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INFLUENCE OF STRESS AND STRAIN CONTROL ON CYCLIC PROPERTIES OF AW-2017A ALUMINIUM ALLOY

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Abstract

The work presents test results of aluminium alloy AW-2017A in variable constant amplitude loading conditions with the cycle asymmetry coefficient R = -1. Tests were performed independently for stress and strain control. Obtained test results enabled to determine Manson-Coffin (M-C) and Wöhler (W) fatigue life curves as well as Ramberg-Osgood (R-O) cyclic strain curve. The aim of the paper is to present differences between M-C and W fatigue characteristics determined in stress and strain conditions. Differences between mentioned characteristics were evaluated on the base of a relative difference. In case of Wöhler (W) curves the value of differences depends on the stress amplitude level S_a and it is between -1.0 to 1.9.

Keywords: *low-cycle fatigue, diagrams of fatigue life, AW-2017A aluminium alloy.*

Nomenclature

$2N_f$ – the number of reversals to failure,
$N_{(s)}$ – fatigue life read from Wöhler curve determined with stress controlled conditions for defined value of stress S_a,
$N_{(\varepsilon)}$ – fatigue life read from Wöhler curve determined with strain controlled conditions for defined value of stress S_a,
S – specimen stress – general notation [MPa],
S_a – sinusoidal cycle stress amplitude [MPa],
$S_{a(\varepsilon)}$ – stress aplitude read from Ramberg-Osgood cyclic strain curve determined with strain controlled conditions for defined ε_{ac} value [MPa],
$S_{a(\sigma)}$ – stress aplitude read from Ramberg-Osgood cyclic strain curve determined with stress controlled conditions for defined ε_{ac} value [MPa],
ε – strain – general notation,
ε_{ac} – total strain amplitude,
$\varepsilon_{ac(\varepsilon)}$ – total strain amplitude read from Manson-Coffin curve with strain controlled conditions for the defined number of reversals of loading $2N_f$,
$\varepsilon_{ac(\sigma)}$ – total strain amplitude read from Manson-Coffin curve with stress controlled conditions for the defined number of reversals of loading $2N_f$,
$\delta_{(Sa)}$ – relative difference of stress amplitude value for Ramberg-Osgood curves determined with stress and strain controlled conditions,

$\delta_{(\varepsilon)}$ – relative difference of total strain amplitude value for Manson-Coffin curves determined with stress and strain controlled conditions,

$\delta_{(N)}$ – relative difference of fatigue life for Wöhler curves determined with stress and strain controlled conditions.

1. Introduction

Fatigue life calculations of structural elements in variable loading conditions are performed with an application of fatigue life curves: Wöhler (W) or Manson-Coffin (M-C). In the range of high cycle fatigue (HCF) life the Wöhler curve is applied while in the range of low cycle fatigue life the Mason-Coffin one. The mentioned W and M-C curves are determined in variable test conditions. The first of them is determined in stress controlled conditions(S_a = const.) whereas the second one in strain controlled conditions (ε_{ac} = const.) [2].

In the work [4] there were presented results of C45 steel (softening-hardeninh steel, $R_m/R_e = 1.6$) performed on plain steel specimens in strain and stress controlled conditions. The comparative analysis between Wöhler and Manson-Coffin fatigue life curves was performed. Differences of fatigue lives between W curves for stress and strain control are: for S_a = 550 MPa – δ_{550} = 21.6 %, for S_a = 250 MPa – δ_{250} = -36.1 %. In case of M-C curves fatigue life differences are: for ε_{ac} = 0.03 – $\delta_{0.03}$ = 51.4 %, for ε_{ac} = 0.0015 – $\delta_{0.0015}$ = -190.1 %. Concluding the author points relatively small differences between fatigue life curves W and M-C determined in S_a = const. and ε_{ac} = const. conditions what enables their interchangeable application.

