm. These peening parameters were applied in fourth and fifth series.

The results of the fourth series are given in Fig. 6. Plates with thickness of 1.6 mm and 2 mm were tested. NC designates samples obtained by NC milling and CR stands for cold rolling. U stands for specimens cut in parallel direction, P for orthogonally cut specimens and *A* is Almen intensity.

The best results were achieved in the case of NC milled specimens that were cut parallel to the rolling direction. NC machining improves fatigue life in a larger extent than any other manufacturing procedure. In some cases the prolongation of the fatigue life was found to be more than double for NC milled samples compared to cold rolled samples cut in orthogonal direction (Fig. 6). The fourth test series indicated that thin Al-Li 8090 plates should always be NC milled after cold rolling and prior to shot-peening.

The improvement of the fatigue life due to selection of the cutting direction ranged from about 15 to 50 % (Fig. 6). This implies that material anisotropy also influences the fatigue behaviour, but in a smaller extent than applied machining treatment.

All positive experiences from previous four tests were gathered and applied in the fifth test series. Results are presented in Fig. 7. The comparison of peened and unpeened material is given. PN designates shot-peened samples and UN stands for unpeened specimens.

The influence of surface conditions has showed the same trend as in the previous series for peened specimens, i.e. samples that were NC milled, polished and cut parallel to the rolling direction have endured the largest number of cycles. It can be observed that the fatigue life is significantly longer than in previous series, i.e. the shot peening considerably improves fatigue life in case of lower fatigue loading.

The results justify the idea of application of shot peening for improvement of fatigue properties of thin aluminium alloy plates, which is of significant importance for intended purposes.

Figure 8 presents fatigue curves for shot peened and unpeened Al-Li 8090 alloy with thickness of 1.6 mm. The figure also shows how influence of material surface condition is decreasing when moving from LCF to HCF area. It can be concluded that the shot peening treatment is of primary importance for improvement of fatigue life.

4. Conclusions

1. Shot peening improves the fatigue life of Al-Li 8090T3 alloy. The effect of shot peening on fatigue is most pronounced under conditions of high cycle fatigue, but has very little effect at low cycle fatigue.

2. The shot peening strengthening effect on the fatigue behaviour cannot be attributed solely to the induced compressive residual stresses. Material surface condition significantly influences the fatigue life of Al-Li 8090 in low cycle fatigue area.

3. Recommended preparation procedure prior to shot peening of Al-Li 8090T3 thin plates includes cutting parallel to the rolling direction, surface polishing and milling by NC machine.

4. It is very complex to determine the best shot peening conditions to increase fatigue strength of thin plates, because it depends on many variables. It was experienced here that high coverage rate of 200 % can lead to overpeening that may result in a lower fatigue life of peened specimens compared to unpeened.

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