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THE FATIGUE BEHAVIOUR OF ALUMINIUM FOAM

VEDENJE ALUMINIJEVIH PEN PRI PREIZKUSU UTRUJENOSTI

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The aim of this work was to study the fatigue behaviour of aluminium foam during compression-compression cyclic loading under an applied load. The reason was to estimate the amount of load for a fatigue life of 10^5 cycles with or without a small amount of permanent plastic deformation determined to be less than 1 mm. The samples were subjected to cyclic loading under various forces (proportion of level force estimated from a uni-axial compression test) in one given direction due to the elimination of the foam anisotropy. Moreover, the fatigue behaviour of the aluminium foam under compression-compression cyclic loading is described macroscopically. It was revealed that 50 % of the applied load estimated from the uni-axial compression test is sufficiently low for a fatigue life 10^5 cycles in the case of a foam density of 0.211 ± 0.007 g cm^{-3}.

Keywords: aluminium foam, fatigue life, level force, endurance limit

Cilj tega dela je bilo preučevanje vedenja aluminijevih pen pri preizkusu utrujenosti s tlačno-ciklično tlačnim obremenjevanjem v odvisnosti od uporabljene obremenitve. Razlog je bil ugotoviti obremenitev za zdržljivost za utrujenost do 10^5 ciklov brez majhne plastične deformacije, manj kot 1 mm ter z njo. Vzorci so bili ciklično obremenjeni z različnimi silami (proporcionalno ravnotežni sili, ugotovljeni pri enoosnem tlačnem preizkusu) v eni smeri, da bi izločili vpliv anizotropije pene. Poleg tega je makroskopsko predstavljeno vedenje aluminijeve pene pri preizkusu utrujenosti s tlačno-ciklično tlačnim obremenjevanjem. Ugotovljeno je, da je 50 % obremenitve, dobljene pri enoosnem tlačnem preizkusu, dovolj, da pena z gostoto 0,211 ± 0,007 g cm^{-3} pri utrujenostnem preizkusu zdrži 10^5 ciklov.

Ključne besede: pena iz aluminija, zdržljivost za utrujenost, stopnja sile, maksimalna obremenitev

1 INTRODUCTION

Aluminium foam is known in industry as a good candidate material for the cores of sandwich panels due to its good stiffness-to-weight ratio.[1–4] The effect of composition, manufacturing parameters, sound-absorption properties and electrical behaviour on the foams' properties was already studied for example in[3,5–8]. The deformation mechanism of aluminium foam during uni-axial compression and during uni-axial compression-compression cyclic loading was studied in[5,9–15] macroscopically and by using X-ray computed tomography and surface strain mapping. These studies were focused on determining the deformation modes and revealing the structural character responsible for oremature yielding. Our study is focused on contributing to an estimate of the force at which the aluminium foam can be used for 10^5 compression-compression cyclic loadings.

2 EXPERIMENTAL

2.1 Material

Alporas® aluminium foamed block of composition Al + 1.5 % Ca + 1.6–3 % TiH_2 [2,8] was used for the study. Since the aluminium foam block is anisotropic,[8,16,17] the middle area of the block, which is characterized by the presence of the largest amount of non-uniformities within the structure (the presence of the elongated pores, pore agglomerates, fractured pore faces, microstructural in-homogeneities, etc.) was chosen for an estimation of the level force. The density of the represented area is 0.211 ± 0.007 g cm^{-3}. Uni-axial compression-compression cyclic loadings were performed on a material testing system device (MTS 810) using cubic samples of dimension a = 45 mm. The deformation mechanism on the macro-scale was revealed using a digital camera set on an MTS device

2.2 Estimation of the level force

The uni-axial load-stress behaviour of the aluminium foam has been studied elsewhere[5–7] and is shown in **Figure 1a**. It covers three regions: the elastic region at low loads (includes the hardening region) ended by peak stress, the long load-strain plateau wherein localized plastic collapse propagates from one cell band to another. After all bands collapse densification region of rapid rise of load starts.

The level force (responsible for the plastic collapse of the first cell band within the sample[5–7]) was estimated as an average from 25 uni-axial compression tests according to the DIN norm[18] to 2200 N. It should be noted that 10 of the 25 samples showed a load peak well below (1000 N and 1800 N, respectively) due to the occurrence of large, elongated pores within the structure of the represented area.

