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Effect of Ti on Charpy Fracture Energy and Other Mechanical Properties of ASTM A 710 Grade B Cu-Precipitation-Strengthened Steel

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Abstract

Addition of titanium (Ti) to ASTM A710 Grade B Cu-precipitation-strengthened steel significantly increases the impact absorbed fracture energy and reduces the ductile-to-brittle transition temperature. The effect of Ti correlates with the reduction of the amount of pearlite in the ferritic microstructure. A thorough study of the mechanical properties of Ti-modified A 710-B steel is presented.

Introduction

The ductile to brittle transformation in steels depends on interplay of the fracture stress and the flow stress. In steels the flow stress depends on temperature and strain rate because the motion of screw dislocations is function of temperature and strain rate. In this work the fracture stress has been assumed essentially independent of temperature and strain rate. At high temperatures and low strain rates thermal energy is sufficient to give plastic flow at stresses below the fracture stress, but this is not so at low temperatures and strain rates; thus there is ductile to brittle transformation temperature as shown in Figure 1.

The stress (Peierls stress) to move a long dislocation segment from a deep crystallographic energy valley would be very large. J. Weertman proposed many years ago that a high Peierls energy dislocation would likely move by first forming a double kink [1]. In the BCC metals the kink edges would be in the edge orientation and thus very mobile. Later he suggested that a misfit center would interact with a dislocation to help pull it from its Peierls energy valley [2]. This is depicted in Figure 2.

Such a misfit center will both give increase in yield stress at elevated temperatures where thermal energy is sufficient to nucleate double kinks along the dislocation line but decrease the yield stress at low temperatures where thermal energy is small. The misfit center helps the applied stress displace the dislocation escape from the deep energy valley. This behavior is depicted in Figure 3.

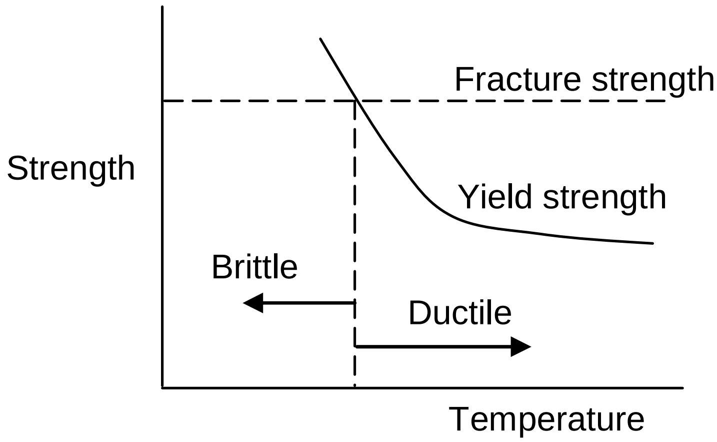


Figure 1 The yield strength at constant strain rate is shown to increase rapidly on cooling intersecting the fracture strength giving a ductile to brittle transformation

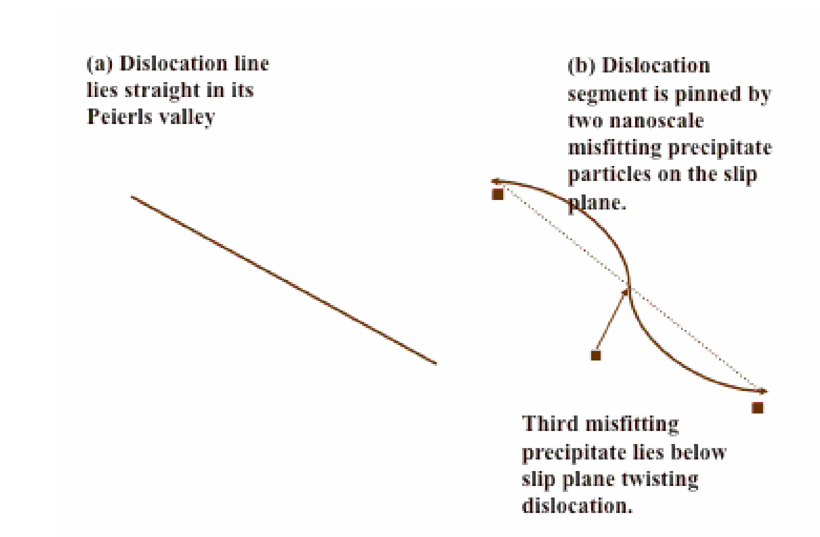


Figure 2 A misfit center lying above or below a dislocation line segment twists it partially out of its Peierls valley reducing the flow stress

