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LOW-CYCLE FATIGUE OF AA2124T851

NÍZKO-CYKLOVÁ ÚNAVA HLINÍKOVÉ SLITINY 2124T851

Abstract

This paper presents an overview of extensive set fatigue tests results in low-cycle domain carried out at the Department of Applied Mechanics at the VŠB – Technical University of Ostrava on smooth specimens made of 2124T851 aluminum alloy. Overall, results of 24 tests of the aforementioned type under proportional loading and 40 tests under non-proportional loading with various strain path shapes were evaluated within the FADOFF project (Fatigue Analysis Documentation Office) supported by the Technology Agency of the Czech Republic. All tests were realized under the zero mean strain at the room temperature. Investigated aluminum alloy has exhibited in the torsion tests significantly shorter lifetime than under the tension-compression symmetrical loading at the same level of equivalent strain amplitude. The experimental set was realized in order to validate low-cycle fatigue criteria in a future work.

Abstrakt

Příspěvek prezentuje přehled výsledků rozsáhlé sady únavových zkoušek získaný na Katedře aplikované mechaniky VŠB – TU Ostrava v nízko-cyklové oblasti na hladkých vzorcích vyrobených z materiálu AA2124T851. Celkem čítaly výsledky shora uvedeného typu 24 testů realizovaných při proporcionálním namáhání a 40 testů při neproporcionálním namáhání s různými tvary deformačních cest a byly vyhodnoceny v rámci projektu FADOFF, podporovaného Technologickou agenturou České republiky. Všechny testy byly realizovány s nulovou střední hodnotou deformace při pokojové teplotě. Zkoumaná hliníková slitina vykazovala v torzních testech výrazně kratší životnost, než při jednoosém symetrickém zatěžování na stejné hladině ekvivalentní amplitudy přetvoření. Experimentální sada byla získána za účelem validace kritérií nízkocyklové únavy v další práci.

Keywords

Low-cycle fatigue, aluminium alloy, non-proportional loading.

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1 INTRODUCTION

The components of engineering structures usually undergo multiaxial loading. The cyclic stress–strain responses under multiaxial loading, which depend on the loading path, are very complex and fatigue behavior of materials and structures is very difficult to be estimated. Many researchers have proposed multiaxial fatigue criteria suitable for different materials at different loading conditions. The multiaxial fatigue criteria published in literature are classified into three categories, namely stress criteria, strain criteria and energy criteria. Traditionally, stress-based criteria have been applied only in the high-cycle fatigue domain [1]. For low-cycle fatigue predictions of number of cycles to initiation of a fatigue crack, a strain quantity must be included into the fatigue parameters, especially in the case of the non-proportional loading [2], [3]. The fatigue analysis can be performed based on results from numerical analysis or data from measurements [4]. During the solution phase of the FADOFF project (Fatigue Analysis Documentation Office) [5], a new version of the PragTic software was developed including various low-cycle fatigue criteria evaluated on a large experimental set, which is presented in this study. The experimental study consists of results of eight uniaxial and fifty-six multiaxial tests. Conventional as well as 3D method [6] were applied for fatigue constants estimation using the uniaxial and torsional data in the conference paper [7]. The conclusion was that results of both methods are comparable. The most important finding of this paper is that the aluminum alloy demonstrates the strongest dependency of life on shear strain amplitude.

2 DESCRIPTION OF EXPERIMENTAL STUDY

Low-cycle fatigue tests were performed at the Department of Applied Mechanics at the VŠB – Technical University of Ostrava using the LABCONTROL 100kN/1000Nm testing machine, see Fig. 1. The investigated material was 2124T851 aluminum alloy. All specimens were made from one plate in longitudinal direction. Three types of specimens were used. The first specimen was solid (Fig. 2), the other two were tubular (Fig. 3, Fig. 4).

