Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 28 (2020) 1875–1882

Structural Integrity Procedia

www.elsevier.com/locate/procedia

1st Virtual European Conference on Fracture

Mixed mechanical-metrological approach to quantify the fractographic damage in mechanical components subjected to cyclic loading

Wojciech Macek[a]*, Robert Owsiński[b], Ricardo Branco[c], Jarosław Trembacz[b]

[a]*University of Occupational Safety Management, Department of Technical Sciences, Bankowa 8, 40-007 Katowice, Poland*
[b]*Opole University of Technology, Prószkowska 76, 45-758 Opole, Poland*
[c]*University of Coimbra, CEMMPRE, Department of Mechanical Engineering, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal*

Abstract

The purpose of this paper is to present a mixed mechanical-metrological procedure, based on a fractographical approach, capable of correlating the fracture deformation behaviour with the fatigue loading history. The degradation mechanisms, which are related to the degree of fatigue damage, are identified from the changes in the dynamic response of the mechanical system. These changes, recorded during the tests by means of uniaxial acceleration sensors, are compared to different surface texture parameters, namely height parameters and material/void parameters, determined for both parts of the fracture surfaces after fatigue damage, and with the force needed for complete failure. The results show a direct relationship between the degree of fatigue damage, accounted for by the changes in the uniaxial acceleration sensors, and the surface texture parameters. This connection between the mechanical system dynamics and the surface metrology can provide a more precise fitness-for-service assessment.

Keywords: Surface texture, surface metrology, fractograpghy, fatigue loading, accelaration measurement.

* Corresponding author.
E-mail address: wojciech.macek@yahoo.com

10.1016/j.prostr.2020.11.010

Nomenclature

a_m	acceleration amplitude measured on the additional mass
a_u	acceleration amplitude measured on the grip
F	force
α	degree of fatigue damage
$\alpha(t)$	current acceleration amplitude ratio
α_0	initial acceleration amplitude ratio
ω	natural frequency
ρ	system damping factor
ν_r	eigen frequency
σ	breaking stress
σ_a	nominal bending stress amplitude

1. Introduction

Structural health monitoring is a powerful tool of modern industry able to continuously evaluate the fatigue damage of engineering parts. Nowadays, fatigue crack detection and fatigue crack monitoring can be done by means of different non-destructive techniques, such as extensometry, acoustic emission, ultrasonic scanning, electric potential drop, digital image correlation, among others (Muhlstein et al., 2004; Macek and Macha, 2015; He et al., 2016; De Cola et al., 2019; Ogrinec et al., 2019; Paunović et al., 2019). Within the most recent proposals capable of correlating the degree of damage induced by fatigue loads, we can mention the new approach proposed by Owsiński et al. (2016) based on the dynamic response variation at critical points of the mechanical component evaluated by acceleration sensors (Owsiński et al., 2017).

In the context of the design of critical engineering components, fatigue damage is usually accounted for by means of stress-based, strain-based, and energy-based parameters (Antunes et al., 2014; Szala et al., 2017; Lesiuk et al., 2019; Branco et al., 2019; Niesłony et al., 2020). The more accurate design methods are generally based on local approaches which is likely to improve design. Nevertheless, the random nature of the fatigue phenomenon, as well as its complex synergistic basis, make critical engineering parts highly susceptible to fatigue failure (Macek, 2019). Therefore, post-failure analyses can provide valuable information on the failure mechanisms (Macek, 2020, 2020a) and their relationships with the loading histories.

In this paper, we present a mixed mechanical-metrological procedure, based on a fractographical approach, capable of correlating the fracture deformation behaviour with the fatigue loading history. The degradation mechanisms, which are related to the degree of fatigue damage, are identified from the changes in the dynamic response of the mechanical system. These changes, recorded during the tests by means of uniaxial acceleration sensors, are compared to different surface texture parameters, namely height parameters and material/void parameters, determined for both parts of the fracture surfaces after fatigue damage, and with the force needed for complete failure. The methodology is tested for fracture samples of 6082 aluminium alloy subjected to different degrees of fatigue damage induced by bending fatigue.

