INFLUENCE OF CRYOGENIC TEMPERATURES AND MEDIA ON THE FATIGUE FAILURE RESISTANCE OF Al - Li ALLOYS

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ABSTRACT

The durability and the fatigue crack growth rate for Al-Li alloy 1460 have been investigated at 300 K (in air), 77K (liquid nitrogen),20 K (hydrogen liquid and gas) and 4 K (liquid helium). As temperature decreases from 300 K to 4,2 K, the durability rises and the FCGR reduces. Besides temperature, the fatigue failure resistance is affected by the state of the coolant. Thus, at 20 K the durability in liquid hydrogen is smaller than in gas. The conceivable mechanisms of the hydrogen interaction with the alloy surface are considered.

KEYWORDS

Aluminium alloys, fatigue crack rate, low temperatures, cryogenic media

INTRODUCTION

The application of Al-Li alloys as structural materials for cryogenic engineering call for detailed studies of their behaviour under cyclic loading at low temperatures. Special attention must be given to the influence of various cryogenic media, in particular, liquid hydrogen, since the alloy is considered here as a material for liquid fuel storage tanks used in aircraft and space systems. The embrittling effect of hydrogen gas at room temperature is well known, but its roles a cryogenic liquid medium in the fatigue fracture of alloys is not yet clear. This work was aimed at studying the characteristics of resistance to fatigue fracture of the Al-Li 1460 alloy at 293-4,2 K incryogenic media-nitrogen, hydrogen and helium, as well as hydrogen gas at temperatures close to 20 K.

MATERIALS AND METHODS

The experimental object was a sheet (h = 6mm) of the Al 1460 alloy, whose chemical composition is given in Table 1. The alloy sheet was treated thermomechanically: hardening from 800 K, 2,1 - 2,9 % deformation, artificial ageing for 24 h at 410 K. The alloy structure has a texture withthe preferential grain orientation /111/, coincide which the direction of rolling. This unrecrystallized structure is typical of Al-Li alloys. The sheet cross-section has a banded structure both in the longitudinal and transversal directions. In the sheet plane the grains are elongated in the longitudinal

TABLE 1 - Chemical composition of 1460 alloy

Contents of elements, % wt						
Cu	Li	Zr	Sc	Fe	Si	Al
2,8	2,15	0,09	0,07	0,08	0,04	rest

direction. The mechanical properties of the 1460 alloys at different temperatures are shown in Table 2.

TABLE 2 - Mechanical properties of 1460 alloy at Low Temperatures.

Temperature, K	**σ_b, MPa**	**$\sigma_{0,2}$, MPa**	**d, %**
293 6,0	540	470	
77 9,0	630	515,0	
20 11,0	700	550	

Experiments were performed using a set up constructed at the Institute for Low Temperature Physics and Engineering of the Ukrainian Academy of Sciences (Abushenkov *et al.*,1986): cyclic tension with the coefficient of load asymmetry R = 0,1, frequency of cycles ν = 30 Hz at 293 K (air), 77 K (liquid nitrogen), 20 K (liquid hydrogen), 4,2 K (liquid helium).To estimate the growth rate, the length of the fatigue crack was measured with an optic long-focused microscope through a viewing window in the cryostat. Employing the method of graphic differentiation of the crack length on the number of cycles, the fatigue crack growth rate (FCGR) (dl/dN) was found and plotted as a function of the amplitude of the stress intensity coefficient ΔK. Fractography as made using an optic MBS-2 microscope, a scanning electron ISM-35 microscope and a transmission electron UEMB-100K microscope.

RESULTS

The results on the cyclic strength of the Al 1460 alloy at 293, 77, 20 and 4,2 K in cryogenic liquids and at 20 K in hydrogen vapours are shown in Fig.1 as σ-N curves. It is seen that at lowering temperature within 293...4,2 K the curves shift towards longer fatigue lives. However, the curve taken at T = 20 K in liquid hydrogen remains practically at the same level as at 77 K; at certain stresses the fatigue life is lower in hydrogen. To find out the reasons and the mechanism of the hydrogen influence, the fatigue life of the alloy in hydrogen gas at 20 K was determined. The sample was cooled in a liquid hydrogen bath and strained cyclically after the cryogenic liquid went down to the lower head of the sample leaving the working part in the atmosphere of hydrogen vapour. The experimental results are given in Table 3 and Fig.2. They suggest that the fatigue life in liquid hydrogen is about half as high as that

in H_2 vapours. To ascertain the stage of fatigue fracture at which temperature and medium manifest their influence, the cryogenic temperature effect upon the fatigue crack growth rate (FCGR) was studied (Fig.3). It is seen that on temperature lowering from 293 to 77 K FCGR decreases in the region of low and moderate rates. At high rates the curves intersect and FCGR grows higher at 77 K than at 293 K (on samples with thickness h = 3 mm). The temperature drop from 77 to 20 K almost does not influence the FCGR at all values of ΔK. A further decrease of temperature to 4.2 K again allows down FCGR. The kinetic diagrams of fatigue fracture (dl/dN - ΔK) at 77, 20 and 4,2 K converge at the point of the critical stress intensity coefficient ΔK_{fc}.

