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ScienceDirect
Journal of Nuclear Materials 367–370 (2007) 1305–1311
journal of nuclear materials
www.elsevier.com/locate/jnucmat

The effect of low-dose neutron irradiation on mechanical properties, electrical resistivity and fracture of NiAl bronze for ITER

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Abstract

Nickel–aluminum bronze is a candidate material for several applications for ITER in-vessel components such as divertor and blanket attachments and remote handling equipment. This paper presents the first results of an experimental investigation of the effect of neutron irradiation on mechanical properties, fracture characteristics and electrical resistivity of NiAl bronze. Specimens of NiAl bronze were irradiated at 150 °C and 300 °C to doses of 10^{-3}; 10^{-2}; $0.7 * 10^{-1}$ dpa in the RBT-6 reactor ($\Phi t_{\mathrm{therm}}/\Phi t_{\mathrm{fast}} \sim 1$) in Dimitrovgrad. It was shown that irradiation at 150 °C leads to minor changes of tensile properties, whereas irradiation at 300 °C results in significant loss of ductility at damage dose of 0.07 dpa. The change of electrical resistively of NiAl bronze is low, ≈3% at the maximum dose studied. The reasons for the high-radiation resistance of NiAl bronze in comparison with copper and copper alloys are discussed.

1. Introduction

Aluminum bronze (known as Nickel–aluminum (NiAl) bronze) is a candidate structural material for several applications for the ITER in-vessel components such as attachments between divertor and vacuum vessel, attachments for high-heat flux components to the divertor cassette, etc., [1]. The main advantages of this material are anti-seizing properties (proven also in vacuum), absence of sparking when subjected to impact with steel, high-mechanical properties, and low-cost.

Among the various available grades of aluminum bronzes the copper alloy UNS No. C63200 has been selected. The main ASTM standard for this bronze is ASTM B 150M-03. The corresponding European specification is EN 12163/12167 and material designation is CuAl10Ni5Fe4 (CW307G).

However, data about the effect of neutron irradiation on the properties of this alloy are lacking. This paper presents the first results of experimental investigation of the effect of neutron irradiation on hardening, embrittlement, fracture and electrical resistivity of NiAl bronze at low-dose irradiation.

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doi:10.1016/j.jnucmat.2007.03.262

Table 1
Chemical composition of studied aluminum bronze

Element	Studied material	ASTM B150M-03 UNS No. C63200
Al	9.41	8.7–9.5
Cu (incl. Ag)	81.00	Remainder
Fe	3.75	3.5–4.3[a]
Ni (incl. Co)	4.54	4.0–4.8
Mn	1.28	1.2–2
Si	<0.01	0.1 max
Pb	<0.01	0.2
Zn	<0.01	
Sn	0.02	

[a] Iron content shall not exceed nickel content.

2. Material and experimental procedure

The material was manufactured by Cerro Manganese Bronze Limited, USA in 2002, heat number F1176. The chemical composition is shown in Table 1.

The following heat treatment was applied in accordance with ASTM B150M – 03:

- hold at 850 °C for 1 h, quench in water;
- temper anneal at 700 °C for 6 h.

Specimens of NiAl bronze were irradiated in the RBT-6 reactor in irradiation facility SMM01-1; SMM01-2; SMM01-3. The irradiation doses in the RBT-6 reactor were 10^{-3}; 10^{-2} and $0.7 * 10^{-1}$ dpa. The corresponding fast neutron ($E > 0.1$ MeV) fluence values were $1.22 * 10^{18}$ n/cm^2, $1.14 * 10^{19}$ n/cm^2 and $1 * 10^{20}$ n/cm^2. Different doses were attained by varying the irradiation time, i.e., 24 h; 240 h; 1500 h. The average ratio of thermal to fast neutrons in the RBT reactor was $\Phi t_{therm}/\Phi t_{fast} \sim 1.04$. Details of the irradiation technique are presented in papers [2,3]. The irradiation temperature, as recorded by thermocouples, was 150 ± 8 °C and 300 ± 10 °C.

Flat tensile specimens (1 mm in thickness, gage length of 10 mm) (STS type) were irradiated in hermetically sealed helium-filled subcapsules. The samples were tested at a strain rate of 1.66×10^{-3} s^{-1} in vacuum. These samples were also used for measurement of electrical resistivity.