2. Experimental procedure

The mix mechanical-metrological procedure developed in the current research is schematised in Figure 1. As shown, it comprises three main parts: (1) fatigue testing; (2) monotonic tensile testing; and fractographic evaluation. As far

Table 1. Mechanical properties of the 6082 aluminium alloy (Niesłony et al., 2016).

E (MPa)	ν	σ_{YS} (MPa)	σ_{UTS} (MPa)	σ'_f (MPa)	ε'_f	b	c
76,998	0.3	250	290	650.6	1.2920	-0.0785	-1.0139

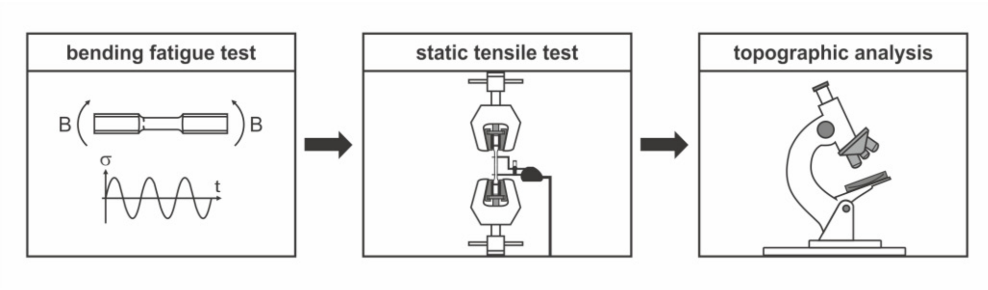

Fig. 1. Scheme of the proposed mixed mechanical-metrological procedure.

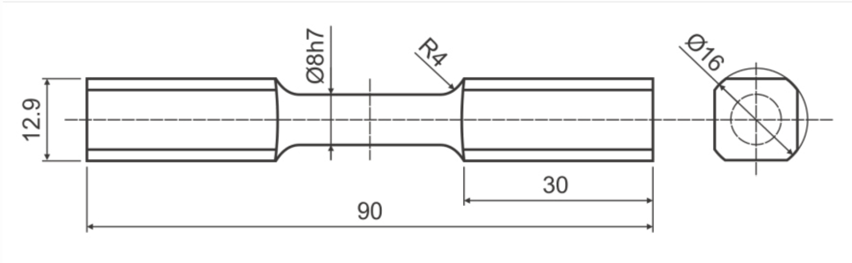

Fig. 2. Specimen geometry (dimensions in millimeters).

Table 2. Fracture surface parameters selected for the fractographic analysis.

Height parameters, S-	Material and void volume parameters, V-
Root-mean-square height, Sq (μm)	Material volume, Vm (mm^3/mm^2)
Maximum peak height, Sp (μm)	Core material volume, Vmc (mm^3/mm^2)
Maximum pit height, Sv (μm)	Void volume, Vv (mm^3/mm^2)
Maximum height, Sz (μm)	Core void volume, Vvc (mm^3/mm^2)
Arithmetical mean height, Sa (μm)	Pit void volume, Vvv (mm^3/mm^2)

as the fatigue tests is concerned, first it is defined an adequate resonant frequency; after that, it is defined the desired loading levels; next, it is completed the fatigue test for a specific degree of damage; and, finally, the results of the test are recorded for further analysis. Detailed information about the setup can be found in the recent paper by Macek et al. (2020). The mutual relationship between the acceleration amplitudes of the mass (a_m) and of the grip (a_u) can be established by the following formula:

$$\alpha = \frac{a_m}{a_u} = \frac{\sqrt{(\omega^2 - \nu_r^2)^2 + 4\rho^2\nu_r^2}}{\sqrt{\omega^4 + 4\rho^2\nu_r^2}} \tag{1}$$

where ω is the natural frequency of the undamped system, ρ is the system damping factor, and ν_r is the eigen frequency (Owsiński et al., 2017). Based on the previous equation, we can conclude that the α ratio is independent of the amplitude of kinematic excitation and, therefore, the degree of fatigue damage introduced into the testing system can be directly related to the α ratio.

