Ductility Enhancement of NiAl-Fe Alloy By Microstructure Control

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The ordered nickel aluminide, NiAl, exhibits an attractive combination of properties such as high melting temperature and low density, thereby offering the potential for use as a high temperature structural material. However, the recent application of NiAl as a structural material is seriously restricted because of its low ductility at ambient temperature. Ductile phase reinforcement is a well-established method to improve the ductility and toughness of brittle materials. Macroalloying with 20~40at.% Fe to introduce ductile γ phase (fcc structure) as a reinforcement to the brittle β phase (bcc base ordered B2 structure) was studied in rapidly solidified material by Inoue et al. and Huang et al.. When the Al content was fixed at 20at.%, the maximum ductility (17% tensile ductility) was obtained in melt spun ribbon containing around 30at.% Fe. Some other techniques such as directional solidification and extrusion were used to further improve the ductility of the $Ni_{50}Al_{20}Fe_{30}$ alloy. The present study is focused on enhancing ductility of the NiAl-Fe alloy by controlling the microstructure. The microstructure was controlled by using directional solidification, varying directional solidification parameters and heat treatment method.

(1) The directional solidification method. The tensile ductility of the equiaxed $Ni_{60}Al_{20}Fe_{20}$ alloy is zero. After directional solidification, tensile ductility as high as ~21% can be obtained. The tensile elongation of the as cast equiaxed $Ni_{50}Al_{20}Fe_{30}$ alloy is only 3.8%. After directional solidification, tensile ductility range between 8.0~14% can be obtained. Fractography observation revealed that the phase boundary of both alloy especially in the $Ni_{60}Al_{20}Fe_{20}$ alloy is very weak. The transverse phase boundary decoheres during the deformation and reduce the ductility of the alloy. Ductility enhancement can be attributed to the reduction of the transverse phase boundary, modification of the orientation of phase boundaries and favorable orientation relationship between the β and γ phases. The ductility of the directionally solidified $Ni_{60}Al_{20}Fe_{20}$ alloy is higher than that of the directionally solidified $Ni_{50}Al_{20}Fe_{30}$ alloy. This is caused by the increasing volume fraction of the ductile γ phase and stress-induced martensitic transformation occurred in the β phase of the $Ni_{60}Al_{20}Fe_{20}$ alloy.

(2) The effect of changing the directional solidification parameters. The microstructure of the $Ni_{50}Al_{20}Fe_{30}$ alloy was further studied by changing the directional solidification parameters. When the pulling rates are higher than 0.19mm/min, coarse dendritic pro-eutectic β phase with interdendritic γ phase surrounded by eutectic area structure is formed. When the pulling rates are less than 0.19mm/min, completely eutectic lamellar structure is formed. Primary dendrite arm spacing, thickness of β lamellae and thickness of the γ lamellae increase with decreasing pulling rate. The yield stress and fracture stress decrease slightly with decreasing pulling rate. An anomalous decrease of the

γ lamellae thickness and increase of the yield stress with decreasing pulling rate occur, which are caused by the change from dendritic solidification to the planar solidification process. The directionally solidified samples with dendritic structure exhibit the highest ductility.

(3) The effect of heat treatment on the microstructure and ductility of the NiAl-Fe alloy. The equiaxed $Ni_{50}Al_{30}Fe_{20}$ alloy and <100> oriented $Ni_{50}Al_{30}Fe_{20}$ alloy single crystal were compression tested in both as cast state and heat treated state. After the sample annealed at 600°C or higher temperature, air cooling increase the ductility and lower the yield stress whereas furnace cooling lower the ductility and increase the yield stress. SEM and TEM observations revealed that after air cooling, a thin layer of ductile γ phase formed at the boundary of the dendrites, the grain boundary and also within the grain. The γ layer and the γ precipitates disappeared after furnace cooling. During the deformation, the γ layer plastically deformed first and cause some dislocation pile up in front of the phase boundary. Some mobile dislocation was nucleated in the neighbouring β phase and make the β phase become ductile. Therefore, precipitation of ductile second phase improves the ductility of the brittle intermetallic alloy.

(4) The effect of solidification pattern and lamellae thickness. In the samples with completely eutectic lamellar structure, only longitudinal composite structure was formed. In the samples with dendritic structure, both longitudinal and transverse composite structures were formed. The elastic modulus of the longitudinal composite and the elastic modulus of the transverse composite can be calculated as:

$$E^L=V_\beta E_\beta+V_\gamma E_\gamma \qquad E^T=(E_\beta E_\gamma)/(V_\gamma E_\beta+V_\beta E_\gamma)$$

When E_β is not equal to E_γ, we have

$$E^L>E^T$$

It means the elastic modulus of the longitudinal composite is greater than that of the transverse composite, i.e., formation of transverse composite structure will decrease the elastic modulus of the sample. During deformation, in the sample with dendritic structure, some load is transferred from pro-eutectic area to the γ rich eutectic and therefore, enhancing the ductility of the sample. The thick interdendritic γ phase and thick lamellar γ phase in the eutectic area of the dendritic sample are very effective in suppressing microcrack propagation, and thus the sample with dendritic structure exhibits higher ductility than that of the sample with completely lamellar structure.

Refining structure's effect is twofold. It decreases the tensile elongation by introducing weak phase boundary and reducing thickness of the ($\gamma+\gamma'$) lamellae which is a microcrack stopper. These two effects are predominant when the structure is coarse. It increases the tensile elongation by introducing interface dislocation source, i.e. make the brittle more ductile. This effect becomes predominant when the structure is very fine. Other factors such as degree of phase boundary alignment and banding defect formation also affect the tensile elongation.

In summary, the ductility of the NiAl-Fe alloy can be greatly enhanced by properly controlling its microstructure.