T. ŚLEBODA*, J. KRAWCZYK*, M. MADEJ*, M. PAĆKO*

THE MICROSTRUCTURE AND PROPERTIES OF FeAl ALLOY STRENGTHENED WITH YTTRIUM OXIDE

MIKROPSTRUKTURA ORAZ WŁASNOŚCI STOPU FeAl UMOCNIONEGO TLENKIEM ITRU

This work is focused on the microstructure and properties of FeAl alloy strengthened with Yttrium oxide (Y_2O_3). Prealloyed FeAl alloy powder as well as the mixture of FeAl powder and 5 vol. % of Yttrium oxide were used in this research. Both kinds of the materials were fully densified by hot pressing at the temperature of 1100°C. An influence of strengthening FeAl alloy with Y_2O_3 on its impact toughness and tribological properties was discussed. The investigations showed greater ability of strengthened FeAl alloy to absorb the energy during impact tests as compared to unreinforced FeAl alloy. Moreover, the study proved, that strengthening of FeAl alloy with Yttrium oxide enhances the possibility to control the structural evolution of this material and has an advantageous influence on its properties.

Keywords: intermetallic, FeAl alloy, powder metallurgy, Yttrium oxide, tribological properties, impact toughness

W niniejszej pracy analizie poddany został wpływ umocnienia tlenkiem itru (Y_2O_3) na rozwój mikrostruktury oraz wybrane własności stopu z grupy FeAl. Jako materiał wyjściowy do badań zastosowano zarówno rozpylany wodą proszek stopu FeAl, jak i mieszaninę proszku FeAl i 5 % obj. tlenku itru. Dyskusji poddany został wpływ umocnienia stopu FeAl na jego udarność oraz własności tribologiczne. Oba rodzaje materiałów zostały w pełni zagęszczone poprzez prasowanie na gorąco w temperaturze 1100°C w atmosferze argonu. Badania wykazały większą zdolność materiału umocnionego tlenkiem itru do absorbcji energii podczas obciążeń w porównaniu do materiału nieumocnionego dyspersyjnymi cząstkami Y_2O_3. Na podstawie wykonanych badań można stwierdzić, że umocnienie stopu FeAl tlenkiem itru poszerza możliwości sterowania jego strukturą oraz korzystnie wpływa na własności tego materiału.

1. Introduction

Many advantages, including a wide range of potential structural and non-structural applications, have resulted in iron aluminides being one of the most intensively studied groups of intermetallics [1,2]. Low density with good strength, excellent corrosion/oxidation resistance at elevated temperatures [3-6], a wide range of chemical stability, and relatively low costs make FeAl alloys especially attractive for the application in chemical, power or automotive industry.

The use of FeAl alloys in structural applications has been restricted due to their considerable brittleness at room temperature. Environmental embrittlement, caused by the release of hydrogen at the surface when moisture reacts with Al in the alloy, is one of the primary causes of such limited ductility [7]. Relatively low cohesion of grain boundaries as well as strengthening by thermal vacancies [8-9] seems to be the next reasons for considerable brittleness of these alloys at room temperature. The addition of beneficial alloying elements (B, C, Zr, Mo) [10,11], refining the grain size of these alloys or introducing the particles of strengthening phase may result in a change of a dominant deformation mechanism from transgranular slip to grain boundary sliding. In this respect, powder metallurgy methods are very promising, since much finer microstructures can be produced [12-14].

2. Test material

As a starting materials for this investigation -100/+325 mesh water-atomized Fe-40at.%Al alloy powder (FeAl alloy) (Fig. 1a) and Yttrium oxide (Y_2O_3) powder of an average particle size in the range of 1÷5 μm (Fig. 1b) were used. The chemical composition of FeAl alloy powder is shown in Table 1.

