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How does the cold-worked Fe-Ni-Al-C alloy obtain its large ductility? -Tensile behaviour at various temperatures-

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Abstract: We investigate tensile behaviour of cold-worked Fe-24Ni-4Al-0.4C (wt.%) at various temperatures. Both stress-strain behaviour and effects of temperature on yield stress and uniform elongation obtained here are very similar to those of other cold-worked metastable austenitic steels; Fe-Cr-Ni-Mn-C, Fe-Cr-Ni-Mo-Mn-Si-C, and Fe-Ni-Mo-Mn-C. However, the relationship between martensite-start temperature (M_s) and martensitic transformation behaviour in the present alloy is apart from other metastable austenitic steels, exhibiting more active martensitic transformation with lower M_s.

1. INTRODUCTION

The development of advanced steels with superior mechanical property is strongly desired for concerning energy efficiency and environmental load [1-2]. In most of steels, the strength and ductility are mutually exclusive, good combination of both properties is therefore very difficult to achieve. In such circumstances, cold-worked austenitic metastable steels (CAMS) like Fe-Cr-Ni-Mo-Mn-Si-C, Fe-Ni-Mo-Mn-C [3-4], and Fe-Cr-Ni-Mn-C [5] are outstanding in mechanical property, where martensitic transformation plays an important role for obtaining such superior properties. Meanwhile, a cold-worked Fe-Ni-Al-C alloy has been reported, which has good combination of strength (Y.S.~2GPa) and ductility (T.E.~20%) in these days [6]. Its property is nearly located in the upper-limit of other CAMS [3]. Its tensile behaviour at room temperature (RT) is similar to those of CAMS. However, its deformation mechanism still remains unclear due to its complicated microstructure and phase constitution, particularly the existence of the second phase (B2-structured phase).

In the present work, simpler phase constitution and microstructure (single austenite phase) were achieved by changing Al content. Then its tensile behaviour was investigated at various temperatures. Results obtained were compared with those of other CAMS.

2. EXPERIMENTAL METHODS

Fe-24.1Ni-4.06Al-0.43C (wt.%) was melted and cast in an induction furnace under an Ar atmosphere. An ingot having a diameter of 50 mm was hot forged into 15 mm in diameter at 1423 K, subsequently homogenized at 1373 K for 24 h, and finally quenched in RT water. A treated ingot was fully-austenized to obtain a grain size of approximately 200 µm. A plate with cross-sectional dimensions of 6 × 11 mm was cut from the ingot and subsequently cold-rolled into a plate with cross-sectional areas of 1.0 × 16 mm (83% reduction in thickness). Tensile tests were conducted by using flat specimens with a gauge length of 14 mm, a width of 6.5 mm and a thickness of 0.8 mm, with an initial strain rate of 3.6×10^{-4} s^{-1} at temperature ranging from -35°C to 90°C. In the present work, uniform elongation is defined as the nominal strain at maximum flow stress. M_s and martensite-start temperature at tensile test (M_d), and the volume fraction of martensite were measured by magnetic measurement. M_s and M_d were determined by observing rapidly increase of magnetic moments of whole horizontal part of samples after cooling or tensile deformation, respectively. The volume fraction of martensite was determined by using the data of samples, which volume fractions of

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martensite were determined in advance by X-ray diffraction method in order to reduce the influence of textures.

3. RESULTS

3.1. Stress-strain behavior

Fig.1 presents stress-strain behaviour of the material at different temperatures. It exhibited upper yield point, which was followed by yield point elongation, a zone of intensive strain-hardening at temperature below 23 ℃. The yield point elongation at RT was proceeded in two steps; from 0 to 20, and 20 to 40% in engineering strain. While, elongation was rapidly decreased at 70 ℃.

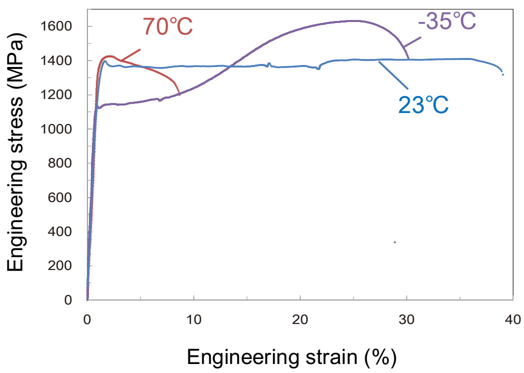

Fig.1. Stress-strain behaviour at various temperatures

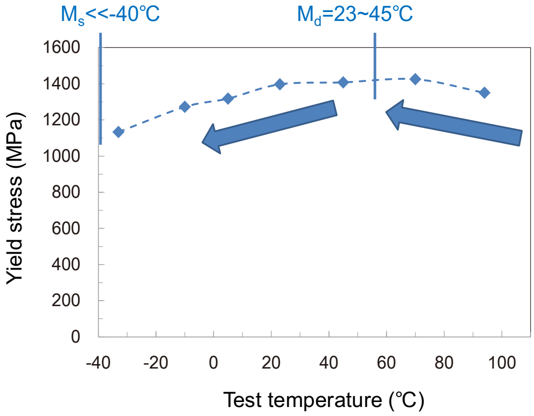

Fig.2. Effect of temperature on yield stress

3.2. Effect of temperature on yield stress

Fig.2 presents an effect of temperature on yield stress obtained from the data shown in Fig.1. In the present material, M_s was far below the lower-limit temperature of the tensile test, and martensitic transformation was not observed by cooling to -73℃. Its yield stress depended on test temperature, and the tendency was changed around RT. It exhibited negative dependence on temperature above RT, while positive dependence on temperature below RT.