The influence of low temperature and medium upon FCGR is manifested in some changes in the macro- and micromechanisms of fracture. As it mentioned, the macrostructure of the final fracture zone in smooth, samples fractured in air at 293 K has an "obique" fracture at a 45 ^{0} angle towards the loading axis. The samples deformed at 77 and 4,2 K are fractured completely in the plane of normal stresses. However in liquid hydrogen the character of fracture changes. The failure has a complex character: the surface of the crack nucleation is smooth, then fracture has a

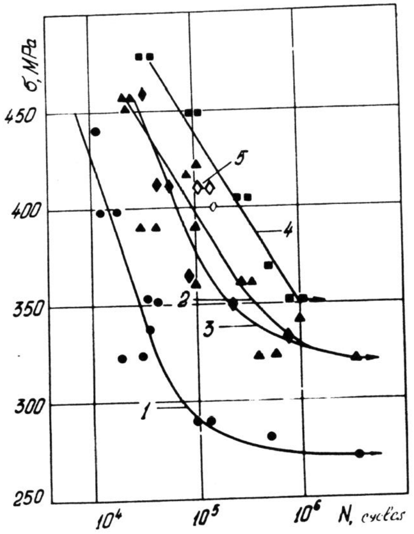

Fig. 1. Fatigue curves of 1460 alloy: 1-293 K, air; 2 - 77 K, liquid nitrogen; 3 - 20 K, liquid hydrogen; 4 - 4,2 K, liquid helium; 5 - 20 K hydrogen vapour.

TABLE 3 - Fatigue life of alloy in liquid and gaseous hydrogen at 20 K

Stress **σ, MPa**	**Medium**	**Fatigue life, cycles**
410	liquid H_2	$4,2.10^4$ $5,6.10^4$ $5,0.10^4$
410	H_2 vapours	$1,1.10^5$ $1,3.10^5$ $1,0.10^5$
400	liquid H_2	$5,5.10^4$ $6,0.10^4$
400	H_2 vapours	$1,5.10^5$ $1,6.10^5$

step-like form, the steps running in short transverse planes.
The electron fractographic studies show variations of the fracture structure depending on temperature and medium. At room temperature the fracture structure is strongly fragmented. The intragrain fracture is seen as delamination in slip planes; temperature and medium. At room temperature the fracture structure is strongly fragmented. The intragrain fracture is seen as delamination in slip planes; there are also cracks along the subgrain bounders, which are parallel to the crack growth direction. A fragmented fracture structure is formed, though the fragments are to a large extent plastically deformed and even the secondary cracks have a rounded shape at the 293 K. The notched samples clearly show facets with striations, the latter forming a regular structure. The alloy studed has secondary cracks coinciding with the striation directions and perpendicular to the plane of crack propagation. At 77 and 4,2 K the fracture also has a fragmented subgrain structure with longitudinal and transverse secondary microcracks. The character of fracture changes in liquid hydrogen. Microfractography of samples fractured in liquid hydrogen revealed a banded structure with smooth regions within it.

DISCUTION

The mechanisms of hydrogen influence on FCGR are studied thoroughly for hydrogen gas at room temperature(Panasyuk *et. al.*, 1987). There are several hypotheses concerning the mechanisms of interaction between hydrogen and the surface of the metal or crack: (i) interaction of hydrogen atoms with dislocation, (ii) relaxed interatomic bonds in the crystal lattice, (iii) creation of nucleation sites of internal pressure, (iv) the formation of hydrides, ets.(Panasyuk *et. al.*, 1987). For the case of liquid hydrogen influence on the FCGR the first mechanism i. e. the interaction between hydrogen and dislocations, seems to be the most probable. The scheme of that interaction proceeds as follows (Panasyuk et. al., 1987). It is assumed that in the plastic zone at the crack tip at $\Delta K < \Delta K_{fc}$ the dislocation elements are in stable equilibrium at the moment preceding fracture. Hydrogen, if available, is trapped by dislocations and brought into the pre-fracture region breaking the equilibrium.

