Effect of Alloying Elements on Microstructure and Properties Of Cast γ-TiAl Intermetallic Alloys

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Abstract

The effect of alloying elements on microstructure and properties of γ-TiAl based Intermetallic alloys produced by an in-house made arc-melting furnace was studied. The phases and microstructure of the produced alloys were characterized using X-Ray diffraction, and scanning electron microscope (SEM) respectively. Physical and mechanical tests were performed at room temperature. The results show that the microstructure of Ti-48Al (in at.%) consists of regions containing α_2 and γ lamellae surrounded by γ grains. For alloys alloyed with Cr (Ti-48Al-2Cr), Mo (Ti-48Al-2Mo), and both Cr and Mo (T [redacted] microstructures consist of colonies containing α_2 and γ lamellae. In all revealed microstructures, some Ti-rich phases were also distributed in the lamellar grains and at grain boundaries. The relative content of α_2 phase in lamellae of Ti-48Al-2Cr-Mo is the highest compared with the other alloys. Measured density had slightly increased when alloyed with Cr and heavy alloying element of Mo. The hardness values of γ-TiAl alloys are relatively high exceeding 50 HRC. Hardness values of γ-TiAl alloys with alloying elements of 2-4 at.% show a weak sensitivity to little changes in concentration of alloying elements. Compared with Ti-48Al, the fracture strength in compression of Ti-48Al-2Cr at room temperature was increased, believed to be due to solid solution strengthening of Cr. The increased fracture strength of Ti-48Al-2Mo and Ti-48Al-2Cr-2Mo was attributed to solid solution strengthening of Mo and Cr. Compared with Ti-48Al, the presence of Cr in Ti-48Al-2Cr and Ti-48Al-2Cr-2Mo had enhanced compressive fracture strain.

Keywords: γ-TiAl, alloying elements, microstructure, hardness, compression strength

Introduction

There has been great interest in research and development of γ-TiAl based alloys as future potential candidates for high temperature applications in aerospace and automotive industries [1]. γ-TiAl based alloys have been the focus of particularly intense activity since they offer their low density, high specific yield strength, high specific stiffness, good oxidation and creep resistance at temperatures higher than those possible with more conventional titanium alloys [1,2]. The constituent phases of γ-TiAl alloys always consist of γ-TiAl (ordered face-centered tetragonal $L1_0$ structure) as the matrix phase and α_2-Ti_3Al (ordered hexagonal DO_{19} structure) as the major second phase [1,3]. γ-TiAl alloys without α_2-Ti_3Al phase, even with low interstitial impurity levels (< 1000 wt. ppm), tend to fracture at room temperature before reaching 0.5-1.0 % plastic strain in tension. Engineering alloys based on the γ-TiAl phase usually have Al concentrations of 45-48 at.% and thus solidify peritectically according to the phase diagram shown in Figure 1 [3]. After solidification, binary γ-TiAl alloys pass through the single-phase field of α solid solution, which decomposes on further cooling according to the reactions $\alpha \rightarrow \alpha + \gamma \rightarrow \alpha_2 + \gamma$ or $\alpha \rightarrow \alpha_2 \rightarrow \alpha_2 + \gamma$.

It is well known that the mechanical properties of binary γ-TiAl alloys can be improved through alloying with various alloying elements. The additions of Cr, Mn, and V were reported to lead to improvement of the room temperature ductility of two-phase alloys, since these elements can enhance plasticity by stabilizing thermal twins that provide nucleation sites for twinning dislocations [3-6]. Other researchers have found that Cr also contributes to α_2-dispersion strengthening in Cr-containing γ-TiAl alloys [7]. Alloying with Mo and Nb enhanced the tensile strengths at room- and elevated-temperatures. These elements are grouped into solid solution strengthening elements [3,8].

Basically, the as-cast microstructure would consist of colonies comprised of γ and α_2 lamellae. Fully lamellar microstructures are beneficial for high temperature strength, fracture toughness and creep resistance, but suffer from poor ductility at low and ambient temperature. For high temperature applications, lamellar alloys probably provide the best balance of mechanical properties [1-3,9].