The goal of the work [3] was to compare Ramberg-Osgood (R-O), Wöhler and Manson-Coffin curves determined in stress and strain controlled conditions. There was tested austenitic steel X5CrMi18-10 (steel that undergo cyclic hardening, $R_m/R_{0,2} = 2.0$) and tests were performed on plain specimens. Relative differences among R_O, M-C and W characteristics were presented as diagrams and the range of their changes is: for R-O – $\delta_{(Sa)} = -0.15 \div 0.16$, for M-C – $\delta_{(\varepsilon)} = -0.20 \div -0.02$, for W – $\delta_{(N)} = -0.90 \div 0.55$. In the summary authors indicate that the value of differences is conected with the type of material and the value of stress amplitudes S_a or the total strain amplitude ε_{ac}.

On the base of works [3] and [4] one can state that differences among R-O, M-C and W curves are conected with cyclic properties of a material. Therefore the aim of this work is the evaluation of values of relative differences among R-O, M-C and W characteristics determined in stress controlled (S_a = const.) and strain controlled (ε_{ac} = const.) conditions for AW-2017A aluminium alloy.

The scope of the work covers the presentation of test results in static and variable loading conditions and the comparative analysis of Ramberg-Osgooda, Manson-Coffin and Wöhler curves.

2. Experimental tests

2.1. Material for test

For tests there was assumed magnesium and copper aluminium alloy AW-2017A (alloy indication AlCu4MgSi (A)) in accordance with PN-EN 573-3:2010 and PN-EN 573-3/AK:1998 standards. Increased constituents of copper and magnesium in the alloy results in increase of strength properties and decrease of plastic properties [1]. Chemical composition of the alloy and percentage of individual constituents was presented in tab. 1.

Material for specimens was bought in a form of a round bar with 25 mm diameter. Material condition was defined as T4 what indicates that aluminium alloy undertook solution heat treatment and aging to obtain stable state.

Table 1. Chemical composition of AW-2017A T4 aluminium alloy

	Percentage of constituents, %									
	Cu	Fe	Si	Mn	Mg	Zn	Cr	Ni	Ti	Inne
		max				max	max	max	max	
In accordance with PN-EN 573-3: 2010	3.5÷4.5	0.7	0.2÷0.8	0.4÷1.0	0.4÷1.0	0.25	0.1	0.1	0.15	Zr+Ti ≤ 0.2

2.2. Test results in static loading conditions

Tests in static loading conditions were performed in accordance with PN-EN ISO 6892-1:2010 standard. Obtained test results are included in table 2 where mean values as well as standard deviations of determined parameters are given. The examplary course of S = f(ε) dependance was presented in fig. 1a. Additionally there was presented a fragment of dependance S = f(ε) for the limited strain range (ε = 2%) in order to present the shape of characteristic in the range of elastic limit (fig.1b). The value of relation R_m/R_e = 1.48.

Table 2. Static properties of AW-2017A alloy in tensile loading conditions

	Static properties of AW-2017A alloy					
	R_e	$R_{0,2}$	R_m	E	A_5	Z
	MPa	MPa	MPa	MPa	%	%
Mean values	316.7	320.1	469.5	73077	16.1	23.0
Standard deviation values	1.3	0.6	4.5	1304	0.8	0.8