At a certain dislocation piling-up and sufficient amount of hydrogen microcracks are formed in front of the main crack. Hydrogen which is within the microcrack produces internal pressure favourable for a more rapid merging of the microcrack and the main crack. The hydrogen-induced disturbance of equilibrium of dislocation pileups may be due either to the decreased lattice friction stress τ_i or to weakened adhesive forces in the spalling plane. Another mechanism suggests (Nelson, 1988) that the hydrogen atoms bound to a moving dislocation are entrained by it and settle at the lattice defects as the dislocation passes through them. Such defects can consist of precipitation of phases or inclusions with weakened bonds along the interface. Both the

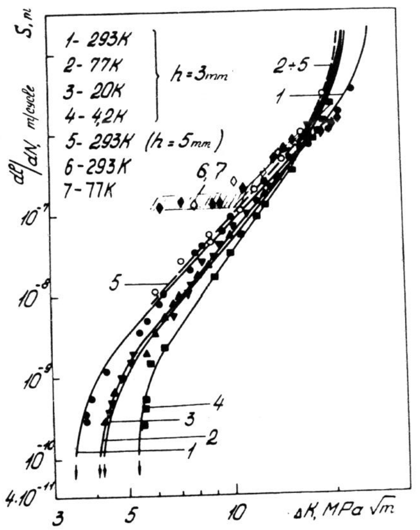

Fig. 2. Fatigue crack growth rate (curves 1-5) and distance between striations (6, 7) to ΔK for 1460 alloy.

mechanisms can operate when the dislocation mobility is high and the hydrogen diffusion rate is low, which is the case at low temperatures.
It is known that in the 1460 alloy after thermal treatment there are precipitation of the intermetallic phases β and T_1 along the grain boundaries. In the process of cyclic

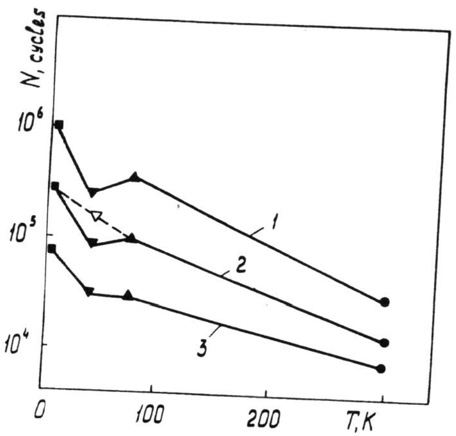

Fig. 3 Fatigue life (N) to temperature for 1460 alloy: a - σ = 350 MPa; b - σ = 400 MPa; c - σ = . 450 Mpa.

deformation in hydrogen, the latter can settle at the inclusions and, as accumulated at the grain boundaries, encourage fracture along the diskshaped grains leading to splitting in the short transverse planes. Besides, within grains there are δ'- precipitations which are cut through by dislocation. This is beneficial for development of planar slip. It is shown (Odergard,1976) that austenitic steels displaying the highest degree of planar slip (low stacking fault energy appear to be most sensitive to hydrogen - induced damage.

Of special interest is the fact that the fatigue life in hydrogen vapour at T = 20 K is higher than in liquid hydrogen. These results may be accounted for by different factors, as follows. The first (Klyavin,1978) supposes diminishing of interaction between a crystal surface and medium as density of medium decreases. It is based on the experiments aimed at estimation of the quality of helium penetration into LiF crystals on their straining in liquid and gaseous helium at T = 4,2 K, as well as on the dislocation density. It is found that the amount of helium penetrating into the sample is higher in the liquid helium medium than in the helium gas. The number of screw dislocations is observed to decrease in the surface layer as compared to the crystal bulk, the decrease being the larger, the higher is the helium density around the sample strained. It is possible to assume that similar situation may occur at interaction of liquid and gaseous hydrogen with the surface of the aluminium alloy cyclically strained.

The second hypothesis relates to the increased fatigue life of the 1460 alloy in hydrogen gas as compared to that in liquid one with lowering viscosity of medium. It is found on results of (Tzou *et. al.*, 1985) in which was shown that the medium viscosity (in experiments in oil at room temperature) essentially affects fatigue crack closure in low strength steel and hence its growth rate. These hypotheses for the case of interaction of liquid and gaseous hydrogen with cyclically strained aluminium - lithium alloy require additional checking

REFERENCES

Abushenkov, I.D., V.V. Chernetsky and V.Ya.Ilyichev (1986). A set up for fatigue tests at low temperatures. Zav. Lab., No.5, 119-120.

Klyavin, O.V. (1978) *Physics of Plasticity of Crystals at Helium Temperatures*, Nauka, Moscow.

Nelson, G.G. (1988). In: *Hydrogen embrittlement* (K.L.Brighten, eds.), pp.256-333. (Metallurgia, Moscow).

Odergand, B.C.(1976). In: *Effect of Hydrogen on Behaviour of Materials* (A. Thompson and M. Berdtein), pp.116-125. AIME , New York.

Panasyuk, V.V.,A.E. Andreikiv and V.S.Kharin (1987). Model of crack growth in deformed metals under hydrogen influence. FKhMM, **23**, No.2, 3-17.

Tzou, J.J.,S. Suresh and O.Richie (1985) Acta Metall., **33**, No.1, 105-117.