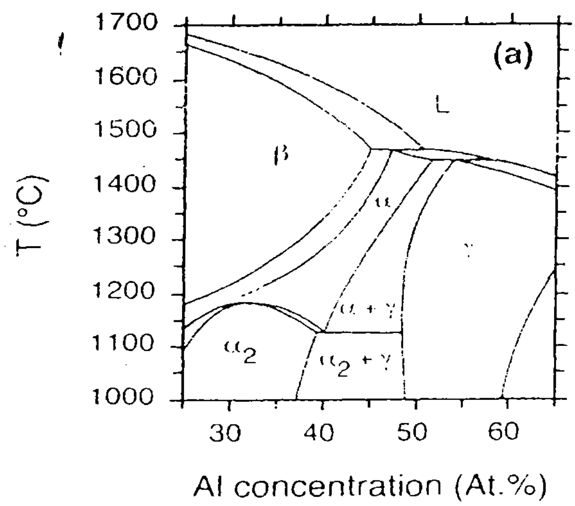

Fig. 1. Binary Ti-Al Phase diagram showing phase equilibria in a concentration range of 45-48 at.% Al [3].

In producing γ-TiAl alloys, arc-melting in vacuum condition is the most widely used process [10-11]. Then melting and casting process has been of greater interest for producing components such as turbine blades and automotive exhaust valves [10]. The advantages of the process are melting process conducted in short time, allowing to remelt several times to ensure good homogeneity of ingots, and it is appropriate for melting highly reactive elements.

In this study, the effect of alloying elements of Cr and Mo on microstructure and properties of γ-TiAl based Intermetallic alloys produced by arc-melting process using an in-house made arc melting furnace was studied. Microstructural features of the γ-TiAl alloys were presented. Physical property and mechanical properties of γ-TiAl alloys were evaluated.

Experimental

Fig. 2 shows an in-house made arc-melting furnace with important parts indicated. The DC power for this arc melting furnace is supplied by TIG welding machine. Argon gas is used to provide protective environment for melting. Melting is carried out in a water cooled copper crucible with the size of melting cell of 35 mm dia. x 20 mm in-depth.

The raw materials used in this study were in powder form. Powders of titanium (average size of 83.81 μm and purity of 99.7 %, STREM Chemicals), aluminium (average size of 72.53 μm and purity of 95.7 %, BDH Laboratory supplies), molybdenum (average size of 122 μm and purity of 99.96 %, STREM Chemicals), and chromium (average size of 50.92 μm and purity of 99 %, STREM Chemicals) were used as starting materials. The powders were initially prepared to the desired compositions of Ti-48Al, Ti-48Al-2Cr, Ti-48Al-2Mo, Ti-48Al-2Cr-2Mo (in at.%) that are further designated as alloy 1, alloy 2, alloy 3, and alloy 4 respectively. Then they are thoroughly mixed in a plastic bottle for 5 hours. The mixture was then compacted in a die by applying a hydraulic press with a pressure of 100 MPa. The size of pellet was 25 mm in diameter. The compact was then ejected from the die cavity at the top by using an ejector, which travels from bottom to top. The compacts were placed and melted in the melting cell of a copper crucible. The DC current of 200 amperes and the DC voltage of 18 V that generate a melting temperature of approximately 2000 °C were used for melting of compacts and a maximum quantity of 17 g ingot of γ -TiAl alloy can be produced. Melting was performed eight times to ensure good homogeneity of ingots.

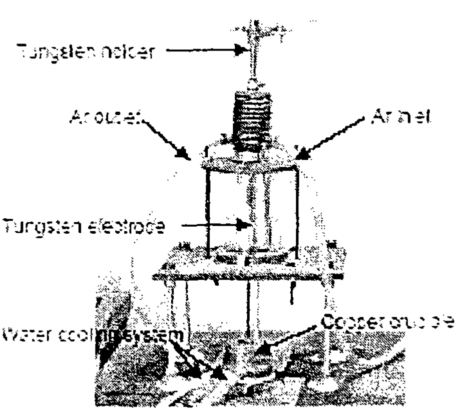

Fig. 2. Photograph of an in-house made arc-melting furnace.