3. Tensile test results

Fig. 1 shows the typical engineering stress–strain curves (σ_{eng} versus δ) curves for NiAl bronze in the unirradiated condition at test temperatures of 20 °C, 150 °C and 300 °C. Obviously, increasing test temperature results both in a decrease in the yield strength and a drop in the uniform elongation, but practically does not affect a strain hardening.

Fig. 2 shows the dependence of tensile properties of NiAl bronze versus test temperature. An increase in test temperature results in a decrease in yield and ultimate strength and minor reduction of the uniform and total elongation.

Figs. 3 and 4 show the typical engineering stress–strain curves (σ_{eng} versus δ) for NiAl bronze irradiated in RBT-6 reactor to a dose of 10^{-3}, 10^{-2}, and 0.07 dpa at 150° and 300 °C, respectively.

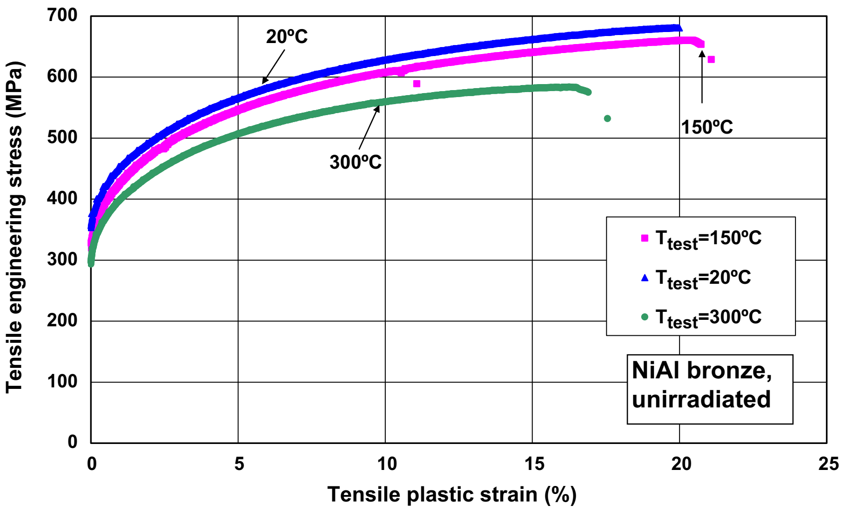

Fig. 1. Engineering stress–strain curves for NiAl bronze.

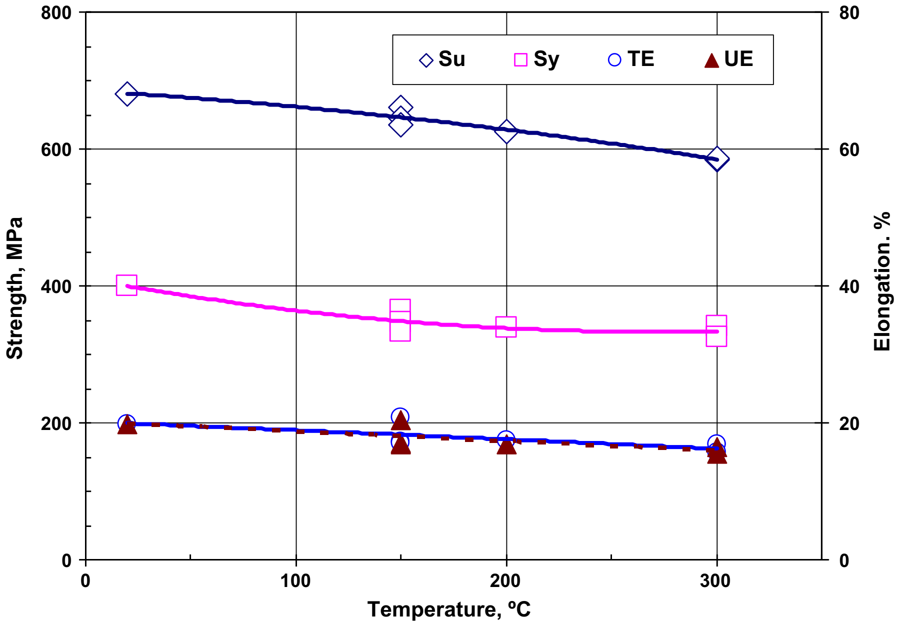

Fig. 2. Tensile properties of NiAl bronze versus test temperature.

