PLASTIC ZONES AROUND NOTCH TIPS AFTER CYCLIC LOADING

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ABSTRACT

The recrystallization method was used to make the plastic zones near the notch tip of SEN specimens visible. The samples were loaded in fully reversed cycles varying the load level and the number of cycles. The results of the tests have shown that the size of the plastic zones regarding the recrystallized area increases rapidly as a function of the cycles. The variation of the radius of the zone parallel to the crack plane is much less. However, the zone sizes in a fatigue process can be different from that observed after a static loading or calculated for the static case. Two Al alloys (AlMg2.5 and AlMg4.5Mn) were studied in the presented investigation. The research work is continued to understand the phenomenon and to study the effect of geometry, materials, etc.

KEYWORDS

SEN specimen, cyclic loading, recrystallization method, plastic zone size.

INTRODUCTION

Plastic strains near the notch or crack tip has been investigated intensively during the last decades. The development of a plastic zone ahead of a notch or crack in a metallic material is a well known fact, which has been demonstrated by both numerical and experimental methods. This great interest can be explained by the strong effect of the plastic zones on the behaviour of the whole component to the contrary of their small sizes compared to the dimensions of the whole part or specimen. This is due to the special location of the plastic zones, because these are located at the site of stress-concentration. Plastic strains within the zone will control the redistribution of stresses in the most dangerous cross section, a phenomena usually regarded beneficial.

Furthermore, plastic deformation absorbes energy, which is significant regarding resistance against crack propagation. However, plastic deformation within the zone changes the material characteristics too and this can lead to not only beneficial but also unfavourable effectes depending on the circumstances. The most important processes from the point of view of engineering practice, which often occure in the plastic zones are crack nucleation, crack propagation and corrosion. These processes can also be combined and can result in a final fracture. To a reliable assessment of the life of a given component the characteristic features of the plastic zone should be known. This includes the size and shape of the zone, the distribution of plastic deformation within the zone, the changing material properties, etc.

To the contrary of the immens work, which has been done in the field of fracture and fatigue, there are still uncleared details regarding the characteristics of the plastic zones. This can be explained by the complexity of the problem, since the parameters of the plastic zones depend on the geometry, material [1], loading history, environment [2] and many others. The plastic zones have been investigated by numerical [3-5] and experimental [6-9] methods as well. Neither of these procedures are perfect. Numerical methods need very exact mathematical descriptions of the material parameters (Young's modulus, yield point, etc.) as a function of temperature, multiaxial stress state and other influencing factors. Instead of that, very often only approximations are applied. The realistic flow curve is often replaced by a straight line: horizontal or with a slope [5], but even in the best case, some factors, as e.g. the influence of the bi- or three axiality of stresses and strains is neglected. Furthermore, the generally applied finite-element calculations deal with an isothrope , homogeneous material, although it is well known that even the elastic deformation varies from grain to grain and the plastic deformation is anything but homogeneous.

Experimental methods are also not much better. All the possible procedures have their limits [7]. Most of them as e.g. hardness measurements, etching, electron channelling, direct optical observation, measuring the distortion of grains are only effective, if the plastic deformation is relatively great (> 2-3%) [1,7]. Others, e.g. Moiré technique, interferometry [2], holography can be used only for small distortions, but are not adequate for large deformations (> 10%). Some methods are only effective on the surface of the specimen (e.g. network, X-ray), others can be used only during the deformation process (thermal photography). Some of them need special materials [10], which do not meet always the other requirements. Considering all the experimental difficulties and the many influencing factors, it is understandable that the published results are in some cases inconsistent.

In the last years more and more work was done to investigate the distribution of plastic strains in fatigue. However, most of the published data refer to the propagating cracks,

where the circumstances are somewhat similar, but not exactly the same as in the case of notches. But the behaviour of the plastic zones ahead of notches is also important, because this is decisive on the first part of fatigue life regarding both crack nucleation and crack propagation processes.. Therefore, the objective of this research was to study the plastic zones near the notch tips and to investigate the influence of repeated loadings.