Diamond-coated blade cutting tool was used to cut ingots into samples. X-ray diffraction (XRD) technique and SEM were used to analyze the phase formed and microstructural features of samples respectively. Metallographic samples were polished and then etched in a solution of 10 vol.% HNO_3, 5 vol.% HF, and 85 vol.% water [12]. Density of cast samples was measured by applying gas pycnometer technique on an Accu Pyc 1330 Micromeritics. Hardness test was performed using a Rockwell type hardness tester LECO. A cubic specimen 7 X 7 X 14 mm in size was cut and used for the compression test. All specimens were polished before testing. Compression test were carried out at room temperature by Shimadzu universal testing machine (UTM) with a crosshead speed of 0.5 mm/min.

Results and Discussion

X-Ray Diffraction Patterns

Fig. 3 shows the XRD patterns of the as cast alloys produced from the arc-melting process. It can be found from the diffraction result that alloy 1 predominantly contains γ phase and a minor amount of α_2 phase (Fig.3a). This can be accounted for from the equilibrium phase diagram indicates the presence of two phases for this nominal composition, Ti-48Al (in at.%). The addition of 2 at.% Cr results in an increase in intensity of the second strongest line belonging to α_2 phase in alloy 2 (Fig. 3b). Thus, the relative content of α_2 phase in alloy 2 had increased. With addition of 2 at.% Mo, the relative content of α_2 phase in alloy 3 become higher than that in alloy 2 (Fig. 3c). On the other hand, the addition of Cr combined with Mo in alloy 4 had resulted in slightly higher relative content of the α_2 phase than that of the γ phase (Fig. 3d). Based on these findings, it is clear that the addition of 2 at.% Cr and/or 2 at.% Mo provide effect on stabilizing the α_2 phase, however, effect of Mo on stabilizing α_2 phase is stronger than Cr. The effect of Cr with its concentration of 2 at.% acting as a α_2 stabilizer in γ-TiAl alloys was also reported by other researcher [13].

Microstructure of As-cast Alloys

Fig. 4 shows back scattered electron (BSE) images of as cast alloys produced by arc-melting process. The microstructure of alloy 1 consists of regions (colonies) containing α_2 and γ lamellae surrounded by γ grains and of some Ti-rich phase in the lamellar grains and at grain boundaries (Fig. 4a). The chemical composition of the Ti-rich phase was analyzed by EDS, and its analysis results were 68.01 at.% Ti and 31.99 at.% C. Based on this results, It is suspected that incorporated carbon in Ti-rich phase most probably comes from raw elemental powders. Microstructures of Alloy 2 with addition of 2 at.% Cr and of alloy 3 with addition of 2 at.% Mo are found to consist of colonies containing α_2 and γ lamellae and there is also some Ti-rich phase in the lamellar grains and at grain boundaries (Fig. 4b and 4c). According to XRD results of alloy 2 and 3, the relative content of α_2 phase in the lamellae of alloy 3 was higher than the content of that in alloy 2. With the combined addition of both 2 at.% Cr and 2 at.% Mo, the microstructure of alloy 4 consists of colonies containing α_2 and γ lamellae and of some Ti-rich phase in the lamellar grains and at grain boundaries (Fig. 4d). However, the relative content of α_2 phase in lamellae of alloy 4 is the highest compared with the other alloys. From revealed microstructures of alloys, it is also found that the relative content of Ti-rich phase in alloy 4 is lower than the content of that in all of the other alloys.

Properties of γ-TiAl Alloys

Measured density of γ-TiAl alloys produced by arc-melting process is shown in Fig. 5. Alloy 1 has a density of 3.97 g/cm^3 and agrees well with measured density of γ-TiAl based alloys ranging from 3.9-4.1 g/cm3 that was well documented in the literature [11]. Due to the additions of alloying elements, particularly heavy elements, densities of γ-TiAl based alloys would increase. In this case, the density of alloy 2 alloyed with Cr slightly increase (4.00 g/cm^3), whereas densities of alloy 3 with addition of 2 at.% Mo and of alloy 4 with addition of both Cr and Mo was increased to 4.02 and 4.14 g/cm^3 respectively.

The results of hardness test of γ-TiAl based alloys are shown in Fig. 6. It can be seen that the hardness values of γ-TiAl alloys are relatively high exceeding 50 HRC. With additions of alloying elements of Cr, Mo or the addition of both Cr and Mo, the hardness values of γ-TiAl alloys had slightly decreased. In this case, it is believed that hardness of γ-TiAl alloys with additions of alloying elements of 2-4 at.% shows a weak sensitivity to little changes in concentration of alloying elements.