The first precipitates to form in the binary Fe-Cu alloys are BCC in structure instead of thermodynamically stable FCC Cu [3]. Further these precipitates are very small (few nanometers) and contain substantial amounts, approximately 33% of Fe [3]. Renewed interest in Cu alloy precipitation strengthened steels occurred because of the need to reduce C content in martensitic steels to achieve improved weldability in relatively high yield strength steels. This is the basis for HSLA 100 steel with 700 MPa yield strength that is used for naval applications [4]. It was found previously [5,6], that tempering of the martensite in HSLA 100 overages the Cu alloy precipitates so they under contribute to the yield strength. If the Mo and Cr are eliminated, added to HSLA 100 to attain a martensitic structure on quenching, the full strengthening effect of

Cu alloy precipitates can be achieved. Investigations of this concept lead to the development of ASTM A710 Grade B steel at Northwestern University. The BCC Cu alloy precipitates are coherent and coplanar with the ferrite matrix and their activation energy for nucleation is small. They form on air cooling from hot rolling. The resulting steel A710 B, has a yield stress of 480-550 MPa in as rolled and air-cooled condition. The strength of the steel increases on aging in 500 to 550°C temperature range [7 - 10].

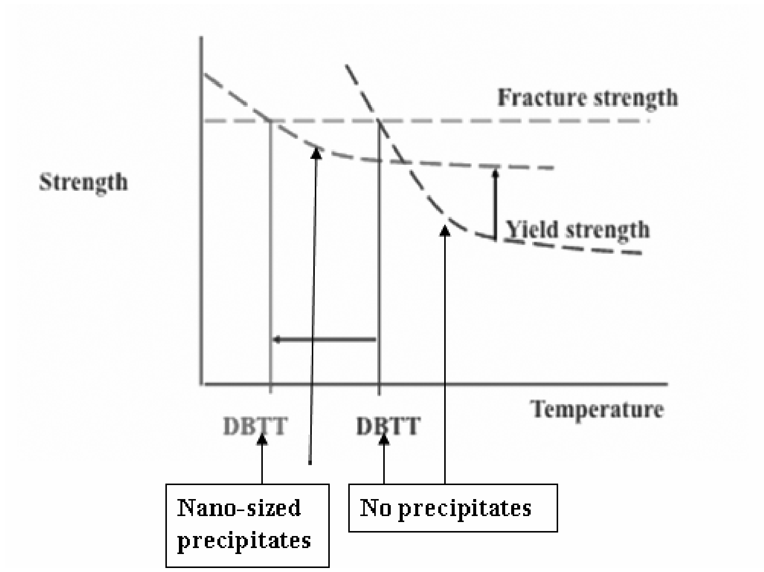


Figure 3 A misfit center strengthens the steel at elevated temperatures but reduces flow stress at low temperatures thereby lowering the ductile to brittle transformation temperature

One of the 45-kg heats of steel made by the former Inland Steel Research Laboratory during development of A710 Grade B steel contained 0.10 wt % Ti. The steel had the remarkable high Charpy impact energy at dry ice and acetone temperature, -95°C. The specimens bent but did not break stopping the Charpy hammer [10]. Concept expressed in Figure 3 explains this result. Ti by reacting with C and N to form T(C, N) raised the fracture strength. The Cu alloy precipitates that are only a few nm in diameter are misfit centers that increase the yield strength at room temperature but decrease the yield stress at low temperatures, thus the lower ductile to brittle transformation temperature.

This remarkable result led us to the present study, the effect of Ti variation on the properties of low carbon nano-scale precipitation strengthened steel.

Experimental Procedure

The steel for this research was made at United States Steel Corporation's Research & Technology Center. A 135-kg vacuum induction melt was split and cast into three 45-kg ingots differing only in Ti content as shown in Table 1. The ingots dimensions were 3-inch-thick by 8-inch-width by 14-inch-length. The Ti content varied from 0.03 wt. pct., the upper limit in the A710 B specification, to 0.10 wt. pct, the amount in the Ti alloyed steel previously investigated.

