

Josef Zapletal – Stanislav Vechet – Jan Kohout – Petr Liskutin \*

## FATIGUE LIFETIME OF 7075 ALUMINIUM ALLOY FROM ULTIMATE TENSILE STRENGTH TO PERMANENT FATIGUE LIMIT

*The aim of this paper is to study fatigue behaviour of 7075 aluminium alloy at room temperature for both important directions (longitudinal as well as transversal) with respect to the direction of forming. Smooth test bars were subjected to symmetrical push-pull loading at stresses which cover the whole range of lifetime from UTS to permanent fatigue limit. The results are presented above all as S-N curves fitted using suitable regression functions which lead to precise and reliable determination of fatigue limits.*

### 1. Introduction

Age-hardened aluminium alloys containing Zn, Mg and Cu belong to structural aluminium alloys with the highest strength. They are usually applied for highly loaded structural details in aircraft, automotive and motorbike industry. These details cannot be welded because due to high predisposition to crackability at higher temperatures those alloys are considered to be unweldable. Studied aluminium alloy marked according to ASTM as 7075 is a typical representative of the mentioned alloys [1, 2]. Although the fatigue properties of 7075 alloy were already studied, e.g. [3-5], only rarely the tests were performed for a number of cycles to fracture higher than  $10^6$  [5]. The contribution of the present paper consists in a complete study covering the whole meaningful range of cycle numbers to fracture from UTS to more than  $10^8$  cycles.

### 2. Experimental

Test bars for tensile as well as for fatigue tests were made of 7075 aluminium alloy delivered as formed rectangular sections with cross-section of  $70 \times 16$  mm by Alcan Decin Extrusion, limited company. Delivered sections were heat treated into T6 state, i.e. by artificial ageing during 4 to 6 hours at temperatures of 160 to 180 °C. Chemical composition determined by the corresponding standard is given in Table 1.

For tensile tests the bars of 6 mm in diameter and of 30 mm in nominal length were used, ended with threaded heads and loaded at a strain rate of  $6 \times 10^{-4} \text{ s}^{-1}$  at a PC controlled TiraTest 2300 testing device. Strain of bars was measured with an extensometer having a base length of 30 mm.

For fatigue loading the test bars of 6 mm in diameter and of 12.5 mm in nominal length with threaded heads were used for low-cycle as well as for high-cycle region. Strain was measured with an axial extensometer with a base length of 12.5 mm. All tests (tensile and also fatigue tests) were performed at room temperature.

All fatigue test bars were loaded in the regime of controlled force with sinusoidal symmetrical push-pull loading cycle (parameters of loading cycle asymmetry were  $R = -1$ , i.e.  $P = 1$ ). For fatigue tests different devices and different frequencies were used. In a low-cycle region a servohydraulic PC controlled Instron 8801 machine was used at a loading frequency of 5 Hz for stress amplitudes of 300 MPa or higher and at a frequency of 30 Hz for stress amplitudes of 250 MPa or lower. In a high-cycle region a high-frequency Amsler HFP 1478 pulsator was used at loading frequency of 144 Hz. While the servohydraulic machine can work at any chosen frequency lower than the limit frequency of the machine, the frequency of the resonant pulsator as the natural frequency of

Prescribed chemical composition of studied aluminium alloy

Table 1.

Element	Zn	Mg	Cu	Si	Mn	Cr	Ti	Al
[wt. %]	5.1 ÷ 6.1	2.1 ÷ 2.9	1.2 ÷ 2.0	max. 0.4	max. 0.3	0.18 ÷ 0.28	max. 0.2	rest

\* Josef Zapletal<sup>1</sup>, Stanislav Vechet<sup>1</sup>, Jan Kohout<sup>2</sup>, Petr Liskutin<sup>1</sup>

<sup>1</sup>Institute of Materials Science and Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Brno, Czech Republic,

\*E-mail: Pepa.Sanguis@centrum.cz

<sup>2</sup>Department of Mathematics and Physics, Faculty of Military Technology, University of Defence, Brno, Czech Republic

an oscillating system is fully determined by the stiffness of the test bar.