2.3 Compression-compression fatigue behaviour

To find out the relation between the ultimate proportions of the level force (LF) and the fatigue behaviour

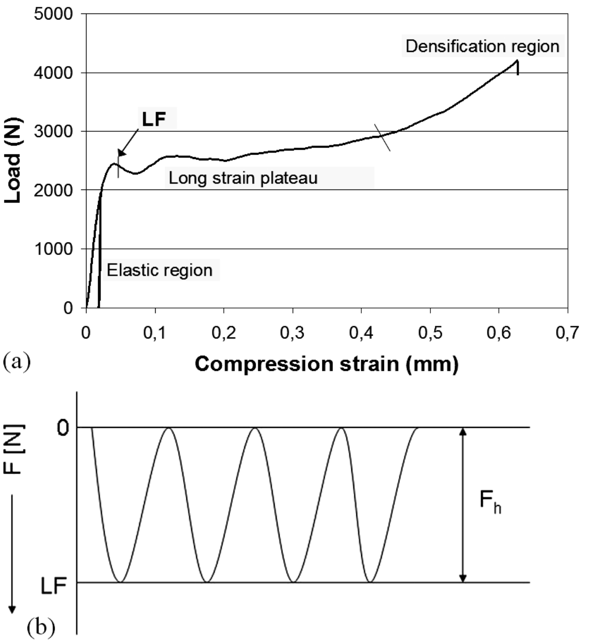

Figure 1: a) Typical uni-axial compression load-strain curve with definition of the level force (LF), b) description of the applied load during the compression-compression cyclic loading

Slika 1: a) Značilna krivulja sila – raztezek z opredeljeno stopnjo sile (LF), b) videz uporabljene obremenitve med tlačno-ciklično tlačnim obremenjevanjem

the samples were loaded by forces increases from 50 % to 90 % LF with a step of approximately 5 % and 10 %. The samples were subjected to compression-compression cyclic loading according to **Figure 1b** during the period over 10^5 cycles. The fatigue life is defined as the number of cycles corresponding to the onset of an abrupt strain jump.

3 RESULTS AND DISCUSSION

3.1 Deformation mechanism

As presented in **Figure 2a**, the compression-compression S-N curves during the cyclic loading are comparable for applied fraction of LF, but the onset of the yielding starts after different number of cycles. While in the case of 90 % LF, it is achieved immediately after the cyclic loading, in case of 69 % LF it starts after 30000 cycles and is characterized by changes in the strain-rates. In the case of 63 % LF, it is achieved after approximately 97000 cycles, which is almost the defined endurance limit (10^5 cycles) – see detail in **Figure 2b**. It suggests that the fatigue life (in case of a rigid material – rapid coalescence and growth of cracks, in the case of foamed material – evolution and subsequent collapse of weak pore bands) is mainly affected by the proportion of the loading force and the mechanism of fatigue damage is delayed with a decrease of the fraction (%) LF.

The deformation mechanism during compression-compression cyclic loading can be described through S-N curves and is revealed macroscopically in **Figure 3**.

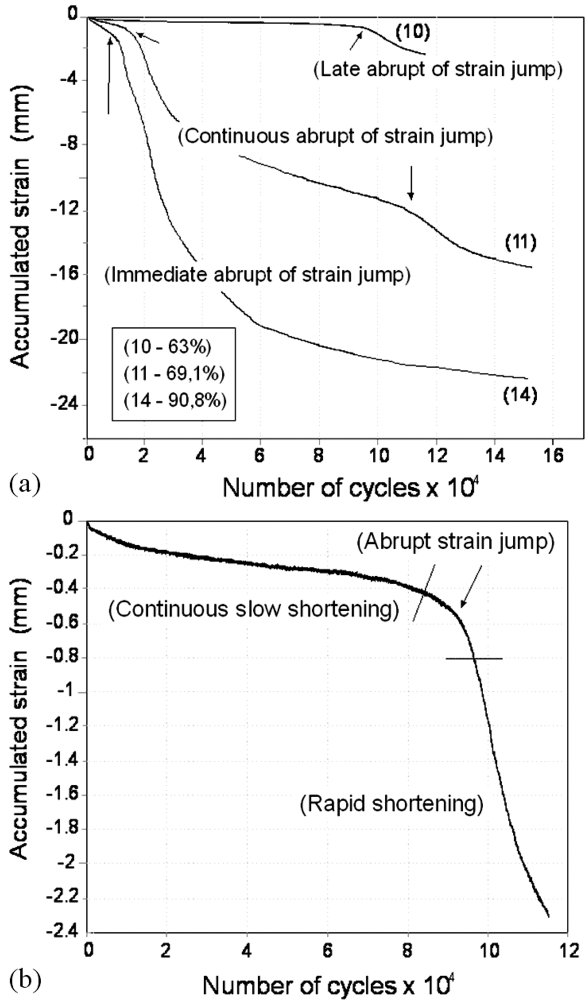

Figure 2: Compression-compression S-N curves; a) representation of the different fatigue life with respect to the proportion of LF, b) detail of the S-N curve