The fracture strengths in compression of γ-TiAl alloys with various alloying elements at room temperature are shown in Fig. 7. The fracture strength in compression of alloy 1 is 755 MPa. Alloy 2 with addition of 2 at.% Cr, alloy 3 with 2 at.% Mo, and alloy 4 with addition of both 2 at.% Cr and 2 at.% Mo, the fracture strengths had increased to 929, 1112,and 1092 MPa respectively. The increased fracture strength in alloy 2 is most likely attributed to solid solution strengthening due to the presence of Cr. For the case of alloy 3, solid solution strengthening due to Mo plays an important role in obtaining the highest compressive fracture strength, but the compressive ductility of alloy 3 does not increase (see Fig. 8). For alloy 4, solid solution strengthening due to both Cr and Mo can be related to increased fracture strength of alloy 4. Although fracture strength of alloy 3 is slightly lower than that of alloy 4, it has the highest compressive ductility compared with the other alloys.

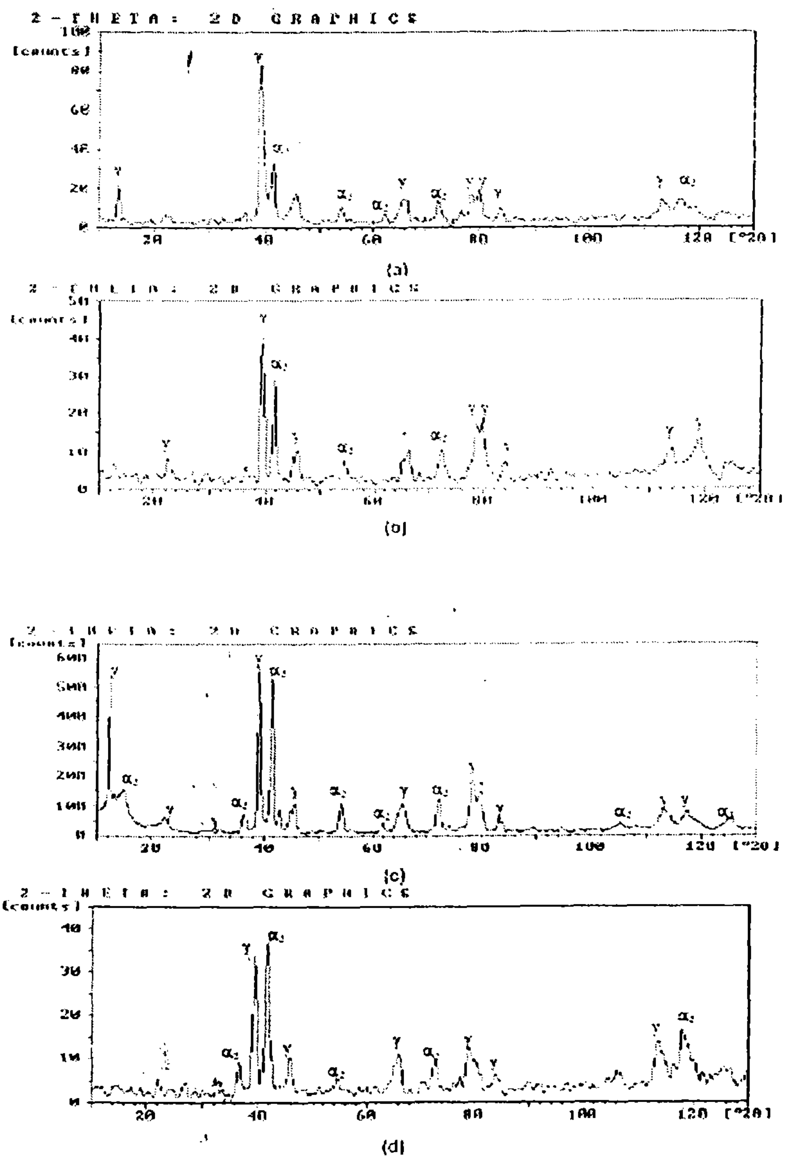

Fig. 3 XRD patterns of as-cast alloys: (a) Ti-48Al, (b) Ti-48Al-2Cr, (c) Ti-48Al-2Mo, and (d) Ti-48Al-2Cr-2Mo. γ: γ-TiAl, α_2: α_2-Ti_3Al.

