

DOI: 10.1515/amm-2016-0051

M. CIEŚLA^{*,#}, G. JUNAK^{*}, A. MAREK^{*}

FATIGUE CHARACTERISTICS OF SELECTED LIGHT METAL ALLOYS

The paper addresses results of fatigue testing of light metal alloys used in the automotive as well as aerospace and aviation industries, among others. The material subject to testing comprised hot-worked rods made of the AZ31 alloy, the Ti-6Al-4V two-phase titanium alloy and the 2017A (T451) aluminium alloy. Both low- and high-cycle fatigue tests were conducted at room temperature on the cycle asymmetry ratio of $R=-1$. The low-cycle fatigue tests were performed using the MTS-810 machine on two levels of total strain, i.e. $\Delta\epsilon_c=1.0\%$ and 1.2% . The high-cycle fatigue tests, on the other hand, were performed using a machine from VEB Werkstoffprüfmaschinen-Leipzig under conditions of rotary bending. Based on the results thus obtained, one could develop fatigue life characteristics of the materials examined (expressed as the number of cycles until failure of sample N_f) as well as characteristics of cyclic material strain $\sigma_a=f(N)$ under the conditions of low-cycle fatigue testing. The Ti-6Al-4V titanium alloy was found to be characterised by the highest value of fatigue life N_f , both in low- and high-cycle tests. The lowest fatigue life, on the other hand, was established for the aluminium alloys examined. Under the high-cycle fatigue tests, the life of the 2017A aluminium and the AZ31 magnesium alloy studied was determined by the value of stress amplitude σ_a . With the stress exceeding 150 MPa, it was the aluminium alloy which displayed higher fatigue life, whereas the magnesium alloy proved better on lower stress.

Keywords : Ti-6Al-4V titanium alloy, 2017A aluminium alloy, AZ31 magnesium alloy, low-cycle fatigue, high-cycle fatigue, fatigue life

1. Introduction

Light metal alloys which yield to plastic working, these including such alloys as titanium Ti-6Al-4V, aluminium 2017A (T451) and magnesium AZ31, find increasingly extensive application in the automotive, machine-building, railway engineering as well as aerospace and aviation industries [1, 2, 3, 4]. The growing interest in light metal matrix based alloys for automotive and aviation applications has primarily stemmed from the pursuit of reduction of vehicle weight and fuel consumption. The first of the aforementioned materials, i.e. the Ti-6Al-4V precipitate strengthened two-phase titanium alloy, is often used on account of its positive correlation between strength and plastic properties. An increase in its tensile strength is obtained on simultaneous decrease of plastic properties through the processes of hyperquenching and ageing. The Ti-6Al-4V alloy is characterised by high strength and good formability [5, 6]. It is used to manufacture components of race cars. Furthermore, it is used in aviation as well as in the chemical industry [1]. For instance, in the aerospace and aviation industry, the Ti-6Al-4V alloy is used for frames, edges of wing attack, hydraulic and pneumatic tubing, landing flaps, connecting fasteners etc. [5]. Also hollow stepped axles and shafts for the machine-building and railway industries are manufactured using this material [2].

Magnesium AZ31, on the other hand, is an alloy characterised by good mechanical properties, being

relatively cheap, at the same time. It may be worked in processes such as rolling, press-forming or forging [7]. Its low density makes it particularly attractive for the automotive industry [3, 4].

So far, the evolution of deformable magnesium alloys and of plastic working methods has been largely constrained. Plastic worked magnesium alloys would be used sporadically, which resulted from technological difficulties connected with plastic working as well as high production costs. Low formability of magnesium alloys at temperatures up to 200°C resulted from a limited number of slip systems in the hexagonal lattice [8-11]. Consequently, the number of alloys processed by plastic working is considerably smaller than that of casting alloys. Mechanical properties of plastic worked magnesium alloys are superior compared to casting alloys [4]. Besides the low density (1.74 g/cm^3), the possibility to use magnesium alloys for manufacturing of structural elements is substantiated by a number of other advantageous mechanical properties [3, 8]. The most beneficial combination of properties has been revealed in alloys representing the Mg-Al-Zn-Mn group, containing up to 8% of Al with the addition of Mn (up to 2) and Zn (up to 1.5%) [1, 12,13].