Slika 2: Tlačno-tlačne S-N-krivulje; a) predstavitev različne zdržljivosti pri utrujenostnem preizkusu v odvisnosti od LF, b) detajl S-N-krivulje

The principle of evolution of the plastic deformation and its spreading within the sample during uni-axial compression and cyclic loading is similar.[9–12] Immediately after loading in the elastic region, the uniform evolution of the plastic hinges within the whole samples was observed. The buckling and bending of the pore walls (**Figure 3a**, **b**) together with the continuous evolution of the plastic hinges follows as the deformation continues into the "hardening region" and through the hardening region.[12] These features are responsible for the loss of stiffness associated with a continuous shortening before the abrupt strain jump presented in **Figure 2b**. The abrupt strain jump is related to a macroscopically viewed plastic collapse of a group of pores within the deformation bands (**Figure 3b**, **c**) and causes changes in the strain rate due to the softening effect after the collapse.[12] Subsequently, in the vicinity of the already plastically deformed group of pores the whole deformation band

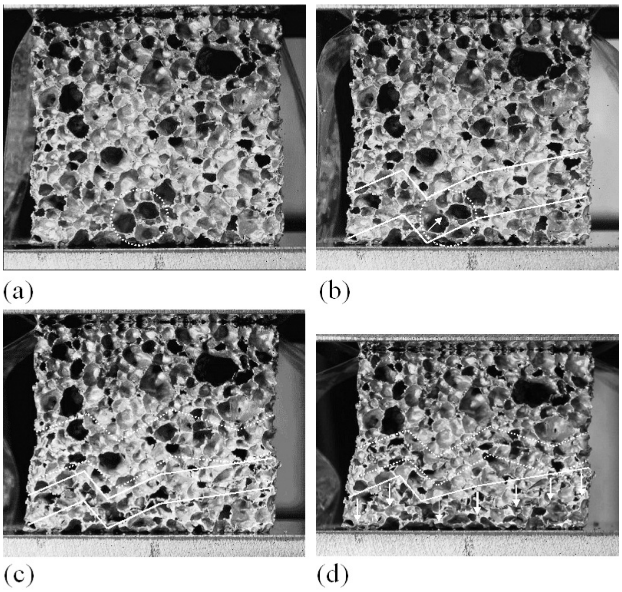

Figure 3: Deformation mechanism during compression-compression cyclic loading in a macroscopic view; a) un-deformed sample, b) buckling of the pore faces within the pore band, c) plastic collapse of the pore band and the creation of another one and d) continuous shortening

Slika 3: Deformacijski mehanizem med tlačno-ciklično tlačnim obremenjevanjem v makroskopskem pogledu; a) nedeformiran vzorec, b) uklanjanje por v pasu por, c) plastično posedanje pasu por in nastajanje drugih por, d) neprekinjeno skrajšanje

closes up and the process is repeated within the other region of the foamed sample (**Figure 3c**, **d**), also accompanied by changes in the strain rate (**Figure 2a**, No.11). However, the changes in the strain rates are omitted if the loading is performed with a high proportion of LF, as presented in **Figure 2a** No.14. Vice-versa, no permanent deformation occurs if the loading is performed by a small proportion of LF to overcome the load of the plastic collapse of the pore band, as seen in **Figure 2a** No.10.

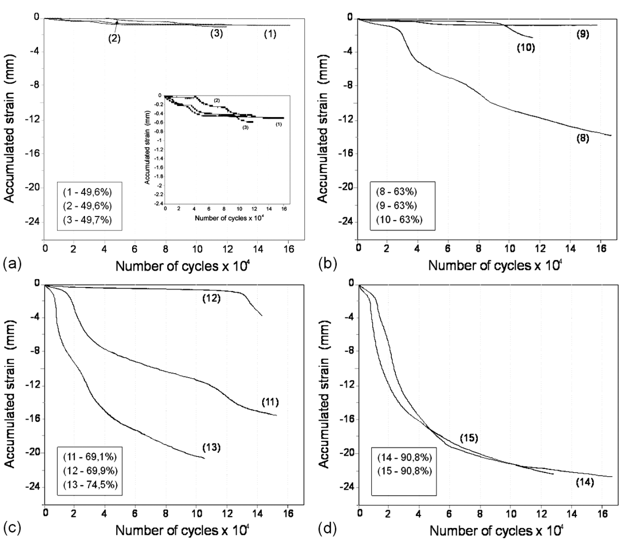

Figure 4: S-N curves for compression-compression cyclic loading for various LF proportion; a) 50 %, b) 63 %, c) 70 % and d) 90 %