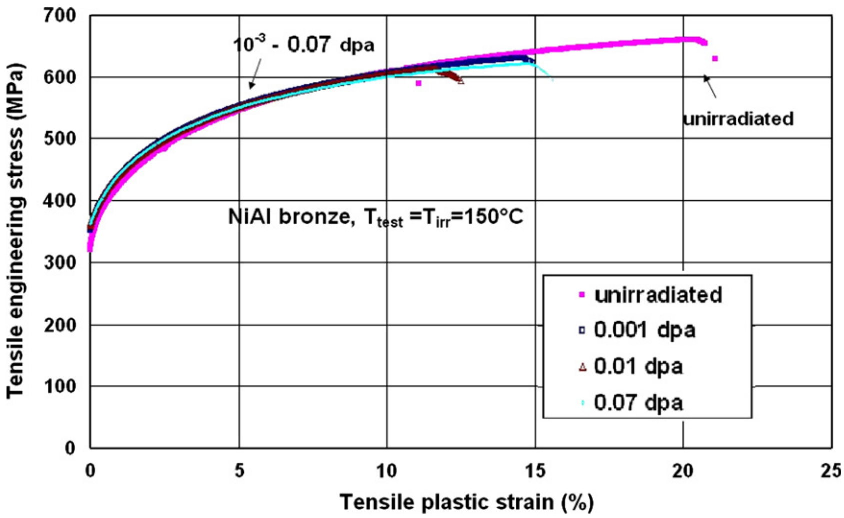

Fig. 3. Engineering stress–strain curves for NiAl bronze after irradiation and testing at 150 °C.

As follows from Fig. 3, irradiation of NiAl bronze at 150 °C results in a slight increase in the yield strength, and insignificant reduction in the uniform elongation. Obviously, the irradiation to a higher neutron dose in RBT-6 reactor results both in a slight increase in the yield strength and a drop in the uniform elongation, but does not significantly affect strain hardening.

Irradiation at temperature 300 °C (Fig. 4) leads to a reduction of the strain hardening, decreases the total and uniform elongation and a minor increase of yield strength. The ultimate tensile strength is slightly decreased. For both irradiation temperatures, it is clearly seen that there is not any loss of strain hardening, which is typical for pure copper [2,4].

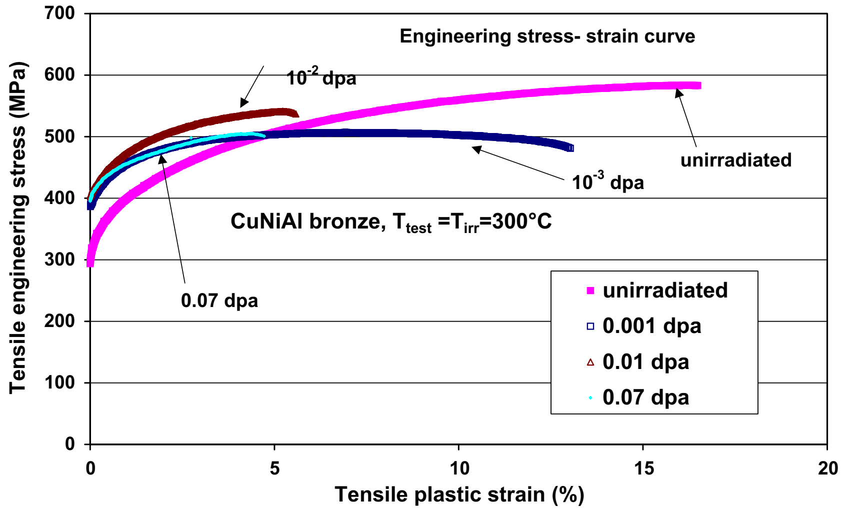

Fig. 4. Engineering stress–strain curves for NiAl bronze after irradiation and testing at 300 °C.