Regarding the fatigue testing program, the material selected was a 6082 aluminium alloy. Its main mechanical properties are compiled in Table 1. The specimen geometry consisted of a smooth cylindrical sample (see Figure 2) with a 8mm-diameter gauge section. Tests were performed under fully-reversed conditions, with a nominal bending stress amplitude (σ_a) equal to 170 MPa, and a frequency of loading changes equal to 78 Hz. A series of tests was done to obtain specific degree of fatigue damage ($\alpha(t)/\alpha_0$), more precisely values in the range 50-90% with steps of 5%. For the sake of clarity, $\alpha(t)/\alpha_0 = 1$ means absence of fatigue damage while lower values of the $\alpha(t)/\alpha_0$ ratio mean higher fatigue damage (Owsiński et al., 2017).

After the completion of the fatigue tests, total failure of the specimens (i.e. separation into two pieces) was induced by means of a computer-controlled electromechanical tension-compression universal testing machine, under position control, at a displacement rate of 1 mm/min. The maximum load, F, applied in each case was recorded. Finally, fracture surfaces were analysed via an optical three-dimensional non-contact focus-variation microscope, model Alicona IF G4 profilometer, equipped with a 10× magnification lens. The effect of the degree of fatigue damage on fracture surfaces was then investigated using different height (S-) and material/void (V-) parameters defined in accordance with the ISO 25178 standard (see Table 2).

3. Results presentation

The typical evolution of the acceleration amplitude ratio (α) with the number of cycles for the bending fatigue tests performed at different loading conditions is exhibited in Figure 3. Overall, we can see a first region, which occupies most of the test, where the α ratio is relatively constant, irrespective of the loading case. In the final stage of the test, there is an abrupt reduction of the α ratio until the total failure of the specimen. These general trends clearly indicate that the proposed procedure is capable of accounting for the degree of fatigue damage induced into the mechanical part.

Figure 4 shows the fracture surfaces obtained in the tests for the same nominal stress amplitude but interrupted for different degrees of fatigue damage. The analysis of the fracture surfaces shows the initiation of two cracks at the surface of the specimens, in radial opposite locations, which propagate towards the centre. The areas of these two regions are clearly dependent on the degree of fatigue damage. Not surprisingly, the specimens subjected to higher values of the α ratio (from the top to bottom) have lower degrees of fatigue damage and, consequently, lower areas associated with the fatigue crack initiation stage. On the contrary, the central region, which is caused by the monotonic tensile loading applied to separate the specimens into two pieces, increases with higher values of the α ratio, i.e. lower degree of fatigue damage.

The values of the maximum applied force F during the monotonic tensile test for the different α ratios are displayed in Figure 5. Although there are a few exceptions, as the α ratio decreases, the applied force for static breaking reduces. This is coherent with the expectations, since higher degrees of fatigue damage imply higher crack lengths and, consequently, lower areas of the uncracked cross-section. This means that the separation of the specimen into pieces can be ensured by applying smaller loads.

The values of the height parameters (Figure 6(a)) and the void/volume parameters (Figure 6(b)) of the two broken sides of the specimens for different degrees of fatigue damage are presented in Figure 6. As shown, for a constant α

