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## Effect of strain rate and temperature on mechanical properties and fracture mode of high strength precipitation hardened ferritic steels

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The effect of strain rate on the flow stress of a low carbon high strength ferritic steel that contains nanometer size Cu–Ni–Al precipitates is found to be much less than that of HSLA 65 that does not have such precipitates. This result is in agreement with the theory that such precipitates locally lower the Peierls stress for screw dislocations in body-centered cubic iron. The fracture mode in the steel is ductile over the wide ranges of strain rate and temperature investigated. © 2006 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

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Nanoscale precipitation strengthening of low carbon ferritic steels is an alternate path to high strength steels from heat-treating to give martensite. Initially a precipitation strengthened ferritic low carbon steel containing approximately 1.35 wt.% Cu and 0.75 wt.% Ni was developed [1–4]. On air-cooling from hot rolling, yield strength of approximately 500 MPa was obtained. The yield strength increased to 700 MPa after solution treating and aging. The microstructure of steel exhibited nanoscale precipitates consisting of alloys of Cu and Fe with a small amount of Ni [5]. Such steel microstructure resulted in very high impact fracture energies at cryogenic temperatures (approximately 350 J). The weldability and corrosion resistance of this steel were better than competing martensitic steels. To further boost the strength, nickel concentration was increased and aluminum was added (Table 1) to increase the volume fraction of precipitates in the ferritic matrix. This steel containing Al-Ni-Cu precipitates [6] (named AlNiCu 150 steel in the text) when solution treated and aged achieved yield strength of 1050 MPa and 20% elongation to failure [7].

This paper describes the further investigation of the effect of temperature and strain rate up to high values on mechanical and fracture properties of the Cu-Ni-Al precipitation strengthened steel. It is well known that steels are brittle at low temperatures because the screw dislocations have a high Peierls stress. At room temperature or above, thermal energy is high enough to allow a screw dislocation lying in its Peierls valley to form a double kink that then expands under the applied stress. At low temperatures, thermal activation is too small to nucleate a double kink by itself giving rise to an increase in flow stress that is close to the fracture stress. The presence of a misfitting precipitate near the dislocation helps nucleate a double kink and lowers the flow stress [8]. Increasing strain rate should have the same effect as lowering the temperature in reducing the thermal energy available for helping kink nucleation. The objective of this research was to ascertain whether or not nanoscale precipitation strengthened AlNiCu 150 steel had a reduced flow stress dependence on strain rate compared to similar steel without such precipitates, namely HSLA 65, for which there are data in the literature [9].

A 50-kg laboratory heat of AlNiCu 150 experimental steel was produced at Ispat-Inland's Research and Development Department (now Mittal Steel Co.) by vacuum melting. Its composition together with the composition of HSLA 65 steel is given in Table 1. The cast steel was hot-rolled into 12.7-mm thick plates and air-cooled. It was then austenitized at 900 °C for

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	С	Mn	Р	S	Si	Cu	Ni	Al	Nb
AlNiCu 150	0.05	0.47	0.005	0.001	0.46	1.34	2.71	0.60	0.07
HSLA 65	0.08	1.40	0.005	0.005	0.24	<0.01	<0.01	0.03	0.04

Table 1. Composition of the steels (wt.%)

30 min, quenched into water, and aged at 550 °C for 2 h. Round ASTM E8 Standard tensile specimens with a gauge length of 50.8 mm were tested at low strain rates  $(1 \times 10^{-3} \text{ to } 1 \times 10^{-1} \text{ s}^{-1})$  at or below-room temperature using a screw-driven or servo-hydraulic MTS machine.

The high strain rate (295 and 718  $s^{-1}$ ) data was obtained using a Kolsky bar apparatus (Fig. 1) with dog-bone shaped specimens of 2.54 mm in diameter and 6.35 mm in gage length. The specimens were screwed between incident and transmitter pressure bars. To conduct the dynamic test, an axial force was stored between the axial hydraulic actuator and the C-clamp, and suddenly released by fracture of an aluminum pin. Upon release of the stored axial force, a stress wave traveled down the incident bar towards the specimen. Part of the wave was transmitted by the sample and part was reflected. Transmitted and reflected pulses were measured by full Wheatstone bridges (strain gauge stations) mounted on the incident and transmitter bars. Analyses of these pulses resulted in the stress-strain curves shown in Figure 2.

The fractography was performed on Hitachi S3500 scanning electron microscope (SEM).

The measured room-temperature stress–strain tensile curves are given in Figure 2. The higher strain rate stress–strain curves show serrated yielding which is related to the wave nature of the loading in the Kolsky apparatus and is commonly observed in such tests with steels. While the elongation to failure at the lower strain rates is 21-22%, it is 29% at a strain rate of  $718 \text{ s}^{-1}$ . The difference is due to a smaller gage length and necking for specimens tested in the Kolsky bar apparatus, 6.35 mm vs 25.4 mm.

Figure 3 shows the effect of strain rate on flow stress at 0.05 strain for AlNiCu 150 steel tested at temperatures down to -51 °C. The flow stress increases when strain rate is increased and also increases when temperature is reduced as it does in other steels. The flow stress change, however, is comparatively small, varying in the range from 1025 to 1120 MPa.