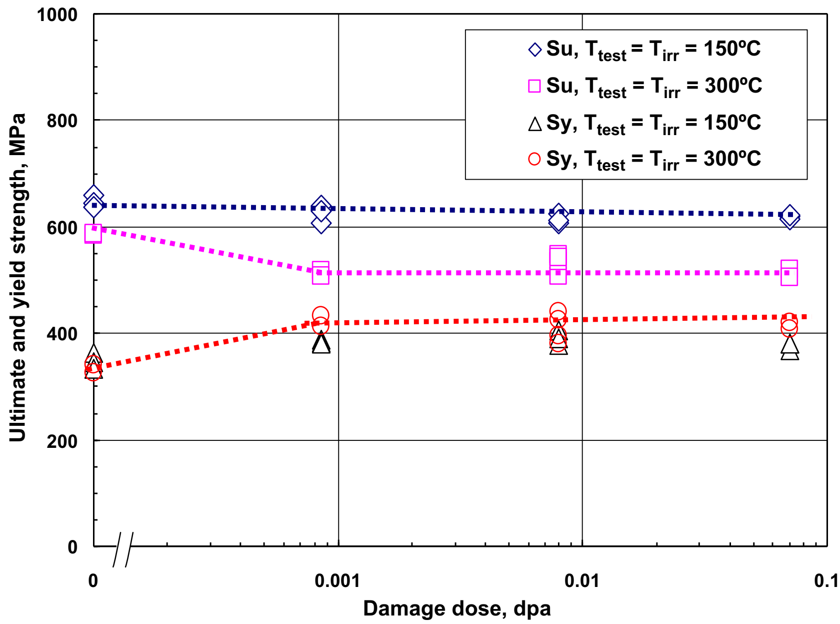

Fig. 5. Ultimate and yield strength as function of damage dose after irradiation at 150 °C and 300 °C temperatures.

Figs. 5 and 6 summarize the dose dependence of tensile and yield strength and elongation of NiAl bronze at irradiation temperature of 150 °C and 300 °C. The uniform and total elongation of NiAl bronze irradiated at 300 °C decreases gradually with increasing damage dose, falling below 5% at damage dose of 0.07 dpa. In contrast, the total and uniform elongation of material irradiated and tested at 150 °C decreased slightly (from 16% to 13%) and it seems that there is no effect of irradiation dose on ductility, at least for condition studied.

4. Electrical resistivity test results

Electric resistivity was measured at ambient temperature before and after irradiation using the tensile specimens. The electrical resistivity of NiAl bronze at room temperature is ~22 μΩ cm. Fig. 7 shows the

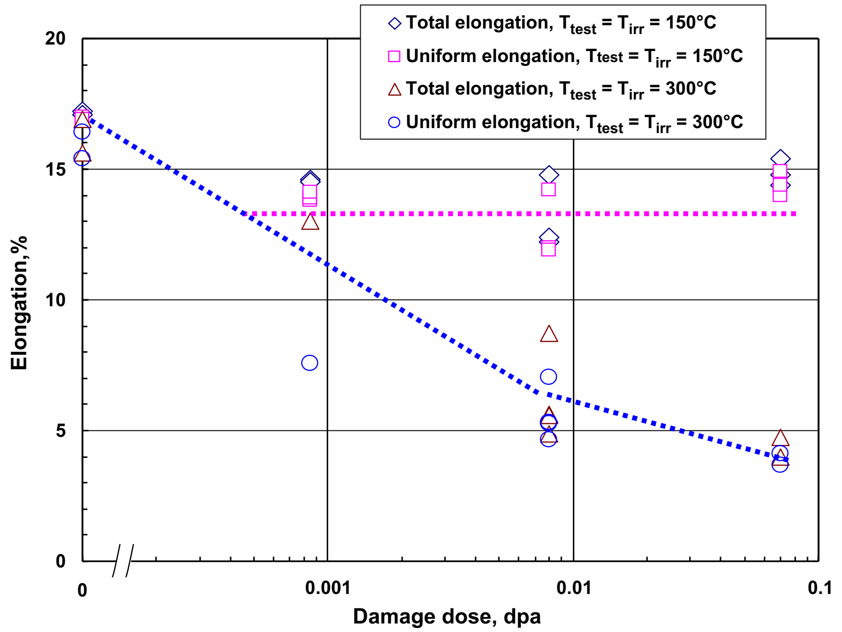

Fig. 6. Total and uniform elongation as function of damage dose after irradiation at 150 °C and 300 °C temperatures.