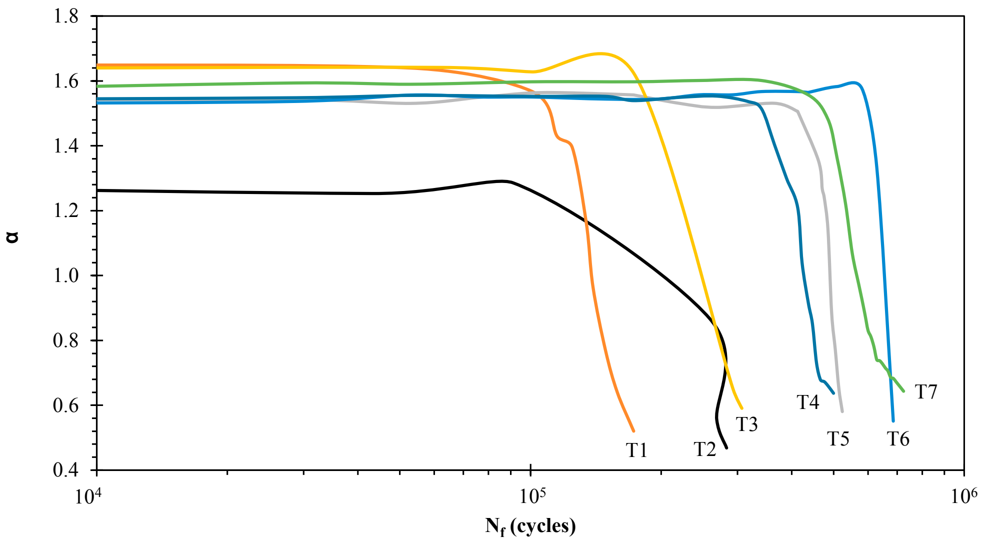

Fig. 3. Evolution of α ratio with the number of cycles (N) for the different fatigue tests. T1 to T7 denote the specimen reference.

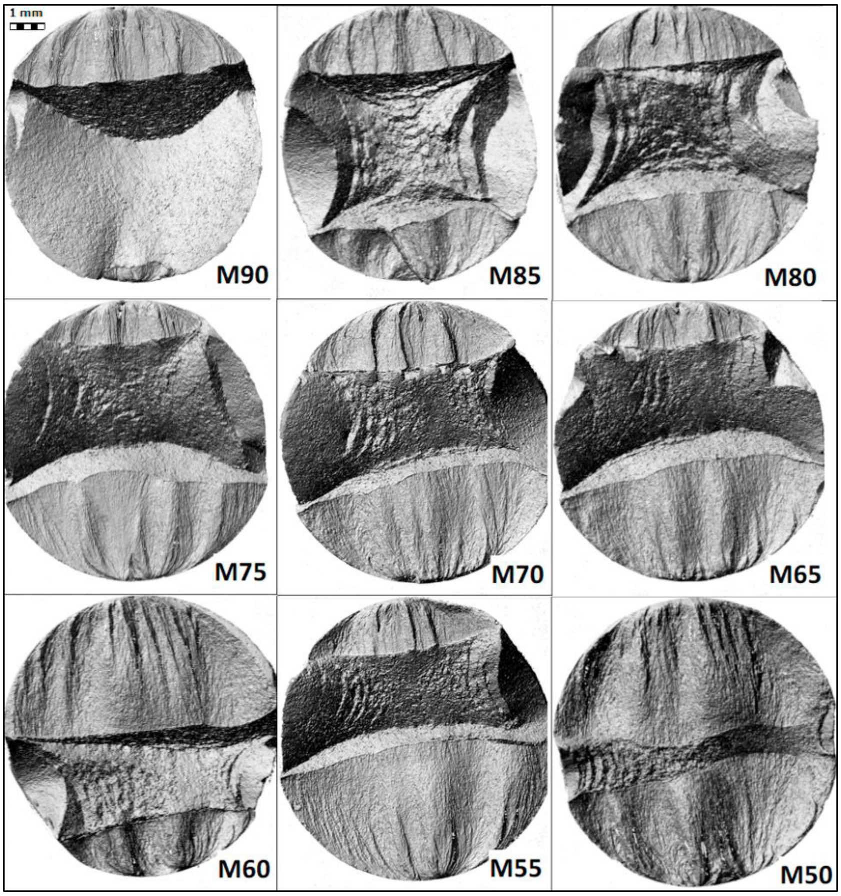

Fig. 4. Fracture surfaces of the mass side for the specimens tested in this study for different values of the α ratio (M refers to the mass side and the two-digit number refers to the value of the α ratio of the test, e.g. M90 corresponds to α=90% for the mass side of the broken specimen). Higher α ratios correspond to lower degrees of fatigue damage and vice-versa.