### 3. Results

#### 3.1 Static tensile tests

The results of static tensile tests (proof stress  $R_{p0.2}$ , UTS  $R_m$ , elongation to fracture  $A_5$  and reduction of area  $Z$ ) are given in Table 2 for both the directions: longitudinal (L) as well as transversal (T). Also Young's modulus values  $E$  are added. Each presented value is an average of three values corresponding to three tested bars.

Static mechanical properties of studied alloy together with Young's modulus Table 2.

Direction	$R_{p0.2}$ [MPa]	$R_m$ [MPa]	$A_5$ [%]	$Z$ [%]	$E$ [GPa]
L	558	627	12.1	18.2	72.3
T	540	612	10.6	16.5	71.6

The results for different directions with respect to the direction of forming are nearly the same. The smallest relative difference (cca 1 %) is between the values of Young's modulus, nevertheless even so small difference in the quantity describing elastic strain behaviour can mean observable anisotropy of alloy microstructure.

#### 3.2 Fatigue results

The studies started by fatigue behaviour for L direction, which was studied up to now more deeply than for T direction, therefore basic considerations will be done for L direction. The first crucial question of all the studies consisted in the fact if not only fatigue tests performed at different frequencies but even using different devices with different incurrence of loading forces (servohydraulic vs. resonant machines) could give well comparable results which, moreover, should be consistent in a very low cycle region also with the values of UTS (which is considered to correspond to one quarter of a loading cycle). A clear graphical answer is given in Fig. 1; the all experimental results seem to lie on one smooth curve without any discontinuity or discrepancy. Therefore, there is no reason to infrim the regularity of fatigue tests performance.

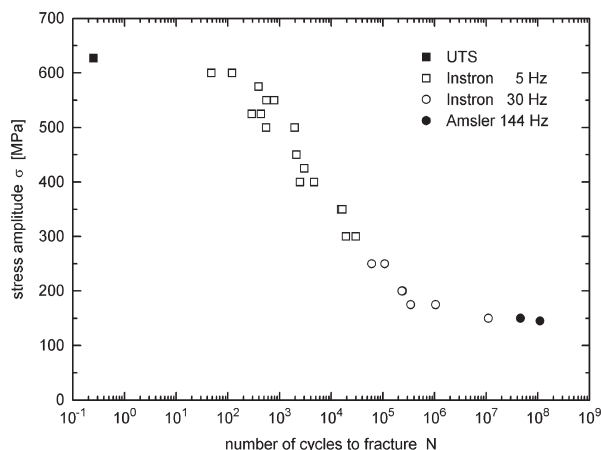


Fig. 1 Results of tensile and fatigue tests performed at different conditions lying on one smooth curve without any discontinuity.

#### 3.3 Fit of S-N curves

For the fit of S-N curves covering the whole range of the number of cycles to fracture from UTS to permanent fatigue limit (so called gigacycle fatigue is not considered here because no results for  $10^9$  and more cycles to fracture were available) only two regression functions are suitable: the Palmgren function [6]

$$\sigma(N) = a(N + B)^b + \sigma_\infty \tag{1}$$

or the Kohout and Vechet function [7]

$$\sigma(N) = \sigma_\infty \left( \frac{N + B}{N + C} \right)^b \tag{2}$$

where  $a, b, B, C$  and  $\sigma_\infty$  are parameters determined in regression calculations. Some of them represent a geometrical characteristic of the regression curve or have a clear physical meaning. Parameter  $b$  is the slope of the curve in the inflexion point if  $\log N - \log \sigma$  fit is used, parameters  $B$  and  $C$  describe the positions of the points with the maximum curvatures of S-N curve and  $\sigma_\infty$  represents limit value of stress amplitude for infinite number of cycles to fracture. The fits using both the regression functions are compared in Fig. 2. The values of regression parameters of both the functions together with the sums  $S$  of squares of deviations are presented in Table 3, together with fatigue limit values  $\sigma_C$  for  $10^8$  cycles (in contrast to ferrous alloys the fatigue stress of aluminium alloys is decreasing with increasing number of cycles to fracture even above  $10^7$  cycles, therefore not  $10^7$  cycles as for ferrous alloys but  $10^8$  cycles create the base for the determination of fatigue limit of aluminium alloys).