The 2017A aluminium alloy (T451) is superior in terms of its press-formability and bendability. Corrosion resistance of this alloy is moderate, but on account of such properties as strength, for instance, it is widely applied in production of

* SILESIAN UNIVERSITY OF TECHNOLOGY, FACULTY OF MATERIALS ENGINEERING AND METALLURGY, DEPARTMENT OF METALS TECHNOLOGY, 8 KRASIŃSKIEGO STR., 40-019 KATOWICE, POLAND

Corresponding author: marek.ciesla@polsl.pl

TABLE 1

Chemical composition of selected light metal alloys

Material	Chemical composition, element content, wt. %										
	Zn	Ti	Al	Si	V	Cu	Mn	Fe	Ni	Mg	Other
Ti-6Al-4V	-	89.30	6	-	4	-	-	0.35	-	-	0.34
AZ31	0.71	-	3.0	0.02	-	<0.01	0.2	0.003	-	96.06	-
2017A	0.019	0.023	93.32	0.5	-	4.37	0.6	0.4	-	0.77	-

TABLE 2

Basic mechanical properties of selected light metal alloys

Material	Mechanical properties			
	R_m , MPa	$R_{p0.2}$, MPa	A_5 , %	Z , %
Ti-6Al-4V	410.5	302.1	36.3	63.8
AZ31	316.5	225.2	16.6	22.0
2017A	352.5	326.1	16.5	41.0

automotive components, machine parts and structural elements of aircrafts [1]. The 2017A aluminium alloy is mainly used in the automotive as well as aviation and aerospace industry [1, 14]. It is estimated that more than 60% of an aircraft structure is in fact made of aluminium alloys [1].

What proves decisive in using the aforementioned alloys for structural elements once they are subject to plastic working is, besides their low density, also a number of advantageous mechanical properties (R_m , $R_{p0.2}$, A_5). When plastic worked light metal alloys are used to manufacture equipment components for the automotive as well as the aerospace and aviation industry, these alloys should additionally offer advantageous fatigue characteristics.

Bearing the foregoing in mind under the studies addressed in the paper, fatigue tests were conducted on the said group of light metals. Both low- and high-cycle fatigue tests were carried out at room temperature on the cycle asymmetry ratio of $R=-1$. The low-cycle fatigue tests were performed using the MTS-810 machine on two levels of total strain, i.e. $\Delta\epsilon_c = 1.0\%$ and 1.2% . The high-cycle fatigue tests, on the other hand, were performed using a machine from VEB Werkstoffprufmaschinen-Leipzig under conditions of rotary bending.

Based on the results thus obtained, characteristics of fatigue life $\sigma_a=f(N)$ were developed in order to establish grounds for projecting the life of equipment components made of materials from the aforementioned group.

2. Testing material

The material subject to tests comprised hot-worked rods made of the AZ31 alloy, the Ti-6Al-4V two-phase titanium alloy and the 2017A (T451) aluminium alloy, the chemical composition of which has been provided in Table 1. After press-forming, the rods made of magnesium alloy, 12 mm in diameter, were annealed at the temperature of 400°C with the soaking time of 60 minutes, followed by cooling in air. Basic mechanical properties of the materials examined, established at room temperature based on a statistical tension test, have been collated in Table 2.

3. Methodology and test results

The high-cycle fatigue tests were conducted under conditions of rotary tension using a four-station machine from VEB Werkstoffprufmaschinen-Leipzig (Fig. 1) at room temperature. The samples used in the tests were of cylindrical profile and 8 mm in diameter (Fig. 2). Under the testing conditions, the samples were subject to constant bending moment of M_b following the pattern depicted in the diagram provided in Fig. 3. The course of the sample loading process was sinusoidal with the cycle asymmetry ratio of $R=-1$. The load change frequency came to 60 Hz.