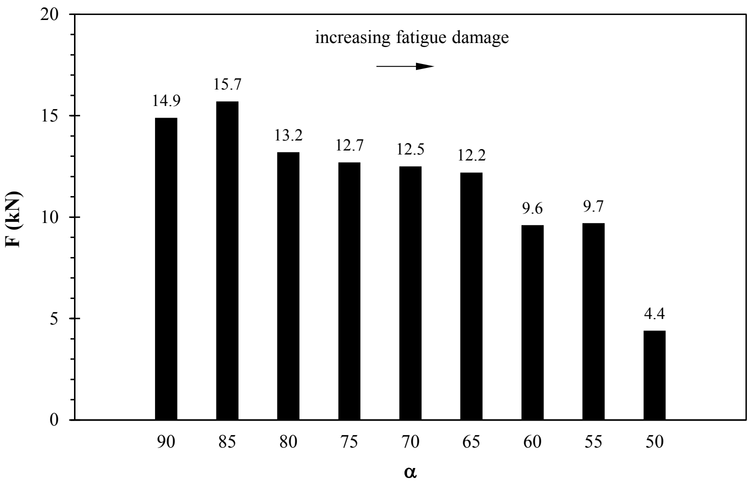

Fig. 5. Maximum applied force of the monotonic tensile tests versus α ratio. Higher α ratios correspond to lower degrees of fatigue damage and vice-versa.

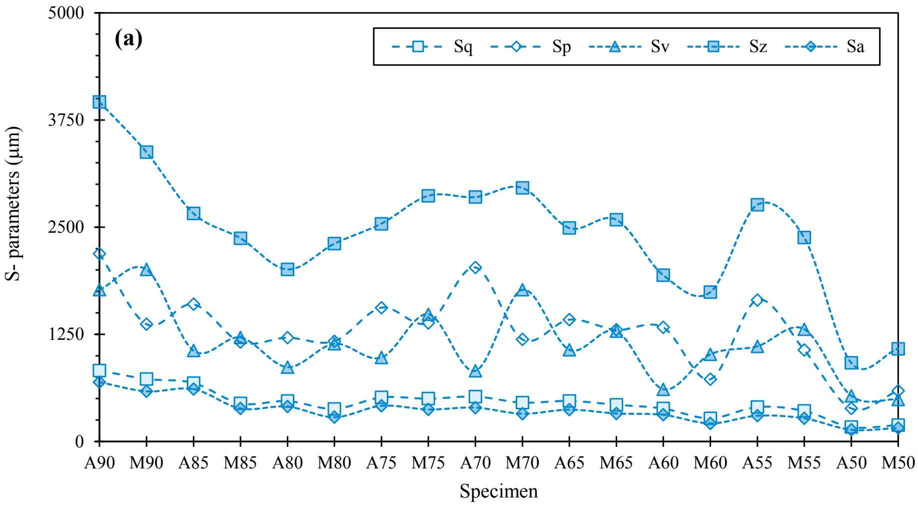

Fig. 6. Surface texture parameters against the α ratio for both sides of the broken specimens: (a) height parameters; and (b) material and void/volume parameters (M refers to the mass side; A refers to the grip side; the two-digit number refers to the value of the α ratio of the test, e.g. M90 corresponds to α=90% for the mass side of the sample). Higher α ratios correspond to lower degrees of fatigue damage and vice-versa.

ratio, the parameters measured for both sides of the specimen show signficant differences. Overall, it is also clear a strong effect of the degree of fatigeu damage on the fracture surface parameters. Although we can see some exceptions, in general, fracture surface parameters decrease with lower values of the α ratio. This fact can be explained by the greater extent of the propagation areas (see Figure 4) associated with higher degrees of fatigue damage, or in other words, lower α ratios. At these regions, the surface texture variations are less expressive which is captured by analysis based on the total area method.