Figure 2. True stress-true strain curves (not corrected for necking) for AlNiCu 150 steel at five different strain rates. Tests performed at 25 °C.



Figure 3. Effect of strain rate and temperature on flow stress at 0.05 true strain for AlNiCu 150 steel.

Figure 4 shows the relationship between flow stresses at 5% strain and strain rate for AlNiCu 150 steel and HSLA 65 (low carbon, manganese) steel [9]. It is obvious that the flow stress of the HSLA 65 steel is affected by strain rate much more than that of the AlNiCu 150 steel. While the AlNiCu 150 steel investigated in the current research has nanoscale precipitates the HSLA 65 does not.

The flow stress  $\tau$  consists of two parts, a thermally activated part,  $\tau_t$ , and an athermal part,  $\tau_a$ . Only  $\tau_t$  is affected by variation in strain rate or temperature.



Figure 1. Schematics of Kolsky bar set-up.



**Figure 4.** Relationship between the strain rate and flow stress at 5% strain for HSLA 65 and AlNiCu 150 steels at 25 °C.

$$\tau = \tau_{\rm t} + \tau_{\rm a} \tag{1}$$

The following equation was used to examine the relationship between strain rate,  $\dot{\gamma}$ , and flow stress:

$$\dot{\gamma} = \dot{\gamma}_0 \exp\left[-\frac{Q - V(\tau - \tau_a)}{k_b T}\right] = \dot{\gamma}_0 \exp\left(-\frac{Q}{k_b T} + \frac{V\tau}{k_b T} - \frac{V\tau_a}{k_b T}\right)$$
(2)

where  $\dot{\gamma}_0$  is a constant, Q is the activation energy, V is the activation volume,  $k_b$  is Boltzmann's constant, and T is absolute temperature.

The activation volume is:

$$V = bdl \tag{3}$$

where b is the Burgers vector, d is the activation distance and l is the activation length. In this case d is equal to b, the distance from one Peierls valley to the next.

For body-centered cubic (bcc) iron the Burgers vector is equal to  $0.248 \times 10^{-9}$  m, thus the activation length is equal to 5.46 nm for HSLA 65 steel and 19.53 nm for NUCu-150 steel. The larger activation length for the alloy with precipitates indicates a larger double kink length as predicted by the theory [6]. Nanosize precipitates thus appear to locally lower the Peierls stress over the length of a double kink along the dislocation.

SEM fractographs of the failed AlNiCu 150 steel specimens, tested at low and high strain rates at room temperature as well as at low temperature and strain rate, are shown in Figure 5. It is evident that ductile fracture occurred over the full strain rate and temperature ranges investigated. As expected from the higher





Figure 5. Fractured surfaces of tested specimens: (a) strain rate =  $1 \text{ s}^{-1}$  and T = 25 °C; (b) strain rate =  $718 \text{ s}^{-1}$  and T = 25 °C and (c) strain rate =  $1 \text{ s}^{-1}$  and T = -40 °C.

nucleation rate under dynamic loading, a slightly more homogeneous dimple structure is observed in the sample failed at highest strain rate.

The flow stress of the high-strength nanosize precipitation hardened ferritic steel (AlNiCu 150 steel) is less sensitive to strain rate than that of HSLA 65 steel that does not have these precipitates. The fracture mode for the AlNiCu 150 steel is ductile over the wide ranges of strain rate and temperature investigated. This observation lends support to the theory that nanosize precipitates interact with screw dislocations in bcc iron locally, lowering the Peierls stress and facilitating formation of a double kink.

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 M.E. Fine, R. Ramanathan, S. Vaynman, S.P. Bhat, Proceedings of International Symposium on Low Carbon Steels for 90's, ASM International, Materials Park, OH, 1993, p. 511.

- [2] S. Vaynman, M.E. Fine, G. Ghosh, S.P. Bhat, Materials for the New MillenniumProceedings of the Fourth Materials Engineering Conference, ASCE, New York, NY, 1996, p. 1551.
- [3] S. Vaynman, I. Uslander, M.E. Fine, Proceedings of 39th Mechanical Working and Steel Processing Conference, ISS, Indianapolis, IN, 1997, p. 1183.
- [4] S. Vaynman, M.E. Fine, International Symposium on Steel for Fabricated Structures, ASM International, Materials Park, OH, 1999, p. 59.
- [5] D. Isheim, M.S. Gagliano, M.E. Fine, D.N. Seidman, Acta Mater. 54 (2006) 841.
- [6] D. Isheim, R.P. Kolli, M.E. Fine, D.N. Seidman, Scripta Mater. 55 (2006) 35.
- [7] S. Vaynman, D. Isheim, M.E. Fine, D.N. Seidman, S.P. Bhat, Proceedings of Materials Science and Technology 2004 Conference, AIST and TMS, Warrendale, PA, 2004, p. 525.
- [8] M.E. Fine, A. Tongen, M.S. Gagliano, Electron Microscopy: Its role in Materials Science (The Mike Meshii Symposium), TMS, Warrendale, PA, 2003, p. 229.
- [9] S. Nemat-Nasser, W. Guo, Mech. Mater. 37 (2005) 379.
- [10] A. Smith et al., ISIJ Int. 44 (2004) 1188.