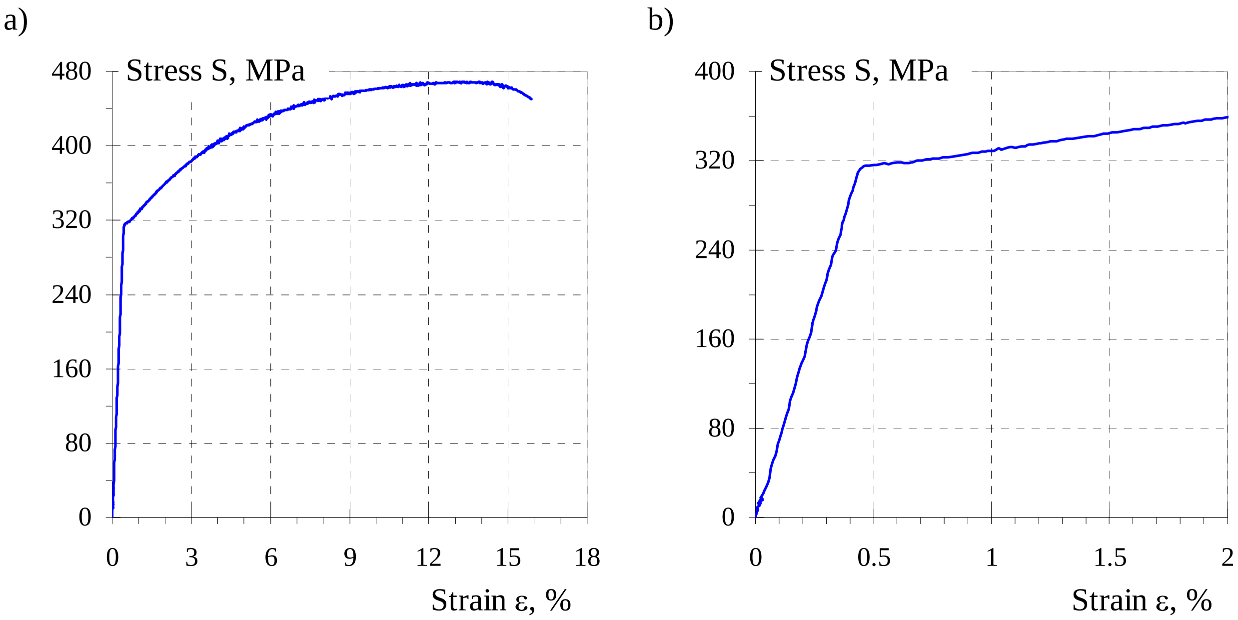

Fig. 1. The examplary dependance S = f(ε) for aluminium alloy AW-2017A (a) and its fragment limited to ε = 2% (b)

2.3. Cyclic properties of aluminium alloy in stress and strain controlled conditions

Tests of steel cyclic properties under stress and strain control was performed in sinusoidal loading conditions characterized by the cycle asymmetry coefficient R = -1. Realization of a loading cycle was performed in accordance with the scheme presented in fig. 2. In tests tere were applied specimens with 10 mm diameter and meseaurement base length 18 mm that fulfill requirements of PN-84/H-04334 standard.

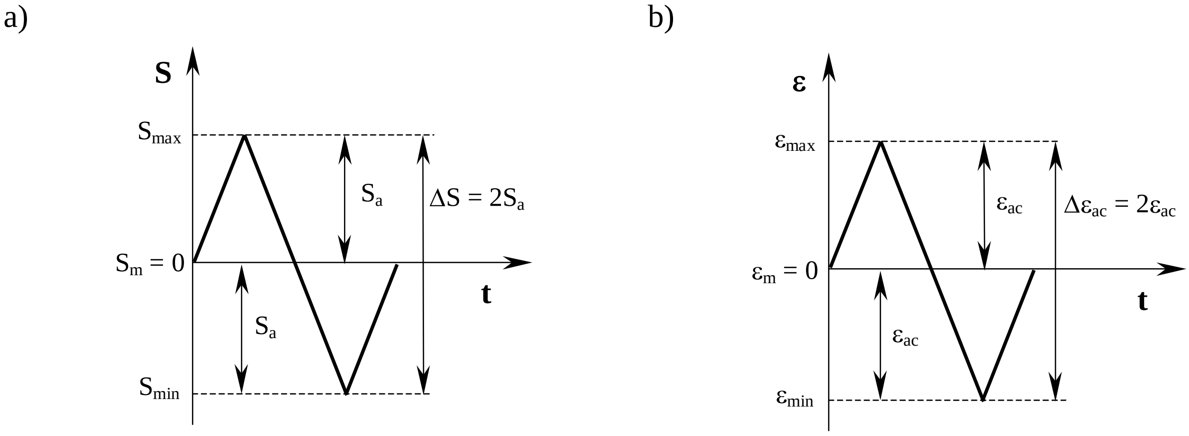

Fig. 2. Loading cycle scheme applied in fatigue tests with control: a – stress, b – strain

Obtained fatigue test results enabled to determine Ramberg-Osgood (S_a-ε_{ac}) cyclic deformation curve described with the formula:

$$\varepsilon_{ac} = \frac{S_a}{E} + \left(\frac{S_a}{K'}\right)^{\frac{1}{n'}} \tag{1}$$