* FACULTY OF METALS ENGINEERING AND INDUSTRIAL COMPUTER SCIENCE, AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, 30-059 KRAKÓW, 30 MICKIEWICZA AV., POLAND

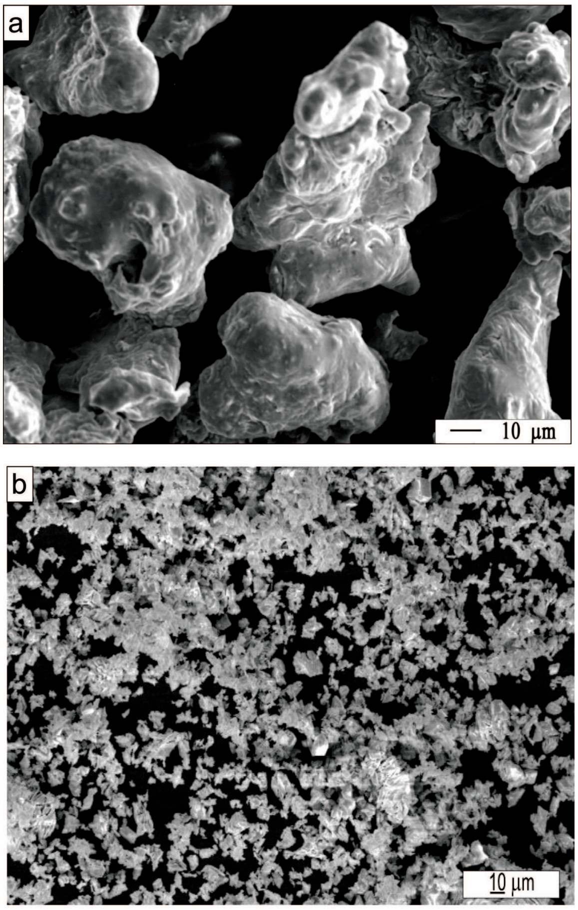

Fig. 1. Morphology of powders used in the investigation: a) FeAl alloy powder, b) Yttrium oxide powder (Y_2O_3). SEM micrographs

TABLE 1
Chemical composition (at. %) of the FeAl alloy powder used in the investigation

Fe	Al	Zr	Mo	Si	B	C	O
Bal.	39.3	0.05	0.19	0.31	0.02	0.22	0.85

Prealloyed FeAl alloy powder as well as the mixture of FeAl powder and 5 vol. % of Yttrium oxide (Y_2O_3) were fully densified by hot pressing under the pressure of 20 MPa at 1100°C during 3 hours under an argon atmosphere. The mixture of FeAl alloy powder and Yttrium oxide was prepared by high-energy milling. A plastic jar and WC balls were used for ball milling. Such milling method, jar material and milling medium guaranteed very intense milling without contamination coming from a jar or grinding medium. The mixture of FeAl alloy powder and Yttrium oxide was milled during 4 hours.

3. Microstructure of hot pressed samples

The microstructure of the compacts obtained from FeAl alloy powder and from the mixture of FeAl powder and Yttrium oxide are shown on Figure 2.

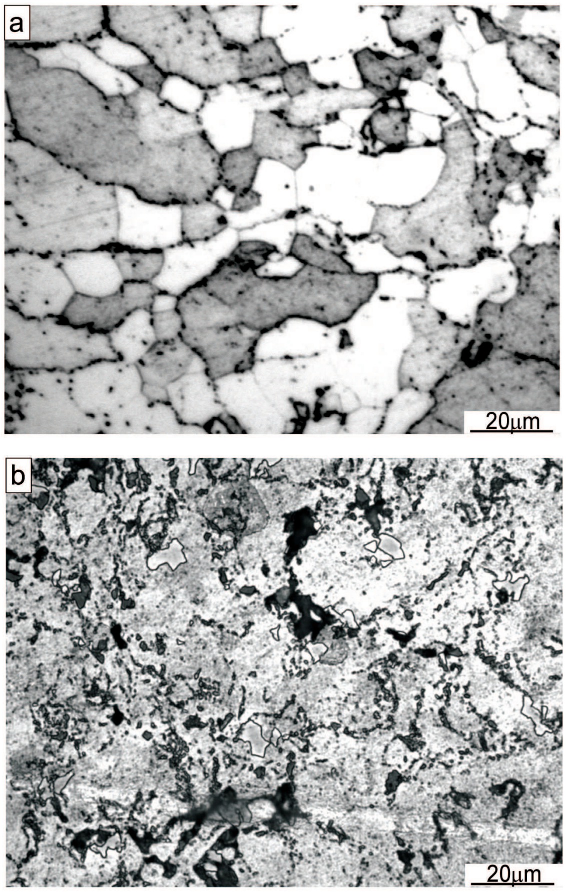

Fig. 2. Microstructure of the compacts obtained from: a) FeAl alloy powder, b) mixture of FeAl powder and Yttrium oxide. Light microscopy

In the result of hot pressing two starting materials for the investigations were obtained. Average grain sizes of all samples were calculated using the linear intercept method according to PN-84/H-04507.01 standard. The mean intercept length was considered as an average grain size. An average grain size in a compact obtained from FeAl alloy powder was 10 μm and an average grain size of compacted mixture of FeAl alloy powder and Yttrium oxide was 5 μm. The nature of the microstructures, reflecting only the powder particle shape and size distributions, shows that hot compacting in this case resulted solely in densification without any further microstructural evolution.