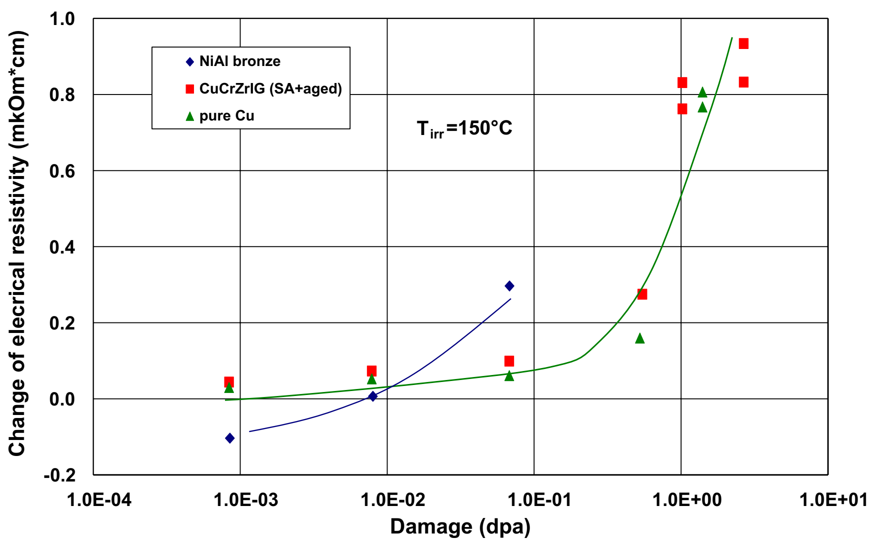

Fig. 7. Change of electrical resistivity of NiAl bronze after irradiation at 150 °C.

change of electrical resistivity as function of neutron dose after irradiation at 150 °C. After irradiation up to a dose of 10^{-3} dpa, some slight reduction (~0.5%) of electrical conductivity was observed. Increasing the irradiation fluence leads to a gradual increase of electrical resistivity. However for the dose range studied, the increase of electrical resistivity is only ~1.5%. The data for NiAl bronze were compared with data for pure Cu [5] and CuCrZr in solution annealed and aged condition [6]. It seems that the behavior is generally very similar.

5. Structure of NiAl bronze

According with phase diagram [7], the microstructure of the NiAl bronze consists of an alpha solid solution and the iron and nickel rich kappa phase. The kappa phase absorbs aluminum from the alpha solid solution. The kappa phase increases the mechanical strength of the aluminum bronze, with no decrease in ductility. Fig. 8(a) demonstrates that typical microstructure of NiAl bronze consists of laminar kappa phase (average size ~30 μm). No remarkable changes of optical microstructure were observed after irradiation.