Slika 4: S-N-krivulje za tlačno-ciklično tlačno obremenjevanje pri različnih LF-razmerjih; a) 50 %, b) 63 %, c) 70 % in d) 90 %

3.2 Estimation of LF

As seen in **Figure 4**, the fatigue behaviour of the foam is very sensitive to the proportion of LF = 2200 N. While during loading at 50 % LF (**Figure 4a**), all the samples achieved the endurance limit, the increment of LF causes a decreased number of samples and is responsible for the premature shortening of the samples accompanied by changes in the strain rate, as presented in **Figures 4b** to **d**. In case of 63 % LF, two of the six samples achieved the endurance limit without premature shortening; if 70 % of LF is applied, only one from three samples reaches the limit, as presented in **Figure 4c**. During cycling at 90 % LF (**Figure 4d**), all the samples collapsed immediately after loading without changes in the strain rate.

4 CONCLUSION

It was revealed that a 50 % of level force is sufficient for uni-axial compression-compression cyclic loading to achieve an endurance limit of 10^5 cycles with no significant deformation, estimated to be less than 1mm. In the elastic region, only the creation of plastic hinges during the loading occurs, but in the region of hardening the buckling and bending of the cell walls start, which overcomes the reversible elastic deformation. The tests were performed on samples chosen from an area with the presence of the largest amount of non-uniformities within the structure at 50 % LF. This suggests that 50 % LF is the force that prevents the buckling and bending of cell faces responsible for the plastic collapse of pore bands. A force above 50 % LF causes continuous damage to the foam before the endurance limit is achieved.

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5 REFERENCES

[1] M. F. Ashby, A. G. Evans, L. J. Gibson, J. W. Hutchinson, H. N. G. Wadley, Metal Foam: A Design Guide, Butterworth-Heinemann, Woburn 2000

[2] J. Banhart, Prog. Mater. Sci., 46 (**2001**), 559–632

[3] F. Simancik, J. Jerz, J. Kovacik, P. Minar, Metall. Mater., 35 (**1997**), 265–277

[4] A. M. Harte, N. A. Fleck, M. F. Ashby, Inter. J. Fatigue, 23 (**2001**), 499–507

[5] U. Ramamurty, A. Paul, Acta Mater., 52 (**2004**), 869–876
[6] E. Koza, M. Leonowicza, S. Wojciechowskia, F. Simancik, Mater. Lett., 58 (**2003**), 132–135
[7] M. Nosko, F. Simancik, R. Florek, Mater. Sci. and Eng. A., 527 (**2010**), 5900–5908
[8] M. Nosko, Reproducibility of aluminium foam properties, Ph.D. Thesis, Institute of materials and machine mechanics SAS, 2009
[9] H. Bart-Smith, A. F. Bastawros, D. R. Mumm, A. G. Evans, D. J. Sypeck, H. N. G. Wadley, Acta Mater., 46 (**1998**), 3583–3592
[10] A. F. Bastawros, H. Bart-Smith, A. G. J. Evans, Mech. Physical Solids, 48 (**2000**), 301–322
[11] H. Bart-Smith, A. F. Bastawros, D. R. Mumm, A. G. Evans, D. J. Sypeck, H. N. G. Wadley, Acta Mater., 46 (**1998**), 3583–3592
[12] A. F. Bastawros, A. G. Evans, Adv. Eng. Mat., 2 (**2000**), 210–214
[13] M. Kolluri, M. Mukherjee, F. Garcia-Moreno, J. Banhart, U. Ramamurty, Acta Mater., 56 (**2008**), 1114–1125
[14] E. Amsterdam, J. Th. M. De Hosson, P. R. Onck, Acta Mater., 54 (**2006**), 4465–4472
[15] A. M. Harte, N. A. Fleck, M. F. Ashby, Acta Mater., 47 (**1999**), 2511–2524
[16] M. Nosko, F. Simancik, K. Izdinsky, P. Svec, R. Florek, Mat. Lett., 65 (**2011**), 1378–1380
[17] M. Nosko, F. Simancik, R. Florek, In: G. Stephani, B. Kieback, editors, Cellular metals for structural and functional applications, Fraunhofer IFAM, Dresden 2009, 246–25
[18] DIN 50134, Testing of metallic materials – Compression test of metallic cellular materials, 2008