Manson-Coffin fatigue life curve (ε_{ac}-$2N_f$)

$$\frac{\Delta\varepsilon_{ac}}{2} = \varepsilon_f^{'}\left(2N_f\right)^c + \frac{\sigma_f^{'}}{E}\left(2N_f\right)^b \tag{2}$$

and Wöhler fatigue life curve (S_a-N)

$$\log S_a = -\frac{1}{m_{(-1)}}\log N + b_{(-1)} \tag{3}$$

Values of parameters appearing in equations (1), (2) and (3) were presented in the table 3.

Table 3. Parameters of equations describing Ramberg-Osgood, Manson-Coffin and Wöhler curves for AW-2017A aluminium alloy

				Test conditions	
				Stress-controlled (S_a = const.)	Strain-controlled (ε_{ac} = const.)
Equation parameters of curves		E	MPa	73077	73077
	M-C	c		-1.1871	-1.3979
		b		-0.1091	-0.0737
		ε_f'		2.406	12.505
		σ_f'	MPa	836	632
	R-O	n'		0.0741	0.0514
		K’	MPa	640	556
	W	$m_{(-1)}$		8.64	13.79
		$b_{(-1)}$		2.9230	2.7817

3. Analysis of test results

Evaluation of obtained test results strain and stress controlled conditions was based on the comparative analysis of Ramberg-Osgood, Manson-Coffin and Wöhler curves that led to determine differences of relative values.

Analysis of Ramberg-Osgood cyclic deformation was conducted on the base of relative difference of amplitudes of nominal stress $\delta_{(Sa)}$ determined from the equation:

$$\delta_{(Sa)} = \frac{S_{a(\sigma)} - S_{a(\varepsilon)}}{S_{a(\varepsilon)}} \tag{4}$$

Results of amplitudes $S_{a(\sigma)}$ and $S_{a(\varepsilon)}$ were read from the Ramberg-Osgood curve for ε_{ac} specific values. Strain-controlled test results were a reference point in the conducted analysis.

Comparison of Mason-Coffin fatigue life curves was conducted on the base of the analysis of difference value of relative total strain amplitude $\delta_{(\varepsilon ac)}$ determined from the equation:

$$\delta_{(\varepsilon)} = \frac{\varepsilon_{ac(\sigma)} - \varepsilon_{ac(\varepsilon)}}{\varepsilon_{ac(\varepsilon)}} \tag{5}$$

Values of total strain amplitudes $\varepsilon_{ac(\sigma)}$ and $\varepsilon_{ac(\varepsilon)}$ were read from the Mason-Coffin curve for specific values of the number of reversals of loading $2N_f$. Strain-controlled test results were a reference point in the conducted analysis.

Differences among test results, shown in a form of Wöhler curves for stress and strain-controlled conditions, were analyzed on the base of a value of relative difference of fatigue lives N calculated from the equation:

$$\delta_{(N)} = \frac{N_{(\sigma)} - N_{(\varepsilon)}}{N_{(\varepsilon)}} \tag{6}$$

Values of fatigue life $N_{(s)}$ and $N_{(\varepsilon)}$ were read from Wöhler curves for specific value of stress amplitude S_a. Strain-controlled test results were a reference point in the conducted analysis.