Fig. 1. Machine for high-cycle fatigue testing under conditions of rotary bending

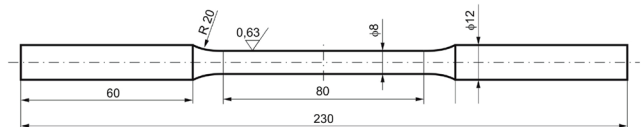


Fig. 2. Geometrical characteristics of the sample tested for fatigue

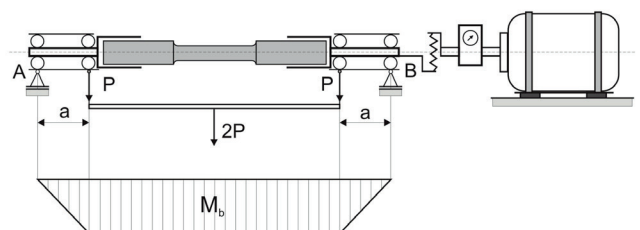


Fig. 3. Pattern of the sample exposure to constant bending moment M_b under fatigue tests

Based on the results thus obtained, one could develop fatigue life characteristics of the alloys studied, expressed as the number of cycles until failure of sample N_f (Fig. 4). The tests proved that up to the number of $N_f = 10^7$ cycles, considerably higher fatigue strength, compared to the magnesium and aluminium alloys, was observed in the Ti-6Al-4V titanium alloy.

The low-cycle fatigue tests were conducted using the MTS-810 strength testing machine. The samples tested were cylinders with the diameter of 12 mm (Fig. 5). The fatigue tests were conducted under conditions of tension and compression, assuming the cycle asymmetry ratio of $R=-1$. The testing machine was controlled by setting the strain to two levels of total strain, namely $\Delta\epsilon_f=1.0$ and 1.2% . In the course of the tests, hysteresis loops characteristic of the balanced stage of the fatigue process, i.e. the saturation state, were recorded. Figures 6 to 8 show sample typical loops for the strain of $\Delta\epsilon_f=1.0\%$, collated with the characteristics of cyclic straining of the alloys studied at $\sigma=f(N)$.

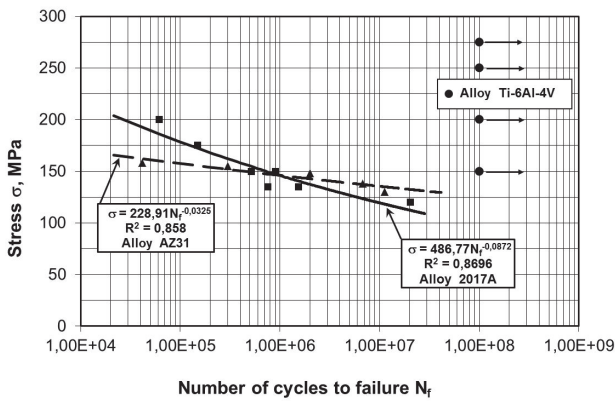


Fig. 4. Fatigue life characteristics of light metal alloys subject to plastic working

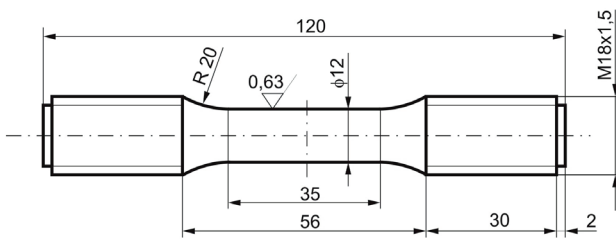


Fig. 5. Geometric properties of the fatigue test sample

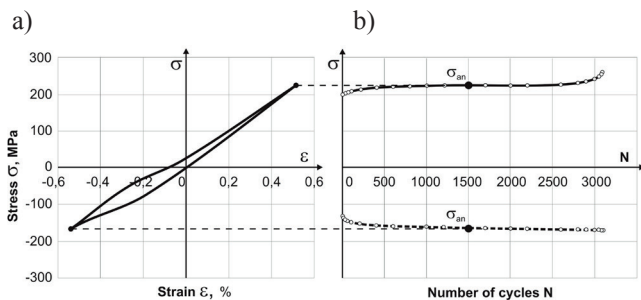


Fig. 6. Hysteresis loop (a) and cyclic strain characteristics (b) for the AZ31 magnesium alloy

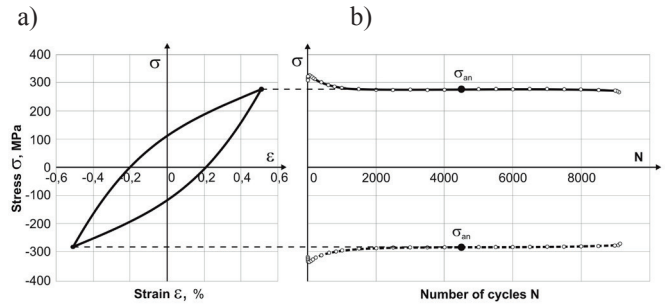


Fig. 7. Hysteresis loop (a) and cyclic strain characteristics (b) for the Ti-6Al-4V titanium alloy