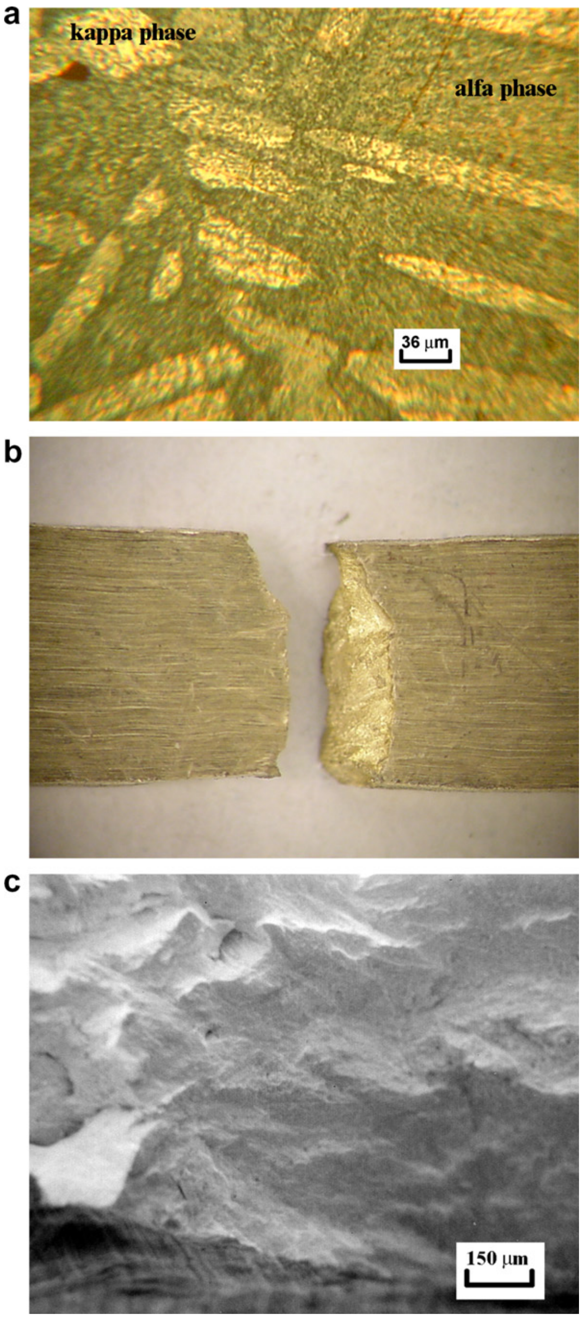

Fig. 8. Structure and fracture character of NiAl bronze: (a) – optical microstructure, (b) – view of fractured tensile sample, (c) – SEM microstructure after irradiation at 150 °C and dose of 10^{-3} dpa.

The view of the tensile specimens after tensile testing at 150 °C is shown in Fig. 8(b). The fracture is ductile and transgranular with satisfactory level of reduction of area (~30%). SEM microscopy investigations of the nature of the fracture of the irradiated specimens tested at 150 °C showed that NiAl bronze specimens also exhibited transgranular fracture (Fig. 8(c)).

6. Discussion

The results show that radiation hardening of NiAl bronze is rather weak and its ductility is slightly reduced under low-temperature neutron irradiation, which distinguishes this alloy from previously studied pure copper and alloys of CuCrZr and GlidCopAl25 type [2,6]. Without results of TEM investigations (which are being carried out), it is difficult to discuss the possible cause of this specific behavior of NiAl bronze. The assumption can be made that Al-saturated solid solution, along with accumulation of radiation defects, might contribute to hardening of this material. Under irradiation aluminum starts leaving the solid solution, and this depletion causes a drop in strength, which is compensated by accumulation of point defects. This assumption is consistent with the resulting changes in electric resistance under irradiation. A slight drop in electric resistance is observed in the low-dose range of ~10^{-3} dpa, as it should be in case of solid solution depletion in Al.

This alloy, when irradiated at 300 °C, is hardened by about 80 MPa, and its uniform elongation is reduced up to 5% at irradiation doses of 10^{-2}–10^{-1} dpa. This level of uniform elongation is typical of other copper alloys of CuCrZr and GlidCopAl25 types irradiated under the same conditions [2,6].

It should be noted that NiAl bronze has high-resistance to low-temperature radiation embrittlement and high-strength of ~600 MPa after irradiation at 150 °C, while retaining satisfactory ductility. At the same irradiation condition other high-strength alloys (e.g., CuCrZr, Cu–Be) typically demonstrate loss of hardening capability and significant reduction of uniform elongation [8].

7. Conclusions

For the first time the effect of neutron irradiation on tensile properties and electrical resistivity of

NiAl bronze was studied. It was shown that irradiation at 150 °C produces slight loss of ductility and minor increase yield strength in the studied damage dose range. However, irradiation at 300 °C leads to severe loss of ductility and minor changes of ultimate and yield strength of NiAl bronze. The electrical resistivity changes at studied conditions are on the level of ~1.5%. The SEM and optical microscopy investigations of irradiated NiAl bronze show that the fracture character of this material is ductile and the fracture is transgranular type.

Acknowledgements

This report was prepared as an account of work undertaken within the framework of ITER Transitional Arrangements (ITA). These are conducted by the participants: Canada, China, the European Atomic Energy Community, Japan, Korea, the Russian Federation and the United States of America, under the auspices of the International Atomic Energy Agency. The views and opinions expressed herein do not necessarily reflect those of the participants to the ITA, the IAEA or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the former ITER EDA Agreement.

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