4. Impact toughness

The impact toughness of both kinds of the investigated materials was determined in Charpy V-notch impact tests using 50 J impact energy Charpy pendulum machine (according to PN-EN ISO 14556:2003/A1). The samples (see Fig. 3) were machined from both FeAl alloy powder compacts and from compacted mixture of FeAl powder and Yttrium oxide. Table 2 summarizes the results of the impact tests.

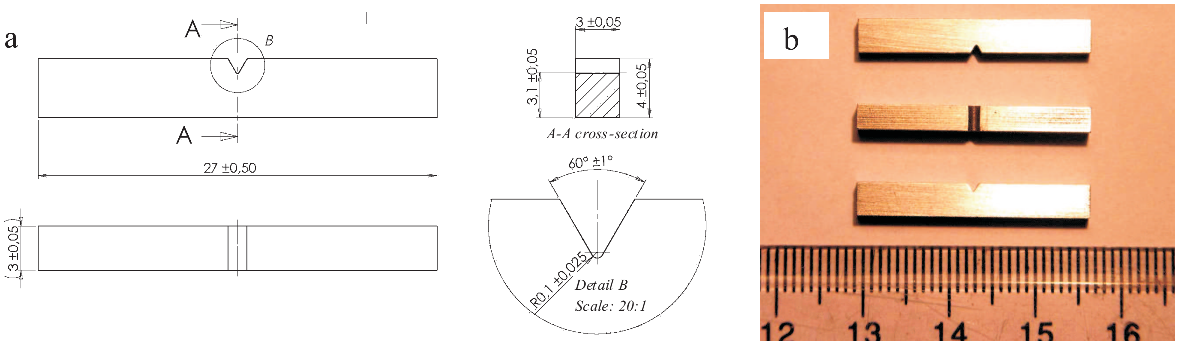

Fig. 3. Samples used in Charpy V-notch pendulum tests: a) geometry of the samples, b) picture of the samples machined from FeAl alloy powder compact

TABLE 2

Impact toughness of the investigated materials

Test material	Impact toughness
	J/cm^2
FeAl	21.1
FeAl + 5 vol.% Y_2O_3	36.9

A greater impact toughness (KVC) of FeAl alloy strengthened with Yttrium oxide proves advantageous influence of strengthening phase (Y_2O_3) on FeAl alloy properties. The greater ability of strengthened FeAl alloy to absorb the energy during impact tests may signify, that this material has greater impact toughness as compared to unreinforced FeAl alloy. The analysis of fracture surfaces (Fig. 4) of samples after Charpy tests showed, that in the case of FeAl alloy powder compact (Fig. 4a) the fracture is mostly transcrystalline and with characteristic areas with plastic deformation. Some parts of the fracture may be considered as brittle one – propagating through prior boundaries of powder particles.

