RAPID PUBLICATION

High-Temperature Mechanical Properties of B2 Type IrAl Intermetallic Compounds Doped with Ni

T. Ono[†], A. Chiba, X. G. Li and S. Takahashi

*Department of Materials Science and Technology, Faculty of Engineering, Iwate University,
4-3-5, Ueda, Morioka 020, Japan*

Compression tests have been conducted to examine the mechanical behavior of polycrystalline $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ intermetallic compounds with $x=0$ to 0.8 at elevated temperatures. The crystal structure of the $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ compounds has been determined to be a B2 type ordered structure by X-ray analyses. Although IrAl fractures without exhibiting appreciable yielding at temperatures up to 873 K, a steady state-like deformation in IrAl takes place at temperatures higher than approximately 1273 K. Ductility of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ is improved with increasing x . On the contrary, the strength decreases with increasing x in the intermediate temperature range. The IrAl alloy exhibits the 0.2% flow stress of 1200 MPa at 1073 K and 350 MPa at 1473 K, having the negative temperature dependence of the strength. Further more, the specific strength of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ is almost independent of x at temperatures higher than approximately 1473 K. The 0.2% flow stress and the specific 0.2% flow stress of $\text{Ir}_{0.2}\text{Ni}_{0.8}\text{Al}$ is significantly higher than that of binary NiAl over the entire temperature range to 1673 K.

Keywords: iridium aluminum, intermetallic compounds, mechanical properties, high-temperature, strength

I. Introduction

The high-temperature ordered intermetallic compound has been a promising candidate for applications such as gas-turbine blades for jet-engines and the electrical power generating equipment. The majority of research programs on fabricating high-temperature structural components has been so far aimed at Ni-based superalloys. However, since the melting temperature of the nickel is 1726 K, significantly higher operating temperatures can not be attained by the Ni-based superalloys. Thus it is necessary to develop an entirely new materials system⁽¹⁾.

Intensive investigations into high-temperature strength of Nb_3Al ⁽²⁾ have been performed to realize practical application at considerably higher temperatures exceeding 1573 K. The intermetallic, however, exhibits poor ductility, caused by the complexity of its crystal structure, and the lack of oxidation resistance prevents the material from being applied as useful high-temperature structural materials. Recently much attention has been focused upon MoSi_2 because of its intrinsically high oxidation resistance, high melting temperature (2293 K), and low density (6.3 Mg/m³). The main drawbacks with MoSi_2 , however, are low ductility and fracture toughness resulting from the complex crystal structure of C11_b. Thus it is considered that monolithic MoSi_2 cannot be used for high-temperature materials.

By considering that IrAl has a melting temperature of 2393 K and has a B2 type ordered crystal structure⁽³⁾, an

IrAl intermetallic compound can be relevantly expected to be a ductile high-temperature material. In addition, since Al_2O_3 film is formed during oxidation in Ir-Al system at temperatures higher than 1573 K⁽⁴⁾⁽⁵⁾, an IrAl intermetallic compound possibly exhibits good oxidation resistance. According to the Ir-Al phase diagram⁽³⁾, IrAl intermetallic phase has a relatively wide solubility range. Thus extensive study on IrAl can be undertaken to improve the mechanical properties such as toughness, ductility and high-temperature strength, as well as the oxidation resistance, by ternary addition.

The aim of the present paper is to report the results on the preliminary investigation into the strength of IrAl intermetallic compounds in the temperature range from room temperature to 1673 K. Here, we will try to reduce the relatively high density (13.68 Mg/m³) of IrAl by substituting Ni for Ir in the composition of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ with $x=0$ to 0.8. Thus effect of Ni addition on mechanical properties and microstructures of the compounds will be reported.

II. Experimental Procedure

$\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ alloys with $x=0$ to 0.8 were prepared using raw materials of 99.99% purity aluminum, 99.9% purity iridium and 99.9% purity nickel. Button ingots were prepared by arc-melting the raw materials four times to attain chemical homogeneity in an argon gas atmosphere and subsequently annealed using a silicon furnace at 1673 K for 259.2 ks in a vacuum of 10^{-4} Pa. Each sample was cut into a size of $2 \times 2 \times 5$ mm³ by a wire-cut spark machine and mechanically polished with emery paper.

[†] Graduate Student, Iwate University.

The buttons were crushed into the small particles by machining and then milling using a mortar for X-ray diffraction analyses. Powders consisting of the particles of 300 mesh size were encapsulated into a silica tube and then heat-treated for 10.8 ks at 1473 K under a vacuum of 3×10^{-3} Pa to remove the introduced strain. The samples for microstructural observations were prepared by grinding on emery papers and finishing on 4000 lapping film.