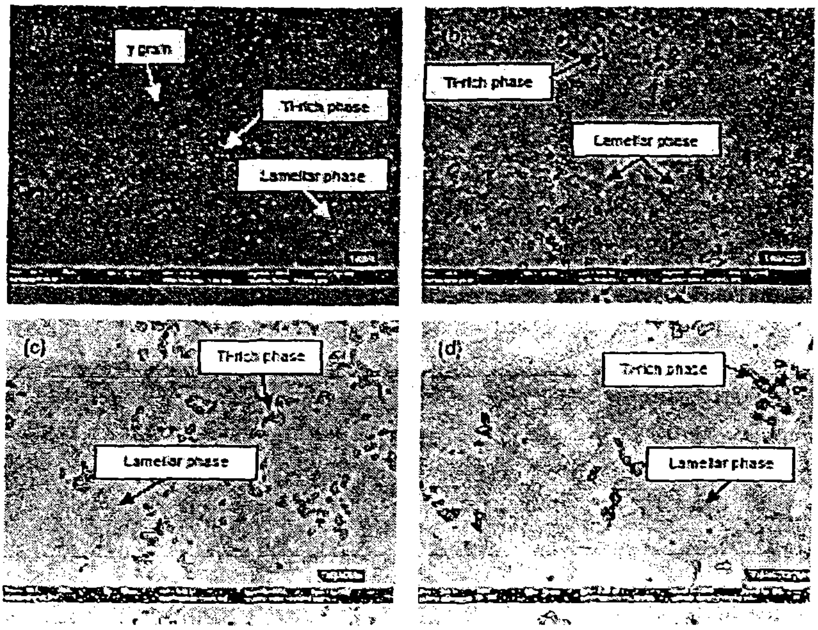

Fig. 4. Back Scattered Electron (BSE) images showing the microstructures of as cast alloys: (a) Ti-48Al, (b) Ti-48Al-2Cr, (c) Ti-48Al-2Mo and (d) Ti-48Al-2Cr-2Mo.

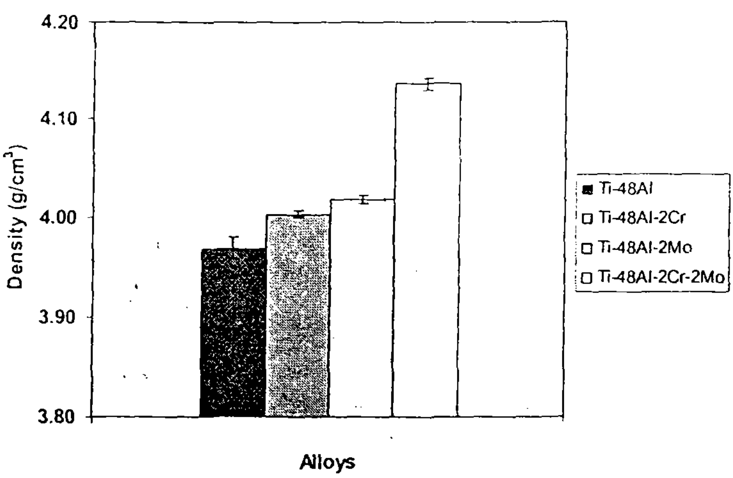

Fig. 5. Comparison of measured density for as-cast Ti-48Al, Ti-48Al-2Cr, Ti-48Al-2Mo, and Ti-48Al-2Cr-2Mo alloys.

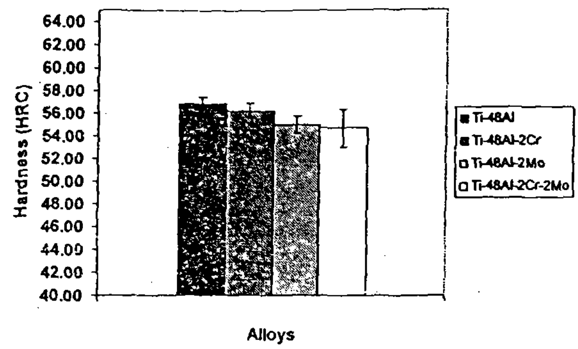

Fig. 6. Results of Rockwell Hardness test for as-cast Ti-48Al, Ti-48Al-2Cr, Ti-48Al-2Mo, and Ti-48Al-2Cr-2Mo alloys.