The correlation of the tensile static force with the degree of fatigue damage has been demonstrated in Figure 5. However, the link between the breaking stress and the fracture surface parameters is not clear. In the present study, this link has been investigated by means of the Sa and Vv parameters, taking into account the measurements for the mass and the grip sides. The breaking stress has been defined from the ratio of the maximum tensile force to the area of the rupture zone. Figure 7 plots the typical trends found in the analysis. Figure 7(a) displays the relationship between Sa and σ while Figure 7(b) shows the relationship between Vv and σ. As can be seen, there is a strong

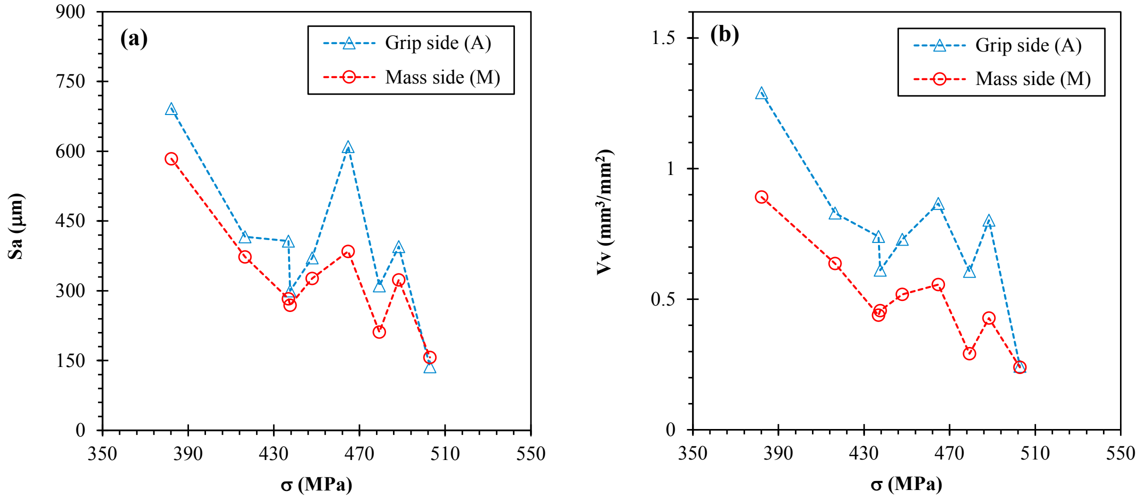

Fig. 7. Evolution of selected fracture surface parameters against the breaking stress: (a) Sa; and (b) Vv (σ is defined by dividing the breaking force by the area of rupture zone).

interconnection between the data for both cases, either for the mass side or the grip side. In addition, we can see that surface paramaters are generally higher for the grip side. It is also interesting to note that the functions evaluated for the mass and the grip sides are relatively similar which demonstrates some reciprocity.

4. Conclusions

The present paper proposed a mixed mechanical-metrological procedure, based on a fractographical approach, able to correlate fatigue loading with the fractographic damage. The degree of damage is controlled by the changes in the dynamic response of the mechanical system. This connection between the mechanical system dynamics and the surface metrology can provide a more precise fitness-for-service assessment. More specific conclusions are the following:

- A multi-crack initiation phenomenon caused by the nucleation of two crack at radially opposite sites were found. The appearance of the fracture surfaces is characterised by a rupture zone, at the central part of the specimen, and two fatigue areas;
- Fatigue areas increase with the higher degrees of fatigue damage, i.e. with the reduction of the α ratio. In an opposite direction, rupture zones decrease with higher degrees of fatigue damage, which results in lower breaking tensile loads;
- A strong correlation between the fracture surface parameters (Sa and Vv) and the breaking stress was observed. In general, Sa and Vv are decreasing functions of the breaking stress. Overall, fracture surface parameters, for a similar breaking stress, are lower at the mass side.

Acknowledgements

This research is sponsored by FEDER funds through the program COMPETE – Programa Operacional Factores de Competitividade – and by national funds through FCT – Fundação para a Ciência e Tecnologia – under the project UIBD/00285/2020.