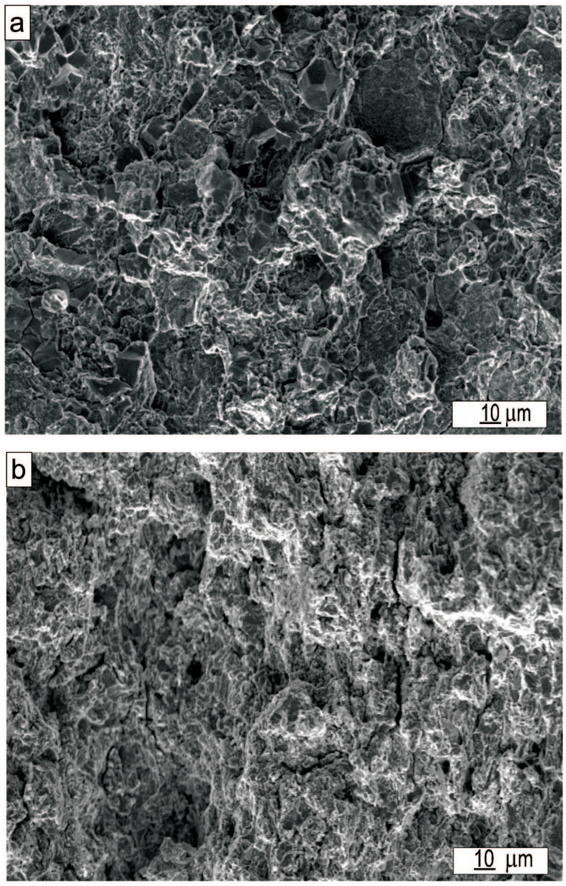

Fig. 4. Fracture surfaces of the investigated compacts: a) FeAl alloy powder compact, b) compacted mixture of FeAl powder and Yttrium oxide. SEM micrographs

In the case of unreinforced FeAl alloy (Fig. 4b) fracture surface is more developed, with visible particles of oxides. The fracture in this case can be described as transcrystalline. Decohesion of the material in some areas (prior powder particles) can also be observed. The greater impact toughness of this material, as compared to unreinforced one, can result from inhibiting the crack development by numerous oxide particles (such as Fe_2Al_3 particles) present on the grain boundaries of the investigated material.

5. Tribological properties

Tribological tests were performed using T-05 tester under the loads of 50 N and 150 N at room temperature. HS6-5-2 tool steel was used as a counter-sample. Single test was performed during 2000 seconds. 4x4x20 mm ("wide sample": the width of 6 mm) and 6x10x16 mm ("narrow sample": the width of 4 mm) samples were used for testing. Tribological set up consisted of a ring (counter-sample) and flat surface of the investigated sample. The differences in the wear mechanisms of the investigated samples, differing by geometry, resulted from the difference in free surface contribution during tribological test. In the case of the tests performed on narrow sample under 50 N load, significant material flow to the free surfaces of the sample was observed. This phenomenon was restricted in the case of the wide sample.

In the case of unreinforced FeAl alloy, a tendency of the material spalling was observed during the test under 50 N load. It was most likely caused by cutting process, ongoing independently of the size of the surface of tribological contact (Fig. 5). Such behavior of the material should most probably be explained by weak cohesion of grain boundaries (prior powder particles).

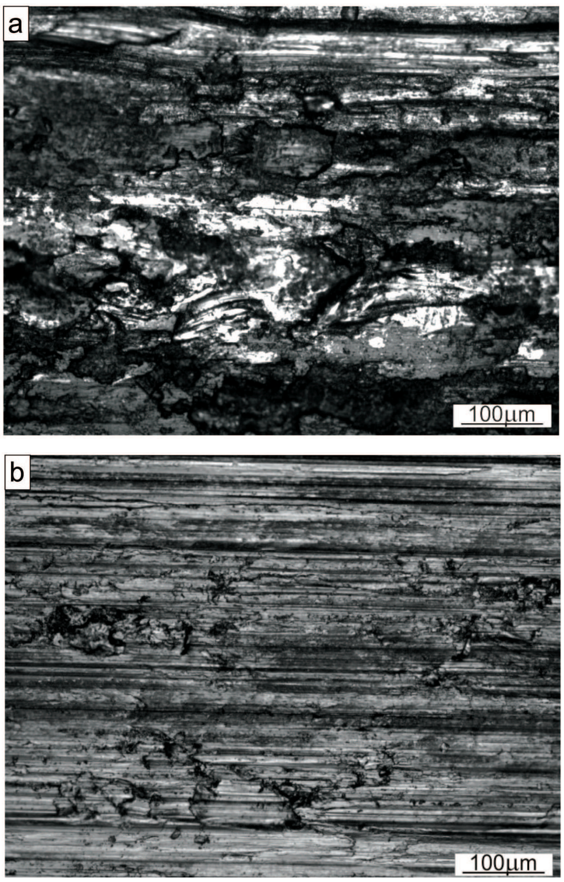

Fig. 5. The surface of the FeAl alloy powder compact after tribological test under 50 N load: a) 4 mm wide sample, b) 6 mm wide sample

Increasing the load to 150 N nearly excludes ridging mechanism during testing the FeAl alloy powder compact. However, in this case, cutting and intense spalling of the tested material takes place. That is why the edges of spallations are in most of the cases oriented perpendicular to the friction direction. This phenomenon causes big local losses of the sample material which are not elongated along the friction direction. The lack of clear differences in the mechanism of wear of the sample, connected with the sample geometry (width) can be observed (Fig. 6).