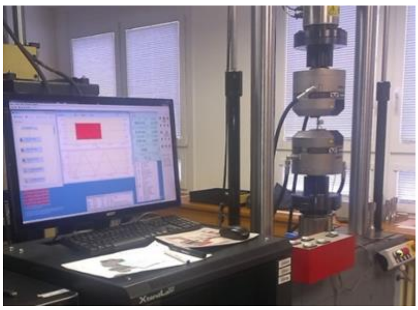

Fig. 1 Electro-servo-hydraulic LABCONTROL testing machine for axial/torsional loading of 100kN/1000Nm.

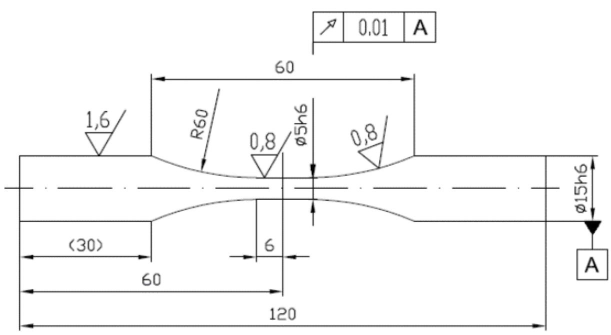

Fig. 2 Solid specimen with diameter of 5 millimeters.

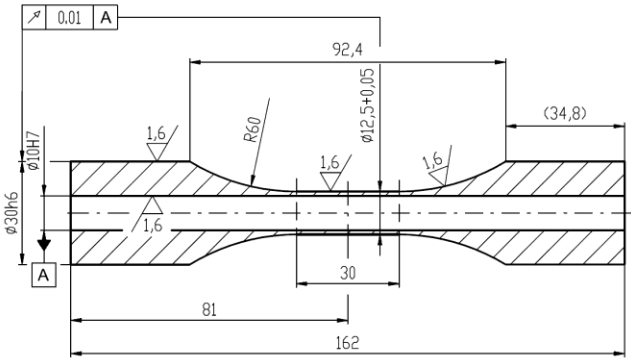

Fig. 3 Tubular specimen with diameters ϕ10/ϕ12.5 mm.

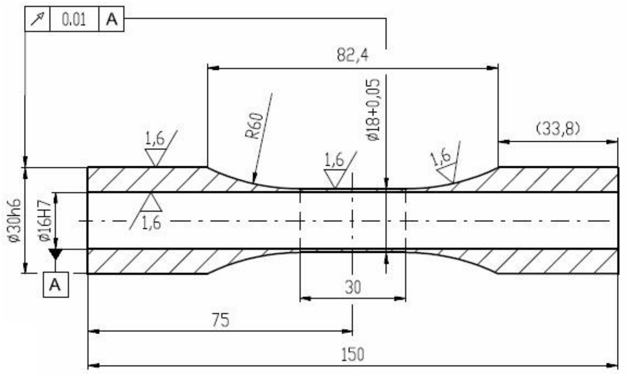

Fig. 4 Tubular specimen with diameters ϕ16/ϕ18 mm

All low-cycle fatigue tests were realized on smooth specimens under strain control with zero mean strain during the cycle. Solid specimens were used exclusively for tests under the fully reversed uniaxial loading, tubular specimens for other tests. The loading paths used in the study are presented schematically in Fig. 5. Eight different cases were realized.