References

Antunes, F.V., Chegini, A.G., Correia, L., Branco, R. (2014). Numerical study of contact forces for crack closure analysis. Int. J. Solids and Struct. 51, 1330-1339. https://doi.org/10.1016/j.ijsolstr.2013.12.026

Branco, R., Prates, P.A., Costa, J.D., Berto, F., Kotousov, A. (2019). New methodology of fatigue life evaluation for multiaxially loaded notched components based on two uniaxial strain-controlled tests. Int. J. Fat. 111, 308-320. https://doi.org/10.1016/j.ijfatigue.2018.02.027

De Cola, F., Quino, G., Dragnevski, K., Petrinic, N., 2019. An extended in-situ method to improve the understanding of fracture mechanics of granular materials using sound measurements. Eur. J. Mech. - A/Solids 76, 1–12. https://doi.org/10.1016/j.euromechsol.2019.02.012

He, Z., Kotousov, A., Berto, F., Branco, R., 2016. A brief review of recent three-dimensional studies of brittle fracture. Phys. Mesomech. 19, 6–20. https://doi.org/10.1134/S1029959916010021

Lesiuk, G., Rymsza, B., Rabiega, J., Correia, J., De Jesus, A., Calcada, R., 2019. Influence of loading direction on the static and fatigue fracture properties of the long term operated metallic materials. Eng. Fail. Anal. 96, 409–425. https://doi.org/10.1016/j.engfailanal.2018.11.007

Macek, W. 2019. Fractal analysis of the bending-torsion fatigue fracture of aluminium alloy. Eng. Fail. Anal. 99, 97–107. https://doi.org/10.1016/J.ENGFAILANAL.2019.02.007

Macek, W., Branco, R., Trembacz, J., Costa, J.D., Ferreira, J.A.M., Capela C. (2020a). Effect of multiaxial bending-torsion loading on fracture surface parameters in high-strength steels processed by conventional and additive manufacturing. Engineering Failure Analysis, 104784.

Macek, W., Macha, E., 2015. The Control System Based on FPGA Technology For Fatigue Test Stand MZGS-100 PL. Arch. Mech. Eng. 62. https://doi.org/10.1515/meceng-2015-0006

Macek, W., Owsiński, R., Trembacz, J., Branco, R. (2020). Three-dimensional fractographic analysis of total fracture areas in 6082 aluminium alloy specimens under fatigue bending with controlled damage degree. Mech. Mater. 147, 103410. https://doi.org/10.1016/j.mechmat.2020.103410

Muhlstein, C.L., Howe, R.T., Ritchie, R.O., 2004. Fatigue of polycrystalline silicon for microelectromechanical system applications: crack growth and stability under resonant loading conditions. Mech. Mater. 36, 13–33. https://doi.org/10.1016/S0167-6636(03)00028-0

Niesłony, A., Böhm, M., Owsiński, R., 2020. Formulation of multiaxial fatigue failure criteria for spectral method. Int. J. Fatigue 135, 105519. https://doi.org/10.1016/j.ijfatigue.2020.105519

Ogrinec, P., Slavič, J., Česnik, M., Boltežar, M., 2019. Vibration fatigue at half-sine impulse excitation in the time and frequency domains. Int. J. Fatigue 123, 308–317. https://doi.org/10.1016/j.ijfatigue.2019.02.031

Owsiński, R., Niesłony, A., 2016. Analytical model of dynamic behaviour of fatigue test stand—description and experimental validation, in: Springer Proceedings in Mathematics and Statistics. https://doi.org/10.1007/978-3-319-42402-6_24

Owsiński, R., NiesŁony, A., 2017. Identification of fatigue cracks on the basis of measurable changes in system dynamics. Stroj. Cas. 67, 77–84. https://doi.org/10.1515/scjme-2017-0020

Paunović, S., Cajić, M., Karlićić, D., Mijalković, M., 2019. A novel approach for vibration analysis of fractional viscoelastic beams with attached masses and base excitation. J. Sound Vib. 114955. https://doi.org/10.1016/J.JSV.2019.114955

Szala, M., Kot, E.A., 2017. Influence of repainting on the mechanical properties, surface topography and microstructure of polyester powder coatings. Adv. Sci. Technol. Res. J. 11, 159–165. https://doi.org/10.12913/22998624/69680