MATERIALS AND TESTING METHODS

The recrystallization method [11] was chosen to determine the plastic strain distribution in the notch root. This procedure has .also its limitations, but according to the authors' oppinion it is an appropriate method to study qualitatively or even quantitatively the plastic strains [12] .However,. not every material can be applied. Mainly fine grained, relatively clean metals or alloys should be used, which can be recrystallized to coarse grains after a small amount of deformation. (This is the so called "critical deformation").

According to our previous experiences, [12,13] Al alloys meet the requirements, therefore two alloys were selected, the chemical composition and mechanical properties of which are given in **Table 1** and **2.**

Table 1. Chemical composition in wt % of the experimental materials.

Symbol	Material	Mg	Mn	Cu	Cr	Si	Fe	Zn	Ti	Al
A	AlMg2.5	2.2	-	0.01	-	0.1	0.3	0.02	0.02	rest
B	AlMg4.5Mn	4.6	0.62	0.08	0.06	0.25	0.3	0.1	-	rest

Table 2. Mechanical properties of the materials.

Symbol	R_{p02} [MPa]	R_m [MPa]	A [%]	Z [%]
A	103	198	N.M.	59
B	146	308	23.5	41

Both materials were available in the form of 10 mm thick plates. SEN specimens with dimensions given in **FIG. 1.** were machined. After machining the test pieces were stress relieved at 200 C for 3 hours to elliminate the effect of any plastic deformation due to the machining process.

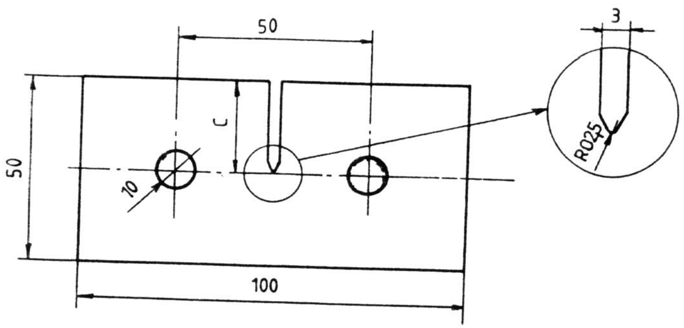


Fig. 1. Shape and dimensions of specimens

The specimens were then loaded in an electro-hydraulic machine in fully reversed cycles (R = -1), load controlled with a loading-rate of 5 kN/s, and a holding time of 2 s at the peak loads. Different load levels were applied, but the nominal stresses did not exceed the yield strength. The ratio of the nominal stresses and the yield strength varied between 0.4 and 0.67. The number of load cycles were also varied. The parameters of the individual tests are given in **Table 3.**

Table 3. Load levels, number of load cycles and the recrystallized areas.

Material	Symbol	σ_{nom}/σ_Y	No. of cycles	Area of recryst. zones [mm^2]	Remarks
AlMg2.5	A1	0.55	1	N.M.	
AlMg2.5	A2	0.55	3	0.83	
AlMg2.5	A3	0.55	10	3.26	
AlMg2.5	A4	0.55	30	10.22	
AlMg2.5	A5	0. 55	43	215.0	Total fracture
AlMg2.5	A6	0.61	1	3.41	
AlMg2.5	A7	0.61	5	4.65	
AlMg2.5	A8	0.61	10	6.15	
AlMg2.5	A9	0.61	13	15.85	
AlMg2.5	A10	0.67	1	3.98	
AlMg2.5	A11	0.67	3	5.43	
AlMg2.5	A12	0.67	6	6.57	
AlMg2.5	A13	0.67	10	226.0	Total fracture
AlMg2.5	A14	0.64	1	1.57	
AlMg2.5	A15	0.64	5	1.77	
AlMg2.5	A16	0.64	10	3.86	
AlMg2.5	A17	0.64	15	6.01	
AlMg2.5	A18	0.64	20	207.0	Total Fracture