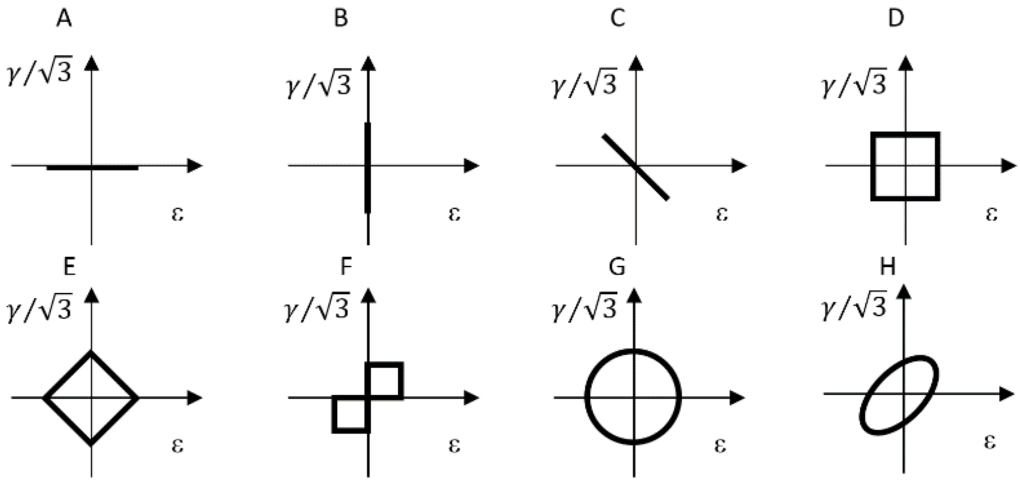

Fig. 5 Strain path shapes in particular cases

A total of sixty-four specimens were tested (eight pieces per a loading path). The number of cycles realized before crack initiation was determined in all tests based on the decrease of force (moment) amplitude of twenty percent in comparison to the saturated values. All experiments were performed at room temperature. The strain rate was equal to 0.01 s^{-1}. The EPSILON 3442 extensometer with a gauge length of 10 mm was used in uniaxial tests. The EPSILON 3550 extensometer with a gauge length of 25 mm was used to measure/control the axial and shear strain under the torsion and multiaxial loadings.

3 RESULTS OF EXPERIMENTS

Experimental data and examples of hysteresis loops for each loading path (Fig. 5) are presented in this section. The strain paths applied in this study were: uniaxial (case A), torsional (B), proportional (C), square (D), rhombic (E), two blocks (F), circular (G) and elliptical (H).

3.1 Results of uniaxial fatigue tests (case A)

The results of uniaxial fatigue tests with constant strain amplitude are summarized in Tab. 1. Subscript “a” means amplitude and subscript “m” means value of variable in a half of fatigue life. Obtained saturated hysteresis loops are displayed in a single graph (Fig. 6).

Tab. 1 Fatigue life under uniaxial loading

id. test	specimen	ε_a	σ_a [MPa]	σ_m [MPa]	N_f
1	8	0.025	455.4	-9	36
2	7	0.02	444.4	-10.6	67
3	11	0.015	424	-10	209
4	10	0.0125	406	-7	520
5	14	0.01	389	-9	642
6	9	0.008	370	-3	1206
7	13	0.0065	358	-4	3194
8	12	0.0055	328	-3	7062

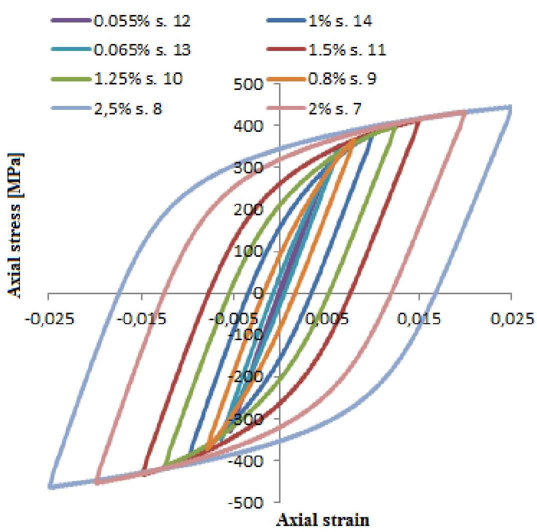

Fig. 6 Stable hysteresis loops – case A (push – pull)