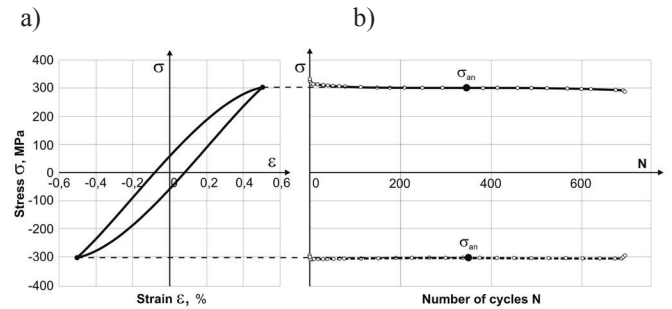


Fig. 8. Hysteresis loop (a) and cyclic strain characteristics (b) for the 2017A aluminium alloy

The low-cycle fatigue tests conducted on the strain of $\Delta\epsilon_f=1.0\%$ revealed the best fatigue life expressed as the number of cycles until failure of sample N_f in the titanium alloy. Significantly worse fatigue life (ca. 3 times lower) was displayed by the magnesium alloy, whereas the lowest fatigue life (ca. 13 times) was established to be characteristic of the aluminium alloy (Fig. 9). A similar correlation between values of life of individual alloys studied was also observed on the strain of $\Delta\epsilon_f=1.2\%$.

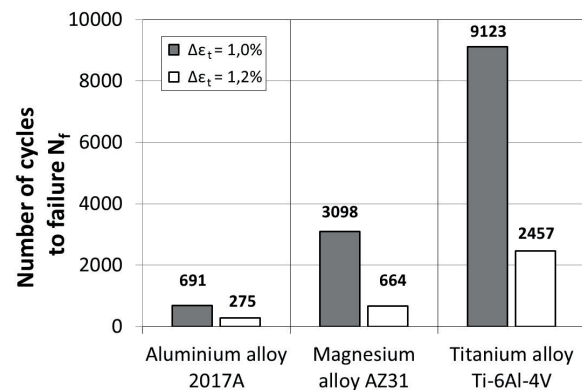


Fig. 9. Fatigue life characteristics of selected light metal alloys subject to plastic working

4. Conclusions

Having analysed the results of the studies of basic mechanical properties (Table 2), one could identify the best strength-related and plastic properties ($R_m=410$ MPa, $R_{p0.2}=302$ MPa, $A_5=36\%$) in the Ti-6Al-4V titanium alloy. The worst mechanical properties ($R_m=316$ MPa, $R_{p0.2}=225$

MPa, $A_5=16,5\%$), on the other hand, characterised the AZ31 magnesium alloy.

The high-cycle fatigue tests conducted under the conditions of rotary bending evidenced both strength and fatigue life to be considerably higher in the titanium alloy compared to the 2017A aluminium and the AZ31 magnesium alloy. Under the conditions of the studies undertaken, no samples made of the alloy in question were found to be cracking in the course of 10^8 cycles while the testing was conducted on the stress of $150\div 275$ MPa. The life of the 2017A aluminium and of the AZ31 magnesium alloy was conditional to the value of the loading envisaged in the fatigue tests. With the stress exceeding 150 MPa, the fatigue life of the aluminium alloy was higher than that of the AZ31 alloy, whereas an opposite correlation was observed on lower stress values.

In the low-cycle fatigue tests, aluminium 2017A and titanium Ti-6Al-4V, after initial insignificant weakening by ca. 10 and 50 MPa respectively, showed characteristic cyclic stability of amplitudal stress. The AZ31 magnesium alloy, on the other hand, revealed cyclic stability (Fig. 4) after initial insignificant strengthening by ca. 30 MPa. An analysis of graphs of the cyclic strain (Fig. 6÷8) implies that the materials studied are characterised by similar values of saturation stress σ_{an} (from 230 MPa for the magnesium alloy to 300 MPa for the aluminium alloy) in a tension half-cycle. A significant difference in terms of the σ_{an} value corresponding to the half-cycle of compression and tension (equalling ca. 60 MPa – see Fig. 6) was revealed for the AZ31 magnesium alloy, this being a consequence of diverging values of $R_{p0,2}$ as determined under the tests of static tension and compression [15].