Each ingot was stripped from the mold upon cooling to room temperature, reheated to 1093°C, hot-rolled to 12.2-mm-thick plate with a finish rolling temperature of 871°C, and then air-cooled to room temperature.

Standard tensile and Charpy specimens were machined in rolling direction. Tensile testing was performed on MTS screw driven machine and Charpy specimens were tested in machine with a 358 J limit.

Specimens for optical microscopy were etched with 5% nitol solution.

Table 1 Compositions of A 710 B steel (wt.%) with varying Ti content made at United States Steel Corporation's Research & Technology Center

Steel	C	Si	Mn	Cu	Ni	Nb	Ti	P	S
A710 B w/0.03% Ti	0.05	0.39	0.50	1.30	0.90	0.06	0.03	0.01	0.005
A710 B w/0.07% Ti	0.06	0.39	0.50	1.29	0.90	0.06	0.07	0.01	0.005
A710 B w/0.10% Ti	0.06	0.39	0.50	1.30	0.90	0.06	0.10	0.01	0.005

Results and Discussion

The effect of increasing Ti from 0.03 to 0.10 % on the microstructure is shown in Figure 4. The Ti reacts with C to form TiC thereby significantly reducing the amount of cementite and pearlite as in interstitial free steels. The TiC particles are too small to be seen at the magnification of Figure 4. The increase in Ti had little effect on the ferrite grain size.

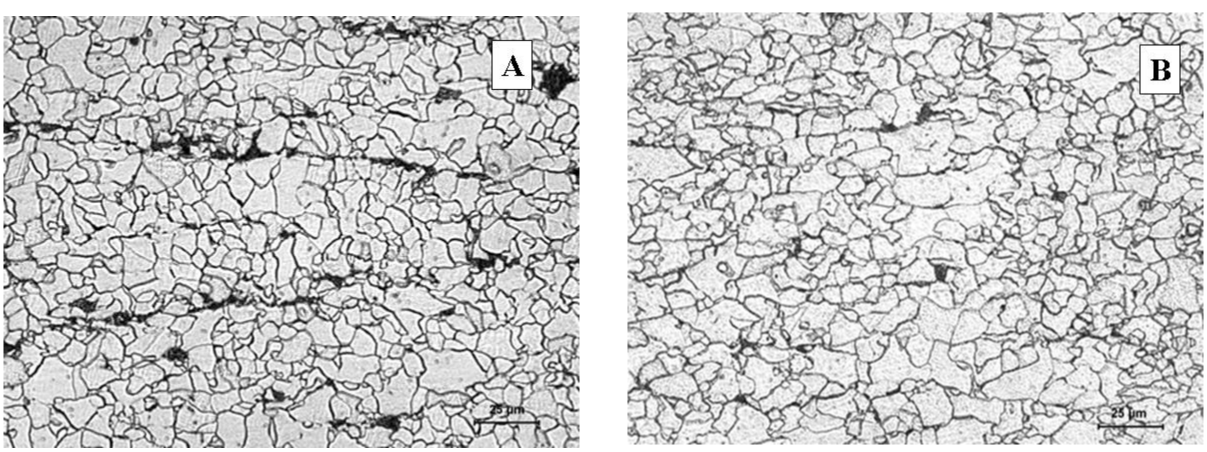
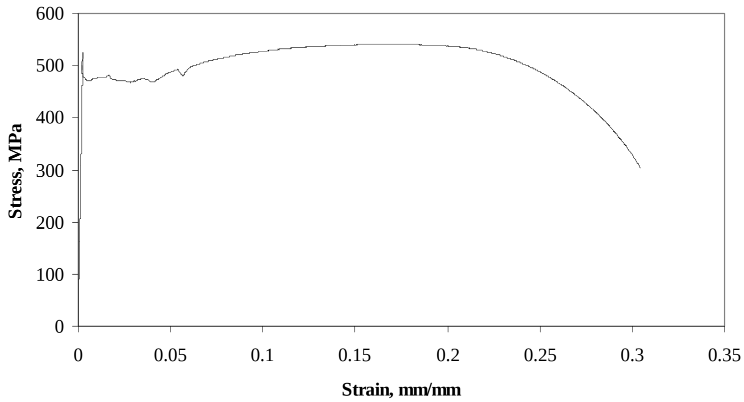
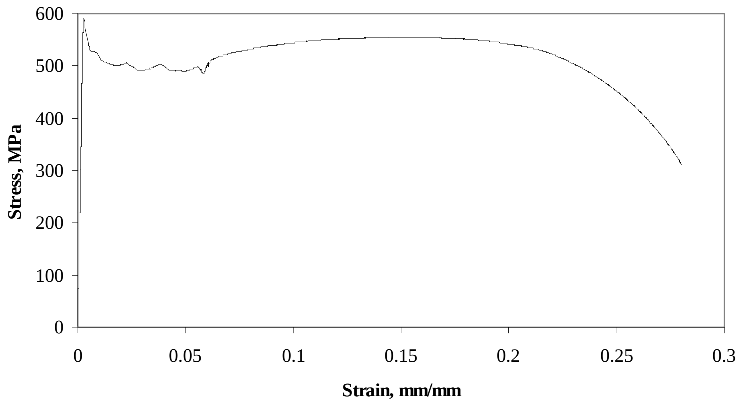