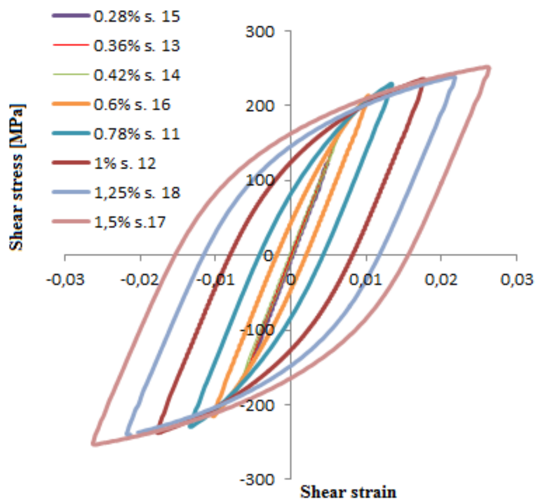

Fig. 7 Stable hysteresis loops – case B (torsion)

3.2 Results of torsional fatigue tests (case B)

The results of torsional fatigue tests with constant shear strain amplitude are summarized in Tab. 2. Saturated hysteresis loops are shown in the graph in Fig.7.

Tab. 2 Fatigue life under torsional loading

id. test	specimen	γ_a	τ_a [MPa]	τ_m [MPa]	N_f	Note
1	17	0.02635	252.9	-0.5	41	sp.12.5/10
2	18	0.02184	239.8	-0.5	85	sp.12.5/10
3	12	0.01800	236.0	-0.8	125	sp.12.5/10
4	11	0.01350	229.6	0.1	152	sp.12.5/10
5	16	0.01037	214.6	-0.8	322	sp.12.5/10
6	14	0.00730	183.3	-0.2	2257	sp.12.5/10
7	13	0.00630	164.4	-1.8	6800	sp.12.5/10
8	15	0.00490	128	-5.3	27890	sp.12.5/10

3.3 Results of multiaxial fatigue tests with proportional loading (case C)

The most important results of the realized multiaxial low cycle fatigue tests with constant shear strain amplitude and constant axial strain amplitude for the case C are given in Tab. 3.

Tab. 3 Main results of proportional multiaxial low-cycle fatigue tests of case C

test	spec.	ε_a	σ_a [MPa]	σ_m [MPa]	γ_a	τ_a [MPa]	τ_m [MPa]	N_f
1	17	0.00889	323.2	-18.3	0.0154	178.9	1.9	165
2	15	0.00731	301.3	-15.9	0.01266	174.0	1.6	226
3	16	0.00549	279.0	-12.1	0.00951	166.2	0.4	704
4	18	0.00422	257.4	-6.4	0.00731	159.1	-0.7	1780
5	19	0.00353	238.1	-3.3	0.00611	150.5	-0.5	2270
6	20	0.00318	232.6	-2.9	0.0055	149.2	2.2	4017
7	21	0.00282	209.8	-1.4	0.00488	133.9	1.8	12680
8	22	0.00245	184.1	2.0	0.00425	121.0	0.5	27656

3.4 Results of multiaxial fatigue tests with trapezoidal loading (case D – square)

The results of multiaxial fatigue tests with constant shear strain amplitude and constant axial strain amplitude with square path (case D) are summarized in the Tab. 4.

Tab. 4 Main results of non-proportional multiaxial low-cycle fatigue tests of case D

test	spec.	ε_a	σ_a [MPa]	σ_m [MPa]	γ_a	τ_a [MPa]	τ_m [MPa]	N_f
1	33	0.01008	448.7	-13.5	0.0175	257.4	-3.1	12
2	35	0.00757	416.8	-12.2	0.0131	239.5	-2.7	53
3	36	0.00608	377.9	-9.8	0.0105	219.1	-1.9	134
4	37	0.00464	319.2	-10.1	0.008	186.7	-1.8	282
5	32	0.00367	274.9	-6.9	0.0064	163.6	-1.2	815
6	34	0.00325	237.8	3.5	0.0056	143.1	-0.1	1421
7	38	0.00269	201.2	-19.6	0.0047	124.1	0.4	4236
8	39	0.00219	165.4	-5.9	0.0038	101.6	1.9	25800

3.5 Results of non-proportional multiaxial fatigue tests with rhombic path (case E)

The results of multiaxial fatigue tests with constant shear strain amplitude and constant axial strain amplitude with rhombic path (case E) are summarized in the Tab. 5.

