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Towards the improvement of fracture toughness of NiAl intermetallics for aerospace applications

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1. Introduction

A lot of research effort has been invested in new advanced material solutions for aerospace industry, especially aimed at replacement of nickel-based superalloys, mainly due to their limited operating temperature. One of the potential replacement for nickel-base superalloys could be nickel aluminide. This intermetallic compound has drawn the attention of experts for more than 40 years, owing to its attractive properties such as high melting point, low density and good oxidation resistance at high temperature. However, low fracture toughness and poor ductility at room temperature limit the application of NiAl in real working conditions [1].

The present paper is concerned with the latter problem, i.e. how to improve the low fracture toughness of NiAl at room temperature, not compromising on other mechanical and physical properties of this compound. The primary objective of this research was to obtain a low density nickel aluminide bulk material with enhanced fracture toughness, flexural strength and high oxidation resistance. By introducing rhenium and aluminium oxide admixtures and using the powder metallurgy techniques (PM) with properly designed process parameters it was possible to increase the fracture toughness from 4 to 17 MPa$\sqrt{m}$, while keeping the oxidation resistance of the new composites on a reasonable level for industrial applications.

2. Material preparation

The powders of NiAl (GoodFellow 99% purity), rhenium (Ecoren 99.9% purity) and alumina oxide (NewMetKoch 99.99% purity) were mixed in a planetary ball mill and sintered in a hot press (HP) at 1400°C under the pressure of 30MPa. The starting powder composition that resulted in composites with the best mechanical properties were also produced using an alternative PM technique – the spark plasma sintering (SPS).

The fracture toughness and bending strength of the manufactured composites were measured on notched (SEVNB) and unnotched specimens in a four-point bending test using universal testing machine Zwick ProLine Z050, according to ISO 6872:2015(E) and ISO 23146:2012 standards, respectively. The oxidation tests were performed in a tube furnace under constant air flow (2l/min). The samples were oxidized at 1100°C and 1300°C in 50 one-hour cycles at each temperature level. The microstructure investigations were carried out using TECNAI FEG (200 kV) transmission electron microscope. In order to determine the chemical composition of the obtained composites the SEM EI Quanta 3D FEGSEM with attached EDAX Genesis and WDS Genesis LambdaSpec spectrometer were used. The phase composition was examined using the XRD analysis (Bruker D8 Discover).

3. Results and discussion

The results of fracture toughness and bending strength measurements are presented in Table 1. The highest improvement of K_{Ic} was obtained for the composite NiAl0.6Re0.5Al_2O_3.

The point analysis has revealed that no reaction occurred between rhenium and nickel aluminide (Fig. 1). Incidentally, alumina oxide was detected in composites with no Al_2O_3 admixture. This effect is traced back to the milling process of NiAl in air atmosphere. The further admixture of aluminium oxide did not influence the previous microstructure arrangement. The addition of rhenium and aluminium oxide to NiAl powder and subsequent pressure sintering of the powder mixtures has significantly improved the strength and fracture toughness of NiAl as compared with the pure NiAl compound sintered under the same conditions (cf. Table 1). The highest value of the fracture toughness was obtained for NiAl0.6Re0.5Al_2O_3 composition.

The improvement of fracture toughness cannot be clearly interpreted yet. The main mechanism could be the Hall-Petch strengthening but it doesn’t explain all the results. The distribution of fracture toughness of the manufactured specimens is similar to the distribution of bending strength.

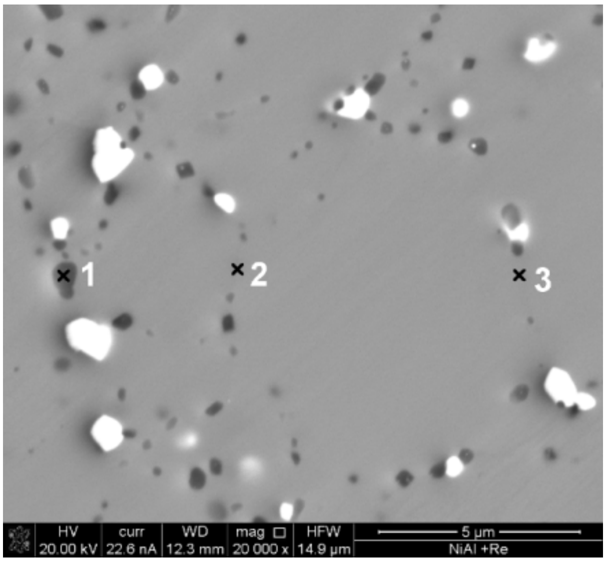

Figure 1. SEM-WDS analysis of NiAl+1.5%Re.

At.(%)	Point 1	Point 2	Point 3
O K	39.27	0.15	2.09
Al K	35.02	52.1	53.13
Re M	0.41	0	0.25
Ni K	25.3	47.75	44.53
Total	100	100	100

The mass change after 50h of oxidation at 1100°C for materials with admixture of rhenium is below 1mg/cm^2 which is very close to the value obtained for pure NiAl. After 50 cycles at 1300°C the oxidation rate increased with increasing content of rhenium, but is below 14mg/cm2 for the worst case (NiAl+1.5%Re), which is still acceptable from the application point of view. Measurements of the oxidation resistance of the manufactured composites with admixture of rhenium and aluminium oxide are in progress.

Table 1. Measurements of flexural strength in four-point bending test and fracture toughness in SEVNB test of sintered NiAl specimens reinforced with rhenium and alumina ceramic.

Material composition	Bending strength [MPa]	Fracture toughness [MPa$\sqrt{m}$]	Highest K_{IC} value achieved [MPa$\sqrt{m}$]
NiAl	428.90	8.08	8.47
NiAl(8h)	856.00	9.80	11.25
NiAl+0.6Re	793.10	13.27	15.00
NiAl+1.5Re	880.70	14.58	16.61
NiAl(8h)0.6Re	962.00	12.35	14.40
NiAl(8h)1.5Re	773.00	13.54	15.74
NiAl(8h)0.6Re/0.5Al_2O_3	1101.40	14.39	**17.84**
NiAl(8h)1.5Re/0.5Al_2O_3	720.62	11.71	13.74
NiAl(8h)0.6Re/1Al_2O_3	991.53	14.38	16.82
NiAl(8h)1.5Re/1Al_2O_3	1024.81	11.27	14.06

4. Conclusions and outlook

The proposed approach of improving the fracture toughness of nickel aluminide intermetallic by admixture of rhenium and alumina ceramic and consolidating the obtained powder mixtures by HP or SPS techniques has yielded sound results. This can be seen as a proof of concept but the highest K_{Ic} value obtained so far (approx. 18 MPa$\sqrt{m}$) is still slightly below the level of 20 MPa$\sqrt{m}$, which is considered the threshold value for any material application in turbine blades of jet engines. Further optimisation of the sintering process parameters is now being carried out to enhance the fracture toughness and ductility of the NiAl/Re/Al_2O_3 MMCs, while keeping their oxidation resistance at an acceptable level.

[1]. K. Bochenek and M. Basista, Advances in processing of NiAl intermetallic alloys and composites for high temperature aerospace applications, Progress in Aerospace Sciences, 79, 136-146, 2015.

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