Values of regression parameters, fatigue limit values  $\sigma_C$  and sums  $S$  for S-N curve of test bars oriented in L direction Table 3.

Function	$a$ [MPa]	$b$ [-]	$B$ [-]	$C$ [-]	$\sigma_\infty$ [MPa]	$\sigma_C$ [MPa]	$S$ [MPa <sup>2</sup> ]
Palmgren (1)	32 967	-0.2862	782.0	-	118.1	135.1	12 848.38
K + V (2)	-	-0.1787	480.5	1 532 411.8	145.2	145.6	11 440.89

The choice of a better regression function is neither simple nor unambiguous: the Palmgren function represents a worse fit (its sum of squares of deviations is 12.3 % higher than that for the Kohout and Vechet function) but, on the other hand, it better takes into account decreasing fatigue stress in the range of number of cycles to fracture above  $10^7$ .

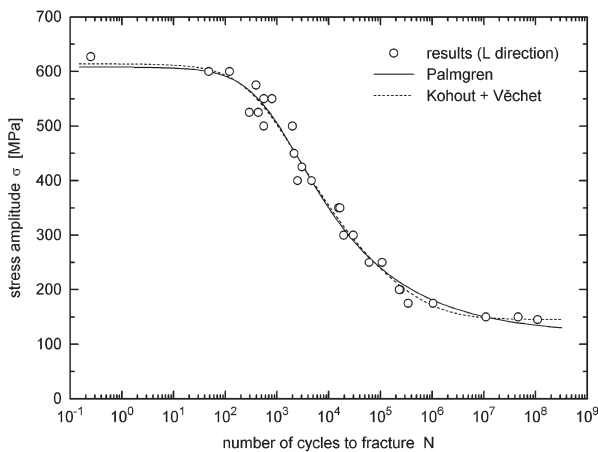


Fig. 2 Comparison of fits using the Palmgren (1) and the Kohout and Vechet (2) regression functions for test bars oriented in L direction.

Up to now the fatigue tests for T direction were performed only using Instron 8801 machine, only up to  $10^7$  cycles to fracture. Also their results were fitted using the Palmgren (1) as well as the Kohout and Vechet function (2), see Fig. 3. The values of regression parameters of both the functions together with the sums  $S$  of squares of deviations and with fatigue limit values  $\sigma_C$  for 108 cycles are presented in Table 4.

The problem to decide which regression function is better is here similar as in previous case of L orientation: a better fit using Kohout and Vechet function (for the Palmgren function the sum of squares of deviations is even 23.9 % higher than for the mentioned one) and a better description of decreasing fatigue stress in a very high cycle region using the Palmgren function.

Finally, the comparison of the results corresponding to different orientations of test bars to the direction of forming is presented in Fig. 4, namely using the Palmgren function. As the figure shows, the difference of both curves is convincingly lower than the dispersion of the results of fatigue tests. Therefore, the differ-

ence of fatigue properties in L and T directions is not important. However, the dispersion of results corresponding to T direction is substantially lower than that corresponding to L direction, see nearly one order lower corresponding sums of squares of deviations.

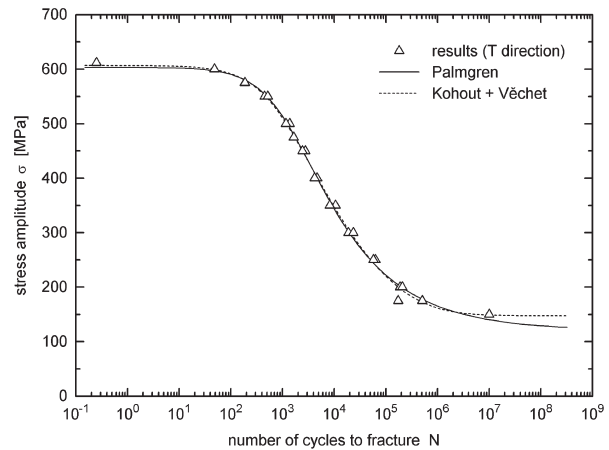


Fig. 3 Comparison of fits using the Palmgren (1) and the Kohout and Vechet (2) regression functions for test bars oriented in T direction.