Tab. 5 Main results of non-proportional multiaxial low-cycle fatigue tests of case E

test	spec.	ε_a	σ_a [MPa]	σ_m [MPa]	γ_a	τ_a [MPa]	τ_m [MPa]	N_f
1	1	0.00997	394.0	-9.3	0.01726	231.1	-1.4	77
2	2	0.00744	384.0	-9.3	0.01289	226.4	-0.8	202
3	5	0.00649	382.3	-7.3	0.01125	221.2	-0.6	238
4	6	0.00554	367.7	-7.8	0.00959	213.8	0.6	320
5	9	0.00452	331.0	-1.7	0.00784	196.3	-0.3	1036
6	10	0.00394	295.3	1.3	0.00682	189.5	0.8	491*
7	11	0.00352	265.3	-0.2	0.00609	168.9	0.8	2256
8	12	0.00282	214.2	1.7	0.00489	138.7	-1.3	14753

*Abrupt fracture occurs.

3.6 Results of multiaxial two block fatigue tests (case F)

The most important results of the realized multiaxial low cycle fatigue tests with constant shear strain amplitude and constant axial strain amplitude for the case F are given in Tab. 6.

Tab. 6 Main results of non-proportional multiaxial fatigue tests – case F

test	spec.	ε_a	σ_a [MPa]	σ_m [MPa]	γ_a	τ_a [MPa]	τ_m [MPa]	N_f
1	1	0.00997	394.0	-9.3	0.01726	231.1	-1.4	77
2	2	0.00744	384.0	-9.3	0.01289	226.4	-0.8	202
3	5	0.00649	382.3	-7.3	0.01125	221.2	-0.6	238
4	6	0.00554	367.7	-7.8	0.00959	213.8	0.6	320
5	9	0.00452	331.0	-1.7	0.00784	196.3	-0.3	1036
6	10	0.00394	295.3	1.3	0.00682	189.5	0.8	491*
7	11	0.00352	265.3	-0.2	0.00609	168.9	0.8	2256
8	12	0.00282	214.2	1.7	0.00489	138.7	-1.3	14753

* Tubular specimen of ϕ10/ϕ12.5 mm.

3.7 Result of multiaxial of out of phase fatigue test (case G)

The most important results of the realized multiaxial low cycle fatigue tests with constant shear strain amplitude and constant axial strain amplitude for the case G are given in Tab. 7.

Tab. 7 Main results of non-proportional multiaxial low-cycle fatigue tests of case G

test	spec.	ε_a	σ_a [MPa]	σ_m [MPa]	γ_a	τ_a [MPa]	τ_m [MPa]	N_f
1	31	0.00998	427.1	-10.3	0.01728	241.0	-2.3	74
2	1*	0.00747	394.3	-9.8	0.01293	229.2	-1.1	135
3	2*	0.00648	373.2	-9.1	0.01122	214.4	-1.2	240
4	3*	0.00551	350.8	-8.2	0.00954	204.0	-1.0	352
5	21	0.00451	318.3	-5.4	0.00782	187.7	1.3	1580
6	26	0.00402	292.6	-12.1	0.00696	176.5	-0.7	4357
7	29	0.0035	261.7	-2.1	0.00607	161.8	1.5	8336
8	30	0.00308	234.0	1.4	0.00533	144.2	1.1	14459

3.8 Results of 45° out of phase multiaxial fatigue tests (case H)

The most important results of the realized multiaxial low cycle fatigue tests with constant shear strain amplitude and constant axial strain amplitude for the case H are given in Tab. 8.

