LETTERS TO THE EDITOR

Amorphous High-Carbon Tungsten Steels Rapidly Quenched from Melts

Investigating the formation and properties of amorphous alloys has been one of the important subjects of recent metallurgical researches. A significant activity has centered on the study of liquid-quenched amorphous alloys containing transition elements like iron, cobalt and nickel and metalloid elements like phosphorus, carbon, boron and silicon, because of the high potentiality of these alloys as practical materials. Recently, the present authors⁽¹⁾⁽²⁾ have studied the effect of alloying elements on the amorphous-forming tendency of iron-based alloys containing only carbon as the metalloid element and have found the perfect formation of an amorphous phase in a wide composition range of the Fe-Cr-C and Fe-Mo-C ternary systems, of the Fe-Cr-Mo-C, Fe-Cr-W-C and Fe-Mo-W-C quaternary systems and of the Fe-Cr-Mo-W-C pentad system. We have found that the addition of chromium, molybdenum and tungsten is effective for the improvement of thermal stability and mechanical strength as well as the enhancement of the amorphous-forming tendency, and among these elements tungsten is most effective. Therefore, a trial was made for obtaining amorphous alloy steels of the Fe-W-C system. This paper presents the composition range of the Fe-W-C amorphous phase and the thermal and mechanical properties of these amorphous alloys.

Specimens were produced in the form of long ribbons of about 1 mm width and 0.03 mm thickness by a single roller-type quenching apparatus⁽³⁾. The identification of the as-quenched phase was made by X-ray analysis using Cu K α or Mo K α radiation and a transmission electron microscope. Hardness of specimens was measured by a Vickers microhardness tester with a 50 g load. The crystal-

lization behavior of the alloys was examined in a differential scanning calorimeter (DSC) at a heating rate of 8.33×10^{-2} K/s. The embrittlement by aging was tested for the specimens annealed at various temperatures for 6000 s in evacuated silica capsules. Ductility was determined by measuring the radius of curvature at fracture in a simple bend test⁽⁴⁾.

Figure 1 shows the formation range of amorphous phase for the Fe-W-C ternary system. The amorphous formation in this system is limited to the range of 19~23 at% C and 9~15 at% W. This figure also shows that the amorphous-forming region lies near the eutectic trough where the melting temperature is high or almost identical as compared with that of eutectic Fe-C binary alloy⁽⁵⁾. Eutectic Fe-C binary alloy, Fe₈₂C₁₈, showed a crystalline microstructure consisting of austenite and cementite, and no amorphous phase was found. Therefore, it is concluded that the replacement of iron with tungsten enhances the amorphous-forming tendency of this alloy.

In general, it is supposed from a kinetic consideration⁽⁶⁾⁽⁷⁾ that the formation of the amorphous phase is closely related to the high reduced glass temperature (T_g/T_m) of alloys. Here T_g and T_m are the glass transition temperature and the melting temperature of alloys, respectively. Since T_g is near the crystallization temperature T_x (in most cases, within 50 K less than T_x), T_g (or T_x) of these amorphous tungsten steels must lie in the range of about 680 to 790 K which is much higher than that (about 423 K)⁽⁸⁾ of the amorphous phase in Fe-C binary alloys obtained by a gun method. Therefore, the enhancement in the amorphous-forming tendency of Fe-W-C alloys appears to be dominated mainly by a remarkable

Table 1 Vickers microhardness (Hv), crystallization temperature (T_x) and critical fracture temperature (T_f) for several amorphous high-carbon tungsten, molybdenum and chromium steels.

Alloy system (at %)	Vickers hardness, Hv (DPN)	Crystallization temperature, T_x (K, 8.33×10^{-2} K/s)	Critical fracture temperature, T_f (K, $\times 6000$ s)
Fe ₆₈ W ₁₀ C ₂₂	1020	723	—
Fe ₆₆ W ₁₂ C ₂₂	1020	754	553
Fe ₆₈ W ₁₂ C ₂₀	1030	754	—
Fe ₆₆ W ₁₄ C ₂₀	1050	793	—
Fe ₇₂ Mo ₈ C ₂₀	820	711	—
Fe ₇₀ Mo ₁₂ C ₁₈	860	760	593
Fe ₆₈ Mo ₁₂ C ₂₀	920	768	573
Fe ₆₆ Mo ₁₂ C ₂₂	930	784	573
Fe ₆₄ Mo ₁₆ C ₂₀	970	838	—
Fe ₅₈ Cr ₂₄ C ₁₈	780	734	—
Fe ₅₄ Cr ₂₈ C ₁₈	850	743	543
Fe ₅₂ Cr ₂₈ C ₂₀	890	729	—

Fig. 1 The composition range for formation of Fe-W-C amorphous alloys. Open circles represent the amorphous state and closed circles crystalline. Binary phase diagrams obtained from Ref. (5) are included.

rise in T_g .

Vickers hardness (Hv), crystallization temperature (T_x) and critical fracture temperature

(T_f) of Fe-W-C amorphous alloys are tabulated in Table 1 together with those⁽¹⁾⁽²⁾ of Fe-Mo-C and Fe-Cr-C amorphous alloys,

wherein T_f is the temperature of aging for 6000 s which led to the fracture of alloys in a perfect bending test. The table shows that the hardness and the crystallization temperature increase with increase in tungsten content and reach a maximum value of 1050 DPN and 793 K, respectively. The hardness of Fe-W-C alloys is higher by about 100 DPN as compared with those of Fe-Mo-C alloys. There is a tendency that the harder alloys have the higher crystallization temperatures. The same tendency has been found⁽¹⁾⁽²⁾ with other amorphous alloy steels such as Fe-Mo-C, Fe-Cr-C, Fe-Cr-Mo-C, Fe-Cr-W-C and Fe-Mo-W-C. T_f of Fe₆₆W₁₂C₂₂, 553 K, is lower than that of Fe₆₆Mo₁₂C₂₂ alloy. The tendency that T_f decreases with increase in hardness has been found previously for Fe-X-Y-C (X, Y: Cr, Mo, W)⁽¹⁾⁽²⁾⁽⁹⁾ and X-Y-P-B-Al (X, Y: Fe, Co, Ni, Cr, Mo)⁽¹⁰⁾ amorphous alloys and interpreted in terms of the enhanced phase separation upon alloying and the strong d-band character of the chromium, molybdenum and tungsten atoms.

In conclusion, the amorphous high-carbon tungsten steel found in the present work is attractive as a high-strength material like other amorphous high-carbon alloy steels of Fe-Cr-C, Fe-Mo-C, Fe-Cr-Mo-C, Fe-Cr-W-C and Fe-Mo-W-C.

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