3.3. Effect of temperature on uniform elongation

Fig.3 shows an effect of temperature on uniform elongation. The data of as-homogenized sample (without cold work) is also shown. In both materials, uniform elongations increased as the temperature decreased, and they were maximized between M_s and M_d. This is typical tendency of transformation-induced steels (TRIP steels) [3]. There were almost no uniform elongations above M_d in the cold-worked samples. This indicates that martensitic transformation during tensile deformation was necessary for obtaining substantial ductility.

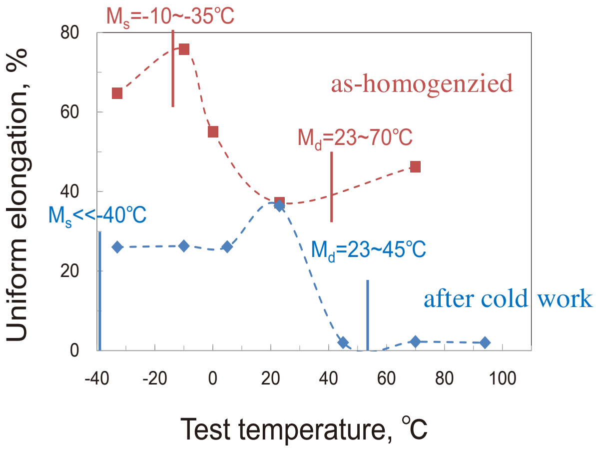

Fig.3. Effect of temperature on uniform elongation

4. DISCUSSIONS

Richman et.al [7] has defined M_s^σ as temperature where yield stress begins to decrease. This decrease is derived from martensitic transformation induced by applied stress with lower value than the yield stress of austenite. According to this definition, M_s^σ in the cold-worked material is around RT, which corresponds to temperature where upper-yield point appeared. The upper-yield point and following yield point elongation are therefore derived from stress-induced martensitic transformation, and that has been reported in some studies in CAMS [5,7]. In addition, results obtained in the present work shows that mechanical behaviour and its dependence on temperature are very similar to those of CAMS. In both the present cold-worked Fe-Ni-Al-C alloys and other CAMS, occurrence of martensitic transformation and its behaviour have great influence on their mechanical properties.

What we should emphasize here is the effect of cold-work on the behaviour of martensitic transformation. Table 1 compares the martensitic transformation behaviour at RT in as-homogenized and after cold work samples with regard to their volume fraction of martensite. The as-homogenized sample exhibited a slight increase after tensile test. In contrast, cold-worked sample exhibited drastically increase after tensile test. M_s temperature is decreased over 35℃ by cold work, which is interpreted as austenite becomes more stable in many cases [8-10] This result therefore indicates the relationship between M_s and the martensite transformation behaviour in the present material is apart from conventional as-homogenized TRIP steels [10], although that of CAMS is still unclear. The reason for this is unknown so far, but deformation behaviour of austenite grains which are surrounding the martensite grain might influence the martensitic transformation behaviour in term of relaxation of grain constraints, as the importance of the relaxation behaviour is pointed out in ref [11].

Table.1. Martensite transformation behaviour in as-homogenized and after cold-worked samples

Volume fraction of martensite (%)	Before test (V1)	After test (V2)	ΔV (V2-V1)
as-homogenized	0	5.2	5.2
after cold work	27.4	91.9	64.5

5. CONCLUSION

Tensile behaviour of the cold-worked Fe-24Ni-4Al-0.4C alloy has been investigated at various temperatures. Stress-strain behaviour exhibited upper-yield point, which was followed by yield point elongation, a zone of intensive strain-hardening at temperatures below RT. The yield point elongation was proceeded in two-steps at RT. An effect of temperature on yield stress was changed around RT, negative effect (ordinary tendency) at higher temperatures and positive effect at lower temperatures. An effect of temperature on uniform elongation was not monotonic, and uniform elongation exhibited its maximum value between M_s and M_d. These results indicate that tensile behaviour of the cold-worked Fe-Ni-Al-C alloy is very similar to those of other cold-worked metastable austenitic steel, and in both materials, deformation-induced martensite transformation plays an important role for obtaining those mechanical properties. However, the relationship between M_s and martensite transformation behaviour in the present alloy is apart from other conventional as-homogenized TRIP steels, exhibiting more active martensite transformation with lower M_s, although those of other cold-worked metastable austenitic steels are unclear.

REFERENCES

[1] K. Lu: Science, 328 (2010), 319-320
[2] M. Militzer: Science, 298 (2002), 975-976.
[3] V. F. Zackay, E. R. Parker, D. Fahr, and R. Bush: ASM Trans. Quart., 60 (1967), 252-259
[4] G. R. Chanani, V. F. Zackay, and E. R. Parker: Metall. Trans. , 2 (1971), 133-139.
[5] D. Fahr: Metall. Trans., 2 (1971), 1883-1892.
[6] T. Furuta, S. Kuramoto, T. Ohsuna, K. Oh-ishi, and K. Horibuchi: Scripta Materialia, 101 (2015), 87-90.
[7] A. A. Lebedev, V. N. Rudenko, and B. I. Koval'chuk: Strength of Materials - STRENGTH MATER-ENGL TR. 15(1984), 1072-1076
[8] T. Maki, Y. Tomota, and I. Tamura: Bulletin of the Japan institute of metals and materials, 38 (1974), 871-876.
[9] Y. Tomota, H. Yoshino, M. Wada, K. Tanabe, K. Kuroki, and I. Tamura: Zairyo, 25 (1975), 717-723.
[10] S. Seo, T. Miyazaki, E. Yajima, and K. Morita: Bulletin of the Japan institute of metals and materials, 37 (1973), 1172-1179.
[11] Y. Suto, T. Omori, R. Kainuma, and K. Ishida: Acta Materialia, 61 (2013), 3842-3850.