(Continued on the next page)

Table 3 continued

Material	Symbol	σ_{nom}/σ_Y	No. of cycles	Area of recryst. zones [mm^2]	Remarks
AlMg4.5Mn	B1	0.41	1	N.M.	Not visible
AlMg4.5Mn	B2	0.41	3	0.09	
AlMg4.5Mn	B3	0.41	5	0.27	
AlMg4.5Mn	B4	0.41	10	3.87	
AlMg4.5Mn	B5	0.41	15	8.30	
AlMg4.5Mn	B6	0.47	1	0.06	
AlMg4.5Mn	B7	0.47	3	0.32	
AlMg4.5Mn	B8	0.47	10	1.63	
AlMg4.5Mn	B9	0.47	15	2.33	
AlMg4.5Mn	B10	0.54	1	0.05	
AlMg4.5Mn	B11	0.54	3	1.23	
AlMg4.5Mn	B12	0.54	6	3.01	
AlMg4.5Mn	B13	0.54	9	N.M.	Total Fracture

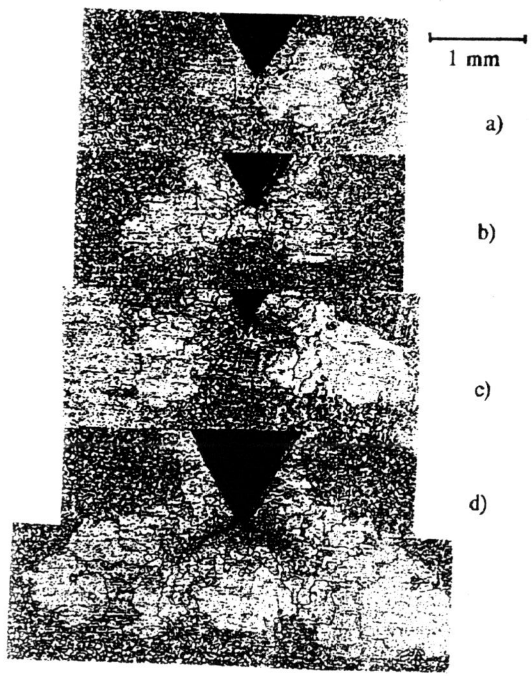
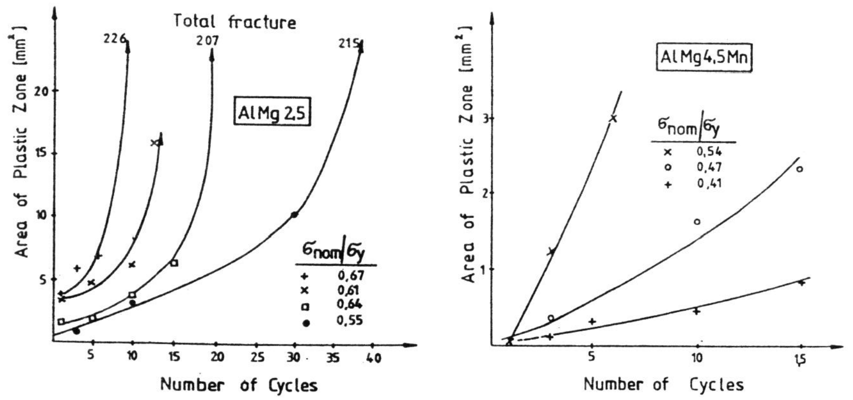


Fig.2. Plastic zones observed on specimens A14 - A17.