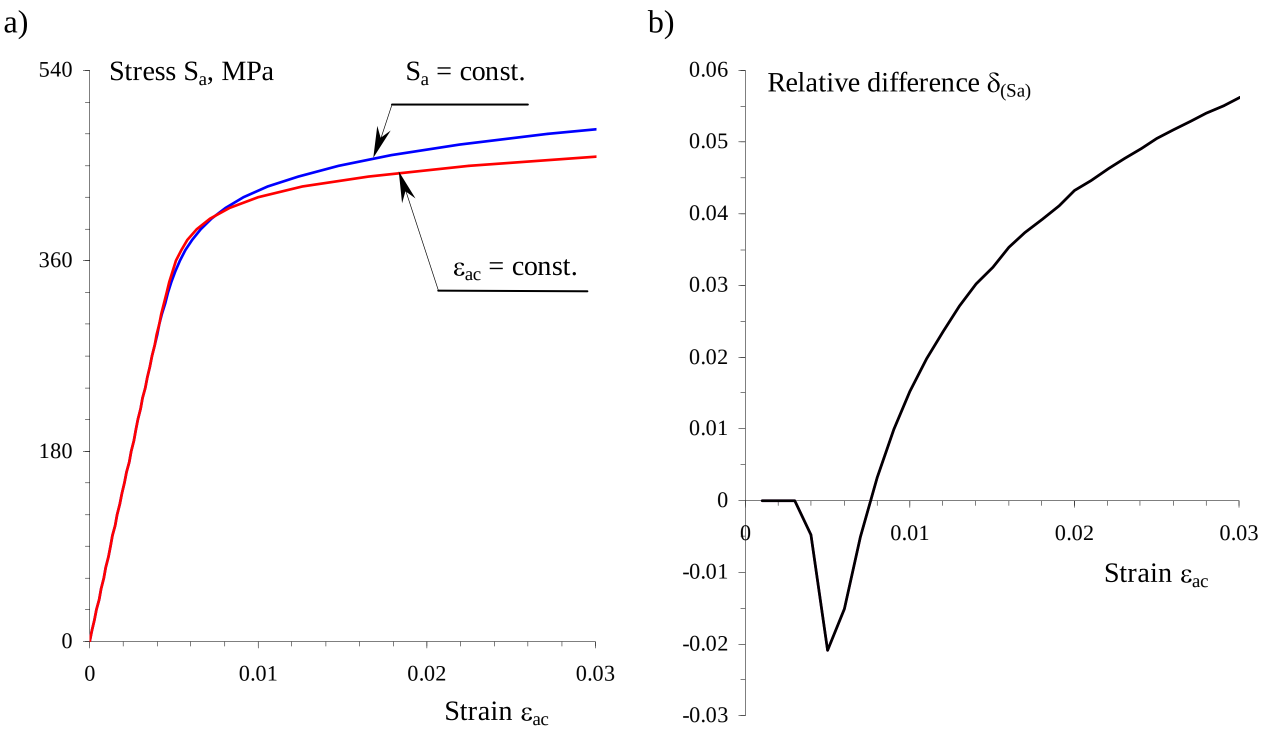

Fig. 3. Comparison of Ramber-Osgood cyclic hardening curves in stress and strain controlled conditions (a) leading to determination of relative difference of nominal stress amplitude S_a (b)