What could also be observed in the course of the fatigue tests discussed was the considerable differentiation in terms of the area of the hysteresis loops (Fig. 6÷8) recorded during the stabilised stage of the low-cycle fatigue process. However, no correlation was found between the area value, reflecting the energy of destruction accumulated in each cycle in the material made of the given alloy (the highest being observed for the titanium and the lowest for the magnesium alloy), and the low-cycle life of N_f (Fig. 6÷8). Concluding, the fatigue life value obtained for the titanium alloy was the highest, and for the strain of $\Delta\varepsilon_i=1,0\%$ and $1,2\%$, it exceeded the life of the magnesium and the aluminium alloy (the latter displaying the lowest fatigue life) several times (Fig. 9). The hysteresis loop distortion observed in the studies of the magnesium alloy (Fig. 6a) as well as the lack of symmetry between the half-cycles of tension and compression in the graphs of cyclic strain (Fig. 6b) resulted from the differing values of $R_{p0,2}$ under the conditions

of static tension and compression [15].

REFERENCES

- [1] K.E. Oczóś, A. Kawalec, *Kształtowanie metali lekkich*, PWN, Warszawa 2012.
- [2] Z. Pater, J. Tomczak, T. Bulzak, *Hutnik - Wiadomości Hutnicze*, **82**, 9, 599 – 603 (2015).
- [3] A. Kielbus, D. Kuc, T. Rzychoń, *Stopy magnezu - mikrostruktura, właściwości i zastosowanie*, Monografia wydana z okazji jubileuszu 40-lecia Wydziału Inżynierii Materiałowej i Metalurgii Politechniki Śląskiej w Katowicach nt. „Nowoczesne materiały metaliczne - terażniejszość i przyszłość”, Katowice, 61 – 102 (2009).
- [4] J.Przondziono, E. Hadasik, A. Kret, W. Walke, S. Lalik, *Hutnik - Wiadomości Hutnicze* **82**, 9, 623 – 626 (2015).
- [5] A. Kościelna, W. Szkliniarz, *Tytan i jego stopy*, Monografia wydana z okazji jubileuszu 40-lecia Wydziału Inżynierii Materiałowej i Metalurgii Politechniki Śląskiej w Katowicach nt. „Nowoczesne materiały metaliczne - terażniejszość i przyszłość”, Katowice, 103 - 136 (2009)
- [6] A. Bylica, J. Sieniawski, *Tytan i jego stopy*, PWN, Warszawa (1985).
- [7] K. Drozdowski, K. Horzelska, *Hutnik - Wiadomości Hutnicze* **82**, 8, 488 - 493 (2015).
- [8] O. Pashkova, I. Ostrovsky, Y. Henn, *New Challenges in Aeronautics*, Moscow 2007.
- [9] A.G. Beer, M.G. Barnett, *Material Science and Engineering A* **485**, 318-324 (2008).
- [10] K.U. Kainer, *Magnesium Alloys and Technologies*. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim (2003).
- [11] S. Rusz, L. Cizek, J. Kedron, S. Tylsar, M. Salajka, E. Hadasik, T. Donič, *Journal of Trends in the Development of Machinery and Associated Technology* **16**, 1, 55-58 (2012).
- [12] B.L. Mordike, T. Ebert, *Materials Science and Engineering A* **302**, 37-45 (2001).
- [13] J. Bohlen, D. Letzig, K.U. Kainer, *Materials Science Forum* **546-549**, 1-10 (2007).
- [14] J. Śleziona, M. Dyzia, J. Piątkowski: *Aluminium i jego stopy*, Monografia wydana z okazji jubileuszu 40-lecia Wydziału Inżynierii Materiałowej i Metalurgii Politechniki Śląskiej w Katowicach nt. „Nowoczesne materiały metaliczne - terażniejszość i przyszłość”, Katowice, 30 – 60 (2009).
- [15] M. Cieśla, G. Junak, W: *METAL 2015. 24th International Conference on Metallurgy and Materials*, Brno, Czech Republic, June 3rd-5th, Conference proceedings (2015).