Lattice constants, crystal structures, and identification of second phase precipitates were determined by X-ray diffractometer using the above powder samples and monochromated $\text{CuK}\alpha$ radiation over $20^\circ \leq 2\theta \leq 120^\circ$. The 2θ angle was calibrated with silicon powder. Compression tests were carried out using the Instron testing machine at an initial strain rate of $1.5 \times 10^{-3} \text{ s}^{-1}$ in the testing temperature range to 1673 K in a vacuum of 10^{-3} Pa. Microstructures of the sample surfaces before compression tests were observed by a metallurgical microscopy equipped with Nomarski interference contrast.

III. Results and Discussion

1. Microstructure and crystal structure

Figures 1(a) and (b) show optical micrographs of a binary IrAl sample and an $\text{Ir}_{0.4}\text{Ni}_{0.6}\text{Al}$ sample respectively. As shown in these figures, the IrAl sample consists of the dendritic structure with second phase precipitates. On the other hand, the $\text{Ir}_{0.4}\text{Ni}_{0.6}\text{Al}$ sample consists of equiaxed grains with small dispersed secondary phases and has an average grain size of approximately $200 \mu\text{m}$.

X-ray diffraction patterns of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ with $x=0, 0.2, 0.4, 0.6$ and 0.8 are indicated in Fig. 2. The diffraction pattern of the IrAl sample exhibits peaks being identified as the CsCl(B2) ordered phase, together with Ir, Al_3Ir and Al_9Ir_3 phases, indicating that an IrAl sample has multiple phases. In addition, the diffraction patterns with $x=0.2$ to 0.6 contain peaks of the second phase precipitates in small amount, although the peaks decrease with increasing x and disappear at $x=0.8$. Therefore it is found in the present investigation that only the $\text{Ir}_{0.2}\text{Ni}_{0.8}\text{Al}$ sample with the highest Ni concentration exhibits a single phase with B2 type crystal structure. However, Axler *et al.*⁽³⁾ revealed that IrAl phase exists over a range of iridium concentration from 48 to 52 mol% in the binary Ir–Al phase diagram and has a B2 type ordered crystal structure up to melting temperature of approximately 2393 K[†]. Thus the present result on the X-ray analyses is inconsistent with that of the previous study⁽³⁾. The inconsistency is due to the difference of annealing treatments for homogenization between the present study and the previous one. We consider that the present annealing treatments are inadequate and the

[†] Similarly there exists a wide solubility range of a B2 type NiAl phase with the melting temperature of 1911 K in the Ni–Al phase diagram⁽⁶⁾. Thus it can be thought that the pseudo-binary system of IrAl–NiAl is a complete solid solution with the B2 type ordered crystal structure.

Fig. 1 The optical micrographs of IrAl (a) and $\text{Ir}_{0.4}\text{Ni}_{0.6}\text{Al}$ (b).

Fig. 2 The X-ray diffraction patterns of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ with $x=0, 0.2, 0.4, 0.6$ and 0.8 . (●: IrAl, ○: Al_9Ir_3 , △: Al_3Ir , □: Ir)

prolonged and/or higher-temperature annealing is necessary to produce a single phase IrAl.

Thus it can be concluded that a single-phase ternary $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ intermetallic compound with the B2 crystal structure can be obtained if the adequate annealing conditions are fulfilled.

2. Lattice constants and densities

Since $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ compounds with $x=0$ to 0.6 contain a small amount of second phases, as described in Section III.1, determination of precise lattice constants except for those of $\text{Ir}_{0.2}\text{Ni}_{0.8}\text{Al}$ cannot be made on the basis of the present X-ray analyses. Therefore, these values should be considered to be tentative ones. Lattice constant of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ is plotted against Ni concentration, x , in Fig. 3. Lattice constants of IrAl, given by the previous investigators^{(7)–(9)}, are also plotted in the figure, showing some discrepancy between the present work and the previous ones. Although the causes for the discrepancy are not certain at present, it is found in general that the lattice constants decrease with increasing x , indicative of Vegard's law holding true. The densities of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ compounds can be obtained from the lattice constants, provided that the compounds have the B2 type crystal structure. The calculated density vs. x for $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ is plotted in Fig. 4, indicating that the density decreases linearly with increasing x .

3. Mechanical properties

Figures 5(a) and (b) illustrate typical compression stress-strain curves for the IrAl and $\text{Ir}_{0.2}\text{Ni}_{0.8}\text{Al}$ samples, respectively, tested at temperatures from room temperature to 1673 K. In these figures, the arrow marks on the stress-strain curves are meant to be points where the compression tests were finished. IrAl fractures before and immediately after the yielding below 1073 K. On the other hand, at temperatures higher than 1273 K, pronounced compressive ductility is exhibited and results in a steady state-like deformation after the yielding. In addition, it is found from Fig. 5(b) that the compressive ductility of the $\text{Ir}_{0.2}\text{Ni}_{0.8}\text{Al}$ sample appears at temperatures as low as 1073 K. Thus it can be concluded from the compression

Fig. 3 The variation in lattice constant of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ with x .