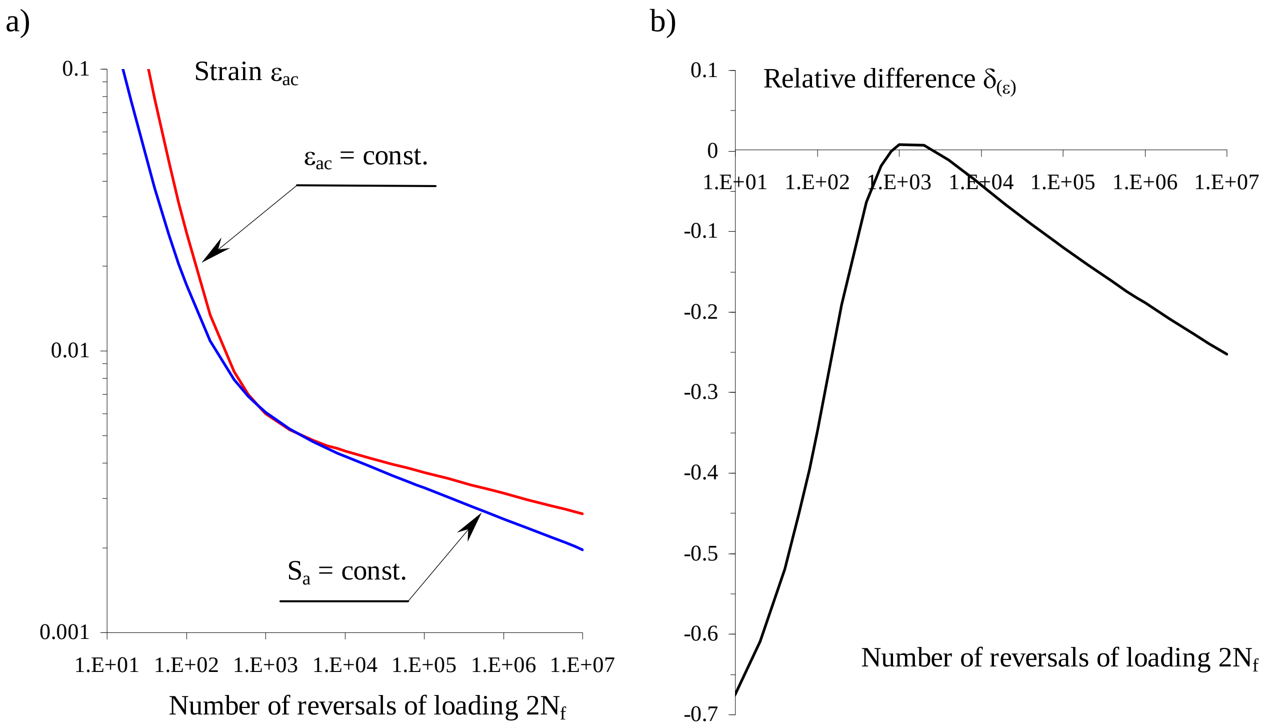

Fig. 4. Comparison of Mason-Coffin fatigue life curves in stress and strain controlled conditions (a) leading to determination of relative difference of total strain amplitude ε_{ac} (b)