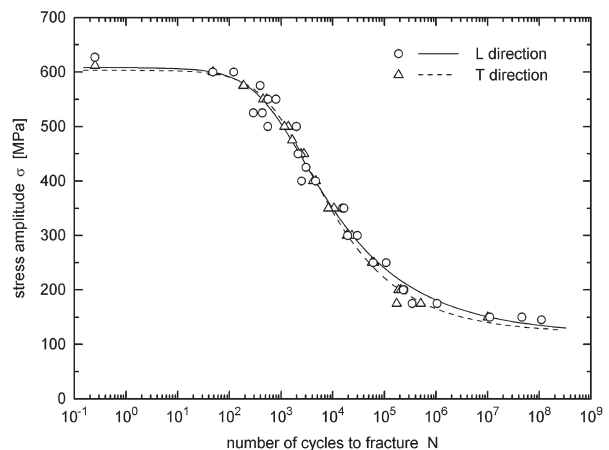


Fig. 4 Comparison of fits using the Palmgren regression function (1) for test bars oriented in both L and T directions.

### 3.4 Static vs. cyclic curve

The stress-strain hysteresis loops of 17 test bars oriented in L direction were observed at stress amplitudes between 300 and 600

Values of regression parameters, fatigue limit values  $\sigma_C$  and sums  $S$  for S-N curve of test bars oriented in T direction Table 4.

Function	$a$ [MPa]	$b$ [-]	$B$ [-]	$C$ [-]	$\sigma_\infty$ [MPa]	$\sigma_C$ [MPa]	$S$ [MPa <sup>2</sup> ]
Palmgren (1)	6 209	-0.3568	1 285.9	-	120.6	140.3	1 824.56
K + V (2)	-	-0.2193	833.0	533 084.8	147.1	148.8	1 472.88

MPa to the state of saturation. Chosen stress levels with saturated values of strain define a so called cyclic deformation curve, see Fig. 5. The points corresponding to single bars are fitted using the Ramberg and Osgood relationship [8] representing the total strain as the sum of elastic strain (proportional to stress according to Hook's law) and plastic stress (power function of stress)

$$\epsilon(\sigma) = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^n \quad (3)$$

where  $\epsilon$  is strain,  $\sigma$  is stress,  $E$  is Young's modulus,  $K$  and  $n$  are constants that depend on the material being considered. As the values of parameter  $K$  are usually extremely high, the original relationship is often modified into the relation [9]

$$\epsilon(\sigma) = \frac{\sigma}{E} + \left(\frac{\sigma}{\sigma_0}\right)^n \quad (4)$$

which was used also in this case. The values of parameters are presented in Table 5.

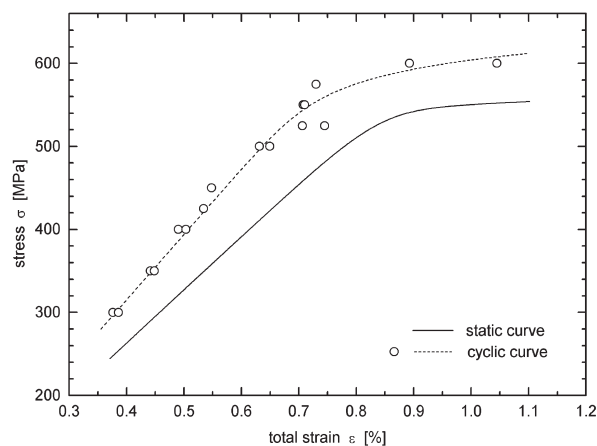


Fig. 5 Comparison of static stress-strain curve with cyclic deformation curve presenting cyclic hardening of studied alloy loaded in L direction.

Parameters of the Ramberg and Osgood relationship for cyclic deformation curve. Table 5.