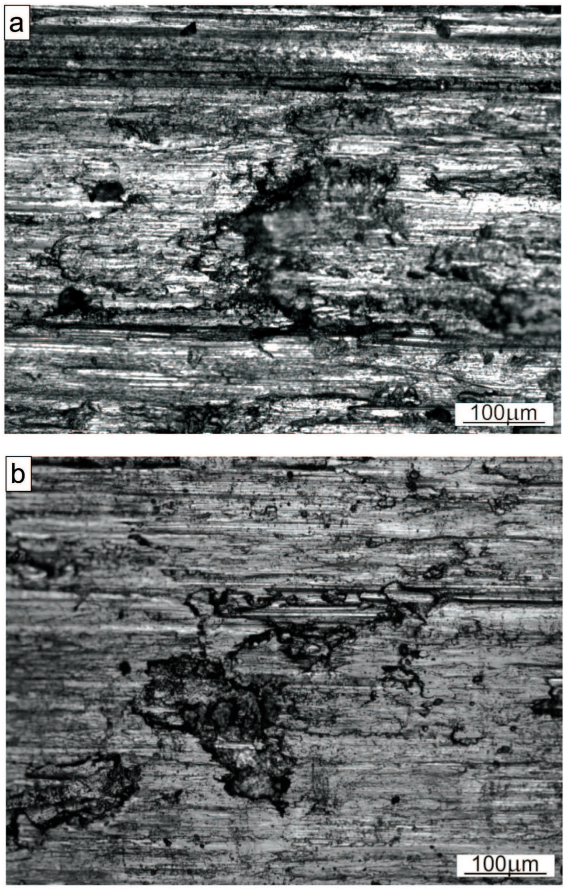

Fig. 6. The surface of the FeAl alloy powder compact after tribological test under 150 N load: a) 4 mm wide sample, b) 6 mm wide sample

The same tribological testing conditions were applied to the samples machined from FeAl alloy powder compacts reinforced with Yttrium oxide. Tribological tests under 50 N load revealed, that the addition of Yttrium oxide to FeAl alloy powder intensifies spallation of the material resulting from cutting (Fig. 7). Ridging as well as adhesive wear could hardly be observed. In the case of wider sample, a more evident location of spallation can be observed (Fig. 7b), contrary to narrow sample, where spallation is more uniform on the entire surface of the sample (Fig. 7a).

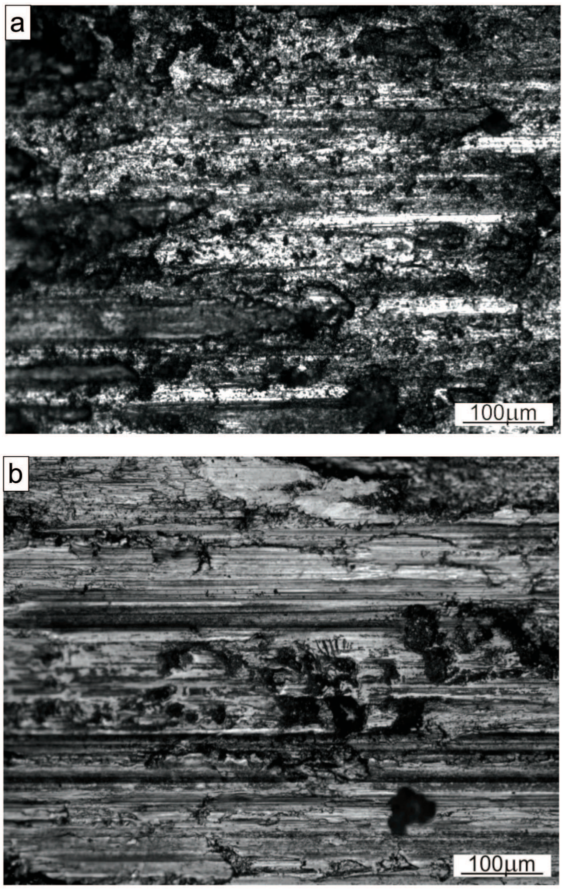

Fig. 7. The surface of the FeAl-5 vol.% Y_2O_3 compact after tribological test under 50 N load: a) 4 mm wide sample, b) 6 mm wide sample

The geometry of the sample also did not influence the mechanisms of wear of the samples tested under 150 N load. In this case cutting prevails and some parts of the spalled material could also be noticed. However, as compared to unreinforced FeAl alloy, some ductile fracture surfaces in the areas of spallation could be observed (Fig. 8). It may indicate the advantageous influence of Yttrium oxide on increasing the cohesion of grain boundaries of the investigated material.