Tab. 8 Main results of non-proportional multiaxial low-cycle fatigue tests of case H

test	spec.	ε_a	σ_a [MPa]	σ_m [MPa]	γ_a	τ_a [MPa]	τ_m [MPa]	N_f
1	41	0.00998	395.5	-8.5	0.01728	242.2	-2.2	70
2	42	0.00748	369.5	-6.5	0.01296	224.1	-1.0	146
3	43	0.00646	354.1	-6.7	0.01119	213.7	-0.4	396
4	44	0.00498	322.9	-6.3	0.00862	190.5	1.1	874
5	45	0.00459	301.7	0.7	0.00795	180.0	0.9	574*
6	46	0.00423	292.6	-1.5	0.00732	177.7	0.7	1912
7	47	0.00351	260.3	-4.1	0.00607	159.5	0.8	5360
8	48	0.00309	229.7	-31.4	0.00536	142.5	18.1	19430

*Abrupt fracture occurs.

4 CONCLUSIONS

Main results of experimental study carried out within the project FADOFF [4] performed on the AA2124T851 material were presented in this contribution.

In order to compare lifetimes for individual cases the amplitude of equivalent strain was calculated for each test as the minimal radius of the circumscribed circle in the diagram axial strain - equivalent value of shear strain. Obtained fatigue life curves are shown in Fig. 8.

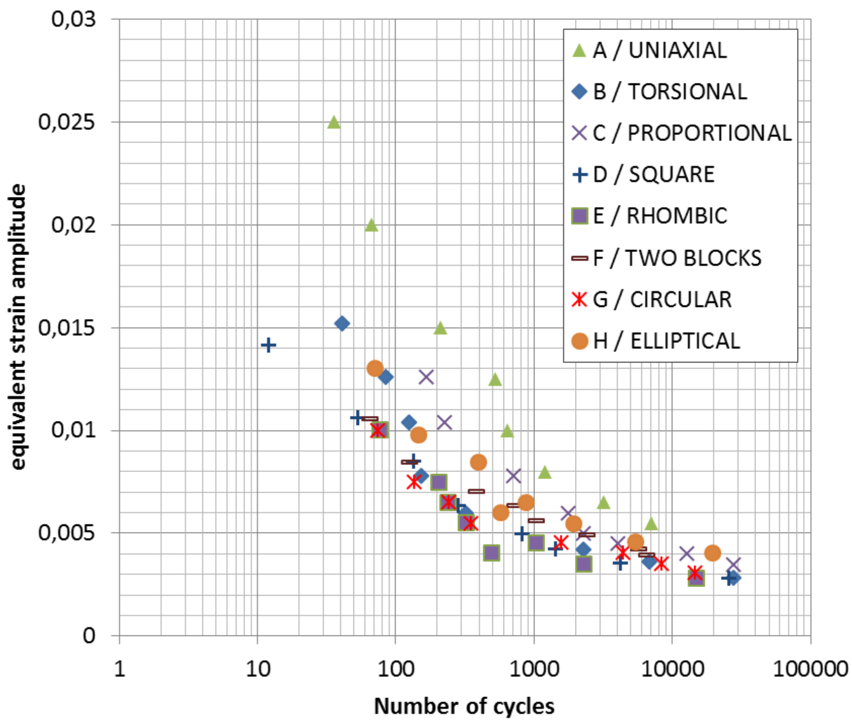

Fig. 8 Fatigue life curves of all investigated cases of material AA2124T851 in FADOFF project [5]

Based on the comparison of individual cases of fatigue tests, the following conclusions can be drawn. The lifetime is considerably longer under tension-compression than under pure torsion at the same level of loading. The shear strain thus has a major impact on the lifetime. Test results of the circular strain path (case G) coincide very well with the results of tests under torsion at smaller amplitudes. With an increasing share of plastic strain amplitude, the influence of the non-proportional hardening of the material seems to be more significant, which results in an increase of the amplitude of stress. A large amount of plastic work is accumulated, which ultimately leads to the lifetime shortening. Lifetime of these specimens, however, falls rather into the category of very low cycle fatigue.

The results of this experimental study are used to validate the particular multiaxial fatigue criteria. It is already clear, however, that the material is very specific because of its unusual behavior.

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