Fig. 8 shows the fracture strain in compression (compressive ductility) of γ-TiAl alloys with various alloying elements at room temperature. The fracture strain in compression of alloy 1 is 7 %. With additions of Cr to alloy 2 and 4, the compressive fracture strains were increased to 14 and 16 % respectively. The fracture strain of alloy 3 alloyed with 2 at.% Mo remains unchanged. Therefore, the presence of Cr in alloy 2 and 4 can enhance compressive ductility.

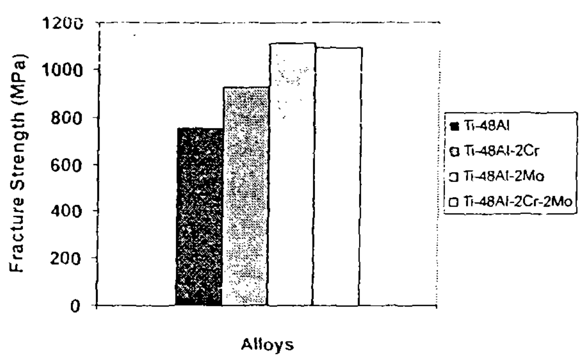

Fig. 7. Comparison of compressive fracture strength at room temperature for as cast Ti-48Al, Ti-48Al-2Cr, Ti-48Al-2Mo, and Ti-48Al-2Cr-2Mo alloys.

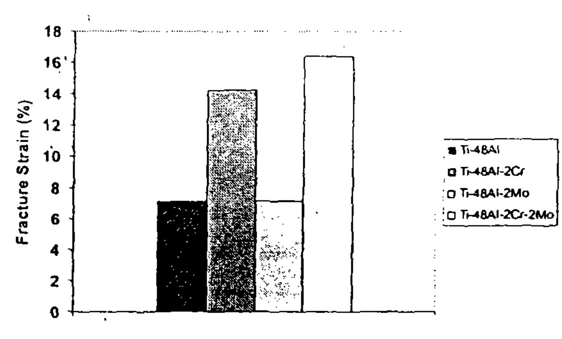

Fig. 8. Comparison of compressive fracture strain (ductility) at room temperature for as cast Ti-48Al, Ti-48Al-2Cr, Ti-48Al-2Mo, and Ti-48Al-2Cr-2Mo alloys.

Conclusions

1. The microstructure of Ti-48Al (alloy 1) consists of regions (colonies) containing α_2 and γ lamellae surrounded by γ grains and of some Ti-rich carbide phases in the lamellar grains and at grain boundaries. For alloys alloyed with Cr (alloy 2), Mo (alloy 3), and both Cr and Mo (alloy 4), the microstructures consist of colonies containing α_2 and γ lamellae and some Ti-rich phases were also distributed in the lamellar grains and at grain boundaries. The relative content of Ti-rich phase in alloy 1, 2, and 3 was qualitatively found higher than the content of that in alloy 4. Based on XRD results, it can be concluded that the relative content of α_2 phase in lamellae of alloy 4 is the highest compared with the other alloys.
2. The alloy 1 have a density of 3.97 g/cm^3, 4.00 g/cm^3 for the alloy 2, 4.02 for alloy 3, and 4.14 g/cm^3 for alloy 4. By additions of alloying elements, particularly heavy elements, densities of γ-TiAl based alloys would increase.
3. Hardness values of γ-TiAl alloys selected in this study are relatively high exceeding 50 HRC. Hardness values of γ-TiAl alloys with additions of alloying elements of 2-4 at.% show a weak sensitivity to little composition changes of alloying elements.
4. Compared with alloy 1, the fracture strength in compression of alloy 2 at room temperature was increased, resulting from solid solution strengthening due to Cr. For alloy 3 the highest fracture strength was achieved, resulting from solid solution strengthening due to Mo. The increased fracture strength of alloy 4 can be attributed to solid solution strengthening due to both Cr and Mo.
5. The fracture strain in compression of alloy 1 is 7 %. The compressive fracture strains of alloy 2 and 4 were increased to 14 and 16 % respectively. The fracture strain of alloy 3 remains unchanged when it was alloyed with Mo. Therefore, the presence of Cr in alloy 2 and 4 can enhance ductility in compression.

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