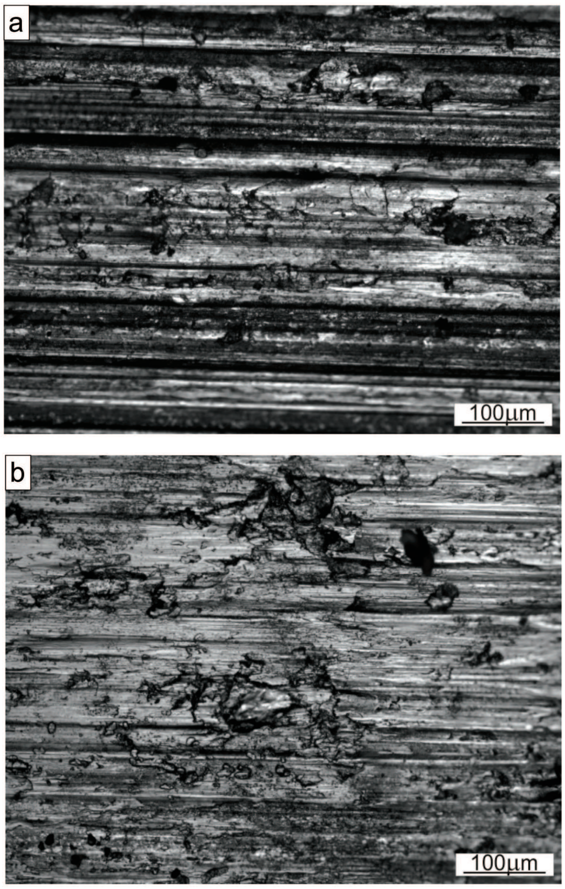

Fig. 8. The surface of the FeAl-5 vol.% Y_2O_3 compact after tribological test under 150 N load: a) 4 mm wide sample, b) 6 mm wide sample

The influence of a load on wear of the reinforced and unreinforced FeAl alloy powder compacts was determined both on wide and narrow samples. Figure 9 shows the results of this part of the study.

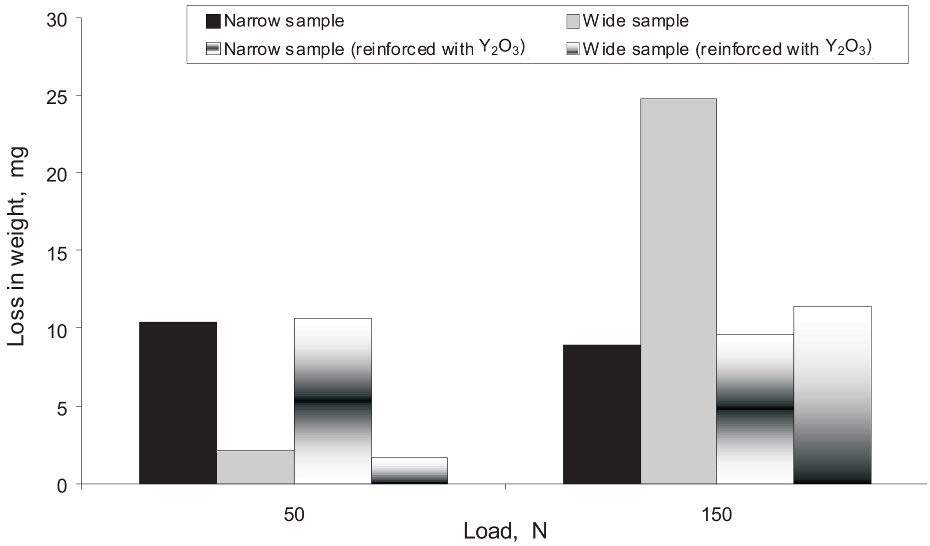

Fig. 9. Loss in weight of reinforced and unreinforced FeAl alloy samples in relation to test load

It can be noticed, that in the case of unreinforced FeAl alloy powder compact, wear of the sample increases with increasing load. Greater loss in weight, observed in the case of wide samples, may be connected with greater size of tribological contact. This phenomenon is more evident for the samples tested under greater load. Increasing the load during the tests performed on narrow, reinforced FeAl samples, slightly decreases their wear. It seems, that Yttrium oxide particles may restrict wear of the investigated material. This phenomenon is even more evident when greater testing load is applied (Fig. 8 shows oxide particles remaining on the surface of tested material). An increase of the testing load (from 50 N to 150 N) in the case of greater tribological contact (wide samples) results in more intense wear due to abrasive influence of spalled Yttrium oxide particles.