Fig. 4 The variation in density of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ with x .

Fig. 5 The stress-strain curves for IrAl (a) and $\text{Ir}_{0.2}\text{Ni}_{0.8}\text{Al}$ (b) tested at temperatures up to 1673 K.

tests that the addition of Ni is effective in improving ductility of an IrAl compound.

The temperature dependence of the 0.2% flow stress and the specific 0.2% flow stress of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ are shown in Figs. 6(a) and (b) respectively; here, the open symbols represent the fracture stress without yielding. The data of the binary NiAl compound, quoted from Noebe *et al.*⁽¹¹⁾, is likewise indicated in these figures for comparison. Although the fracture stresses instead of the 0.2% flow stresses are indicated at temperatures lower than approximately 1000 K, the strength of the $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ intermetallic compounds exhibits a negative temperature dependence and decreases with increasing Ni concentration. From the standpoint of enhancing the high-temperature strength of a NiAl intermetallic compound, it is to be not-

Fig. 6 The temperature dependence of the 0.2% flow stress (a) and the specific 0.2% flow stress (b) for $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$.

Fig. 7 The variation in the 0.2% flow stress (a) and the specific 0.2% flow stress (b) for $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ with x .

ed that the 0.2% flow stress and the specific 0.2% flow stress of $\text{Ir}_{0.2}\text{Ni}_{0.8}\text{Al}$ is significantly higher than that of binary NiAl over the entire temperature range tested^{††}.

Figures 7(a) and (b) show the 0.2% flow stress and the specific 0.2% flow stress of $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$, respectively, as a function of x at temperatures of 1073 K, 1273 K, 1473 K and 1673 K. A marked decrease in the 0.2% flow stress with increasing x can be observed at the temperatures lower than 1273 K, whereas a slight decrease in the 0.2% flow stress with increasing x is found at temperatures higher than 1473 K. It is shown that the flow stress of a metallic material can be expressed by the sum of the two stress terms, namely, internal stress and effective stress⁽¹²⁾; the former is independent of temperature and strain rate. Figure 7(a) suggests that although the effective stress of IrAl decreases with addition of Ni, the internal stress of IrAl is almost immutable for Ni addition. In view of high-temperature application, it should be noted that the specific 0.2% flow stresses at temperatures higher than 1473 K almost remain constant with an increase in amount of Ni addition.

Finally, it can be concluded that an $\text{Ir}_{1-x}\text{Ni}_x\text{Al}$ intermetallic compound is superior to the binary IrAl as a high-temperature material from the view point of the

specific strength, ductility and resistance to oxidation⁽⁴⁾⁽⁵⁾, especially at temperatures higher than 1473 K.

Acknowledgments

The authors would like to thank Mr. M. Sato of Iwate University for help with sample preparation. This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture, Japan.

REFERENCES

- (1) D. P. Pope and R. Daroria: MRS Bulletin, **21** (1996), 30.
- (2) Y. Murayama, S. Hanada and K. Obara: Mater. Trans., JIM, **34** (1993), 325.
- (3) K. M. Axler, E. M. Foltyn, D. E. Peterson and W. B. Hutchinson: J. Less-Common Met., **156** (1989), 213.
- (4) T. C. Chou: J. Mater. Res., **5** (1990), 378.
- (5) K. N. Lee and W. L. Worrell: Oxid. Met., **32** (1989), 357.
- (6) P. M. Hansen: *Constitution of Binary Alloys*, Second Edition, Genium Publishing Corporation, (1985).
- (7) P. Esslinger and K. Schubert: Z. Metallkd., **48** (1957), 126.
- (8) H. Schulz, K. Ritapal, W. Bronger and W. Klemm: Z. Anorg. Chem., **357** (1968), 299.
- (9) K. Axler and R. B. Roof: Adv. X-ray Anal., **29** (1986), 333.
- (10) Becker and Ebert: Z. Physik., **16** (1923), 165.
- (11) R. D. Noebe, R. R. Browman, C. L. Cullers and S. V. Raj: *High Temperature Ordered Intermetallic Alloys IV*, ed. by L. A. Johnson, D. P. Pope and J. O. Stiegler, Mater. Res. Soc. Symp. Proc., **213**, Pittsburgh, Materials Research Society, (1991), p. 589.
- (12) A. Seeger: Phil. Mag., ser. 7, **45** (1954), 771.

^{††} It can be concluded that addition of Ir to NiAl is effective in enhancing the high-temperature strength of a NiAl intermetallic compound.