After the tests the specimens were heat treated: the alloy A at 500 C for 20 min and the alloy B for 520 C for 40 min, which treatments were selected by previous recrystallization tests. Then a thin surface layer in the notch tip area was removed by electrical polishing and etching (Material A) or by mechanical grinding and macro etching (Material B). The optimal process has been choosen by experience and according to the behaviour of the materials. Plastic zones became visible, as it is illustrated on **Fig.2.** The shape and the size of each zone was determined. The zones are butterfly-wing shaped, as predicted by plasticity theories. The sizes are strongly increasing with the number of load cycles. It should be remembered that the critical deformation in the given cases (materials and heat treatments) was approximately 4%., that means that the real plastic zones, where the local stresses exceed the yield strength are even greater. **Fig.3** and **4.** shows the measured areas as a function of cycles using the load level as a parameter.

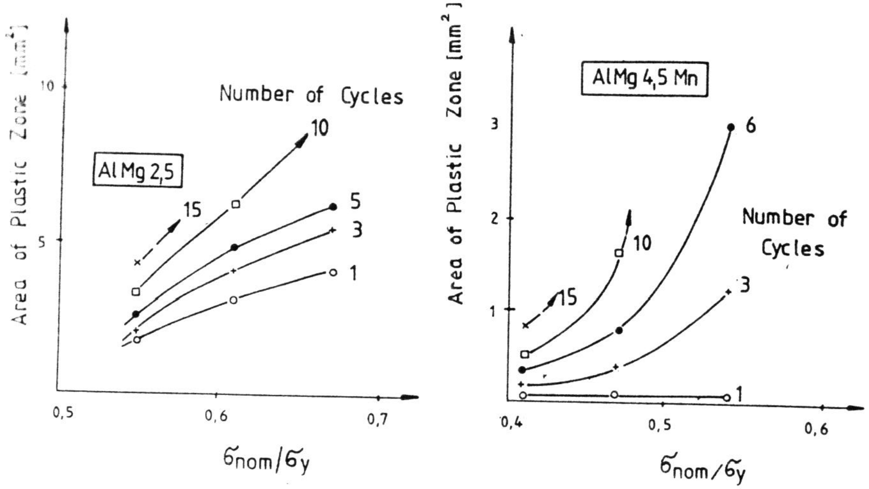


Figs.3 and 4. The area of plastic zones as a function of the number of load cycles.

DISCUSSION

It should be emphasized that the radius of the notch was in our case 0.25 mm, which correspond to the standard impact bending test specimens, but it is far from the almost infinetely sharp crack. Therefore, a direct comparison with the published data is not reasonable. Likewise, the formulae used for calculating the plastic zone size is not very helpful, since they provide generally the length of the radii, but not the area. A more exact analysis will be done soon. However, according to the published data and calculations relating cracks, more concentrated plastic zones were expected also in this case. It is generally accepted that the plastic zones after a fully reversed load cycle are less, than the zones after the first tensile half cycle. The rate between them is 1/4 [3,14]. Therefore, a concentrated zone has been expected with gradually accumulating plastic deformation, which should result a gradually refining in the recrystallised grains. Instead of this, their is no sign of the strain accumulation in the vicinity of notch root before the initiation of small cracks. Fine grains could be observed only after this stage and they are only near the small, nucleated cracks (see the fine grains in Fig. 2c and d). On the other hand the region of medium plastic strain (about 4%) is extending drastically. This tendency was observed in the case of both materials and at every load level.

Comparing the two materials, it was found that the areas of the plastically deformed zones (plastic strain > 4%) differ very much. On the specimens of alloy A much greater zones was observed than on the specimens of alloy B. Low cycle fatigue tests on hour-glass shaped specimens have shown, however, that both materials are of a cyclic hardening type, with the difference that the grade of hardening is much higher of alloy B. Another disagreement of the two materials investigated can be experienced when plotting the results as a function of the loading level (Figs. 5. and 6.).



Figs.5. and 6. Plastic zone sizes a a function of the load levels.

The nature of the two groups of curves is very different. Further tests with other types of materials, with different geometries and load histories are going on. This will help to a better understanding of this phenomenon, clear up the contradictionary observations and lead probably to a theoretical explanation.

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