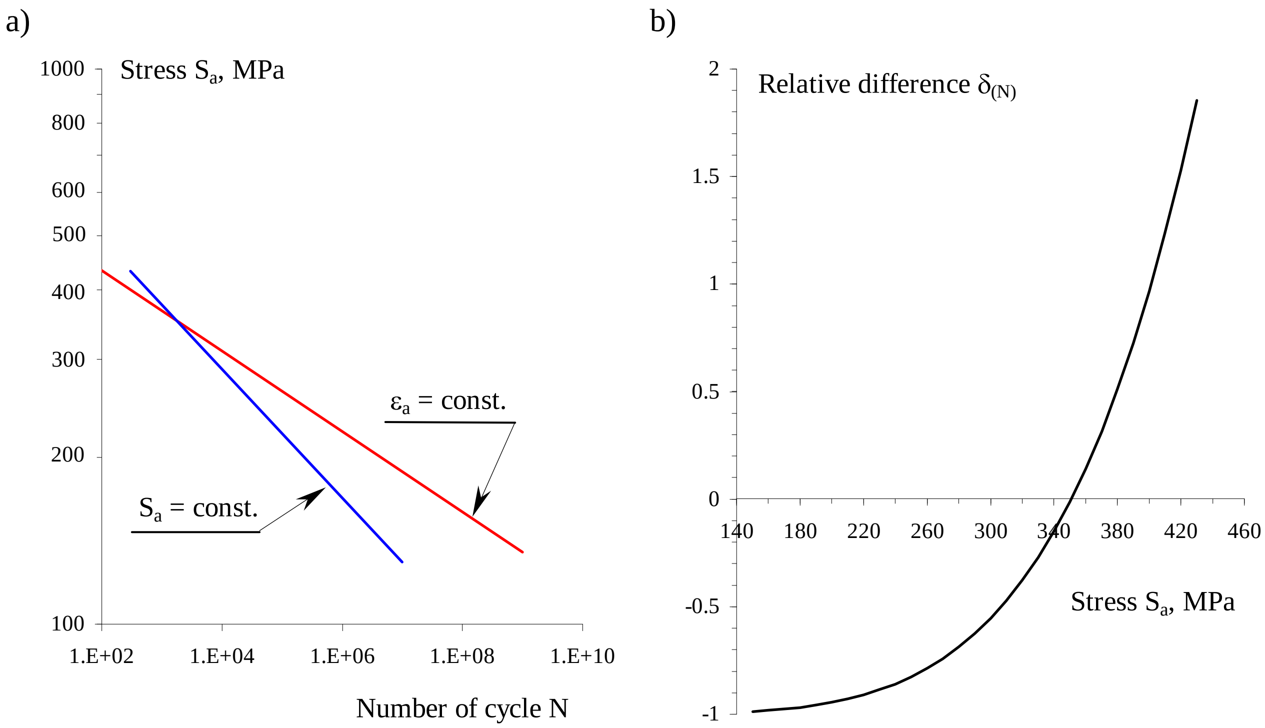

Fig. 5. Comparison of Wöhler fatigue life curves in stress and strain controlled conditions (a) leading to determination of relative difference of number of cycles N (b)

In fig. 3a there were presented test results in the form of R-O curves determined in stress controlled (S_a = const.) and strain controlled (ε_{ac} = const.) conditions. Mutual position of curves indicates their high conformity. It is confirmed by the diagram of relative value difference of stress amplitude $\delta_{(Sa)}$ that was presented in fig. 3b. In the range of $\varepsilon_{ac} < 0.003$ curves of R-O indicatates high conformity ($\delta_{(Sa)} = 0$). In the range from $\varepsilon_{ac} = 0.003$ to $\varepsilon_{ac} = 0.0077$ the curve for ε_{ac} = const. Is characterized by higher values of S_a. Maximum value of relative difference is $\delta_{(Sa)} = -0.021$. In the range of $\varepsilon_{ac} \geq 0.0077$ the curve R-O determined for S_a = const. is characterized by higher values of S_a. Maximum value of relative difference is $\delta_{(Sa)} = 0.056$.

Mutual position of Mason-Coffin fatigue life curves for stress and strain control is presented in fig. 4a whereas values of realive difference determined from the formula (5) in fig. 4b. For the range of number of reversals $2N_f < 800$ and $2N_f > 2100$ higher values of total strain amplitude ε_{ac} are connected with the fatigue life curve obtained in strain controlled conditions. The highest values of relative difference were obtained for $2N_f = 10^1$ ($\delta_{(\varepsilon)} = -0.67$) and for $2N_f = 10^7$ ($\delta_{(\varepsilon)} = -0.25$). For the range of reversals $800 < 2N_f < 2100$ there were obtained higher values ε_{ac} for S_a = const. Value of relative difference is $\delta_{(\varepsilon)} \approx 0.008$.

In fig. 5a there is presented mutual position of Wöhler curves that were determined in dynamic and kinematic controlled conditions. Determined values of relative difference $\delta_{(N)}$ (fig. 5b) for the analyzed range of stress amplitude changes S_a, limit from $\delta_{(N)} \approx -1.0$ (dla S_a = 150 MPa) to $\delta_{(N)} \approx 1.9$ (dla S_a = 430 MPa). Fatigue life curves cross in a point that refers to a value of S_a = 350 MPa. For the value S_a < 350 MPa the curve determined in conditions of ε_{ac} = const. Is characterized by higner values of fatigue life N whereas for S_a > 350 MPa higher values of N were obtained for the curve determined for S_a = const.

4. Summary

Performed analysis of test results of AW-2017A aluminium alloy enables to formulate following remarks:

a. Comparative analysis of R-O, M-C and W curves determined in stress(S_a = const.) and strain (ε_{ac} = const.) controlled conditions indicated ranges of changes of relative values that are for:
   - cyclic strain curveswykresów R-O: $\delta_{(Sa)} = -0.021 \div 0.056$,
   - fatigue life curves M-C: $\delta_{(\varepsilon)} = -0.67 \div 0.008$,
   - fatigue life curves W: $\delta_{(N)} = -1.0 \div 1.9$.

b. Curves of relative differences ($\delta_{(Sa)}$, $\delta_{(\varepsilon)}$, $\delta_{(N)}$) for AW-2017A aluminium alloy are characterized by similar change of values as for X5CrNi18-10 austenitic steel [3]. Concurrence of results can be caused by similar cyclic properties of mentioned alloys because the materials can be classified as the ones that undergo cyclic hardening.

References

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