Parameter	$E$ [GPa]	$\sigma_0$ [MPa]	$n$ [-]
Value	78.8	769.9	25.0

The cyclic curve situated higher than the static curve shows that the fatigue loading leads to cyclic hardening of the studied alloy. Also the value of *cyclic* Young's modulus about 10 % higher than the values of *static* Young's modulus (cf. Tables 2 and 5) denotes cyclic hardening.

All regression calculations were made in MS Excel using supplement *Solver* with suitably chosen parameters and tools which take into account a higher degree of non-linearity of used regres-

sion functions. All calculations ran without any complication, only some difficulties appeared during regression of the cyclic deformation curve because the region of strain above the bend of the curve is covered with two points only.

#### 4. Discussion

Nearly the same 7075-T651 aluminium alloy was studied by Zhao and Jiang [3] using nearly the same servohydraulic machine (Instron 8800) but only up to  $10^6$  cycles to fracture. It is surely no surprise that our and their results of fatigue tests are not (with respect to the dispersion of experimental data) distinguishable. A markedly higher fatigue limit is presented for 7075-T6 alloy by Wang et al. [5], but the higher value can be explained by a higher-order frequency of loading cycles in the ultrasonic region (19.5 kHz).

The results show nearly no difference between different orientation of test bars with respect to the direction of forming, see Table 2 dealing with static behaviour in tension and Fig. 4 dealing with fatigue behaviour. On the other hand, certain deviations can be observed: substantially different dispersion of fatigue results and slightly different values of Young's modulus which is not usually too sensitive to microstructure. First metallographic studies show certain, but not substantial difference, in the arrangement of strengthening precipitates. It seems that the tools of statistics would be useful for the description of small differences in microstructure. This aspect is going to be studied.

The resulting fatigue limits  $\sigma_C$  determined as the values of fitted curves for  $10^8$  cycles to fracture depend on the type of regression function. Their values are lower for the Palmgren function (1) and higher for the Kohout and Vechet function (2), see Tables 3 and 4. As the former gives too conservative values and the latter too progressive values, the intervals between them seem to be quite representative approximations of fatigue limit values, i.e.  $(140 \pm 5)$  MPa for L direction and  $(144 \pm 4)$  MPa for T direction. Also overlapping intervals of the fatigue limit values are evidence of unsubstantial difference in fatigue behaviour in both mentioned directions.

In the paper the term *permanent fatigue limit* is several time used (also in the title) similarly as for ferrous metals although the fatigue stress of aluminium alloys decreases even above  $10^7$  cycles to fracture. It means that this term is not too suitable for those alloys. Just this decreasing fatigue stress is the reason why the Kohout and Vechet function with surely better fit is not unambiguously preferred and the Palmgren fit giving more conservative values of fatigue limit is slightly favoured. The decision between both the mentioned regression functions needs a substantially larger set of fatigue results of aluminium alloys.

Generally said, cyclic hardening is typical for the metals with lower level of stress properties and cyclic softening is observed at fatigue loading of hardened metals, e.g. deeply formed or quenched steels. In age-hardened alloys only precipitation strengthening is

exploited, increasing dislocation density during fatigue loading and interactions among dislocations and precipitates lead to additional hardening. These mechanisms were confirmed by profound study of the mechanisms of cyclic deformation [10] as well as by finite element prediction [11]. Cyclic hardening following after age-hardening represents a substantial advantage of these types of structural materials leading to their wide applicability in many branches of industry.

## 5. Conclusions

1. The studied 7075 alloy reaches a very high level of strength and deformability as a result of optimized age-hardening.
2. No discontinuity or discrepancy was found among the results of fatigue tests performed using different frequencies of fatigue loading and even different testing devices (all results lie on one smooth S-N curve).
3. Fatigue loading of the studied age-hardened alloy leads to further cyclic hardening.

4. Mechanical properties of the test bars oriented longitudinally and transversally to the direction of forming are only negligibly different.
5. The fit of S-N curves from UTS to permanent fatigue limit can be made using the Palmgren or the Kohout and Vechet regression function. The Palmgren function takes better into account the fact of decreasing fatigue stress in a very high cycle region leading to more conservative and, thereby, safer values of fatigue limit, the Kohout and Vechet function gives substantially better fit of experimental data. The decision between both the mentioned functions needs further extensive studies.

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