6. Conclusions

Basing on the performed investigations the following conclusions can be drawn:

1. High-energy milling of the mixture of FeAl alloy powder and Yttrium oxide is very effective method of doping FeAl alloy with oxide particles.
2. Greater ability of strengthened FeAl alloy to absorb the energy during impact tests may signify, that this material has greater ability to fracture toughness as compared to unreinforced FeAl alloy.
3. Strengthening FeAl alloys with Yttrium oxide particles significantly restricts ridging of this material.
4. Reinforcing FeAl alloys with Y_2O_3 has the advantageous influence on increasing the cohesion of grain boundaries of the investigated material.
5. Wear of unreinforced FeAl alloys increases with increasing load during tribological testing, contrary to reinforced FeAl alloy.
6. It can be stated, that strengthening FeAl alloy with Yttrium oxide particles enhances the possibility to control the structural evolution of this material and has an advantageous influence on its properties.

Acknowledgements

The authors of this study would also like to thank Mr. Marcin Zelek for help in this research.

REFERENCES

[1] N. S. Stoloff, Iron aluminides: present status and future prospects, Materials Science and Engineering **A258**, 1-14 (1998).
[2] N. S. Stoloff, C. T. Liu, S. C. Deevi, Emerging applications of intermetallics, Intermetallics **8**, 1313-1320 (2000).
[3] M. L. Escudero, M. C. Garcia-Alonso, J. L. Gonzalez-Carrasco, M. A. Munoz-Morris, Possibilities for improving the corrosion resistance of Fe-40Al intermetallic strip by prior oxide protection, Scripta Materialia **48**, 1549-1554 (2003).
[4] F. Lang, Z. Yu, S. Gedevanishvili, S. C. Deevi, T. Narita, Isothermal oxidation behavior of a sheet alloy of Fe-40at.%Al at temperatures between 1073 and 1473 K, Intermetallics **11**, 697-705 (2003).
[5] S. PalDey, S. C. Deevi, Cathodic arc deposited FeAl coatings: properties and oxidation characteristics, Materials Science and Engineering **A355**, 208-215 (2003).

[6] F. Lang, Z. Yu, S. Gedevanishvili, S. C. Deevi, T. Narita, Cyclic oxidation behavior of Fe-40Al sheet, Intermetallics **12**, 451-458 (2004).
[7] D. J. Duquette, Environmental resistance of intermetallic compounds and composite materials, Materials Science and Engineering **A198**, 205-211 (1995).
[8] C. T. Liu, J. Strigner, J. N. Munday, L. L. Horton, P. Angelini, Ordered intermetallic alloys: an assessment, Intermetallics **5**, 579-596 (1997).
[9] S. C. Deevi, V. K. Sikka, Nickel and iron aluminides: an overview on properties, processing, and applications, Intermetallics **4**, 357-375 (1996).
[10] C. T. Liu, E. P. George, P. J. Maziasz, J. H. Schneibel, Recent advances in B2 iron aluminide alloys: deformation, fracture and alloy design, Materials Science and Engineering **A258**, 84-98 (1998).
[11] P. J. Maziasz, C. T. Liu, G. M. Goodwin, Overview of the development of FeAl intermetallic alloys, Proceedings of the 2nd International Conference on Heat-Resistant Materials II, compiled by K. Natesan, P. Ganesan & G. Lai, Gatlinburg, Tennessee, 555-566 (1995).
[12] T. Sleboda, J. Kane, R. N. Wright, N. S. Stoloff, D. J. Duquette, Materials Science and Engineering **A368**, 332-336 (2004).
[13] T. Sleboda, P. Hale, R. N. Wright, N. S. Stoloff, D. J. Duquette, Thermomechanical processing of P/M FeAl alloy; Science and Technology of Powder Materials: Synthesis, Consolidation and Properties; eds. Leon L. Shaw et.al, p. 55-62, Materials Science and Technology 2005.
[14] T. Śleboda, Influence of processing history on the mechanical behavior of P/M FeAl alloys, Steel Research International **79**, 493-498 (2008).

Received: 7 March 2009.