Figure 4 Optical micrographs of (A) A710 B with 0.03 wt pct Ti and (B) Ti-modified A710 B with 0.10 wt pct Ti

The results of room temperature tensile tests are shown in Figure 5 and summarized in Table 2. Increasing the Ti content from 0.03 wt % to 0.10 wt % gives little increase in yield stress but there is a significant increase in ultimate tensile stress. The small increase in work hardening is suggested to be due to Orowan looping around the small Ti precipitates. The elongations to failure in all three steels were almost the same, 28 to 30% in 25.4-mm- gage length specimens.



(A)



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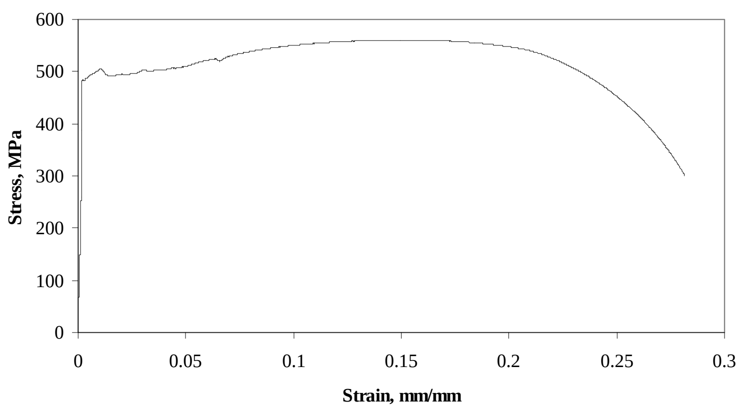

(C)

Figure 5 Stress-strain curves for A709 Grade B with (A) 0.03% Ti, (B) 0.07%Ti and (c) 0.10%Ti

Table 2 Yield stress, ultimate tensile strength, and elongation to failure

Steel	0.2% Offset Yield, MPa	UTS, MPa	Elongation to Failure, %
A710 B w/0.03% Ti	480	545	30
A710 B w/0.07% Ti	507	590	28
A710 B w/0.10% Ti	493	583	28

The Charpy impact energies were measured over the temperature range 25 to -73° C. The results are given in Table 3 and the average Charpy values are plotted versus temperature in Figure 6. The arrows indicate that the specimens did not break in the Charpy apparatus. The specimens bent but were only partially fractured with a ductile fracture surface. Thus the true fracture energy for these specimens is higher than 358 J, the limit of the Charpy machine. Figure 7 is a photograph of such a specimen showing its fracture surface. The unusually high shelf fracture energy at the higher test temperatures must result from the fracture stress being significantly higher than the yield stress. As shown in Table 3 and Figure 6, the >358 J level shifted to a lower temperature as the Ti content increased. The high fracture energies seen in the 0.10 Ti modified A710 B steel is not equaled by any other ferritic relatively low alloy steel as far as the authors know.

Table 3 Charpy fracture energy (J) of A710 Grade B and the two Ti modified A710 B steels

T, ºC	A710 B w/0.03% Ti	A710 B w/0.07% Ti	A710 B w/0.10% Ti
24	>358	>358	>358
-23	271	>358	>358
-40	212	309	>358
-51	250, 279	290, 306	336
-62	282, 201	227, 293	252, 255
-73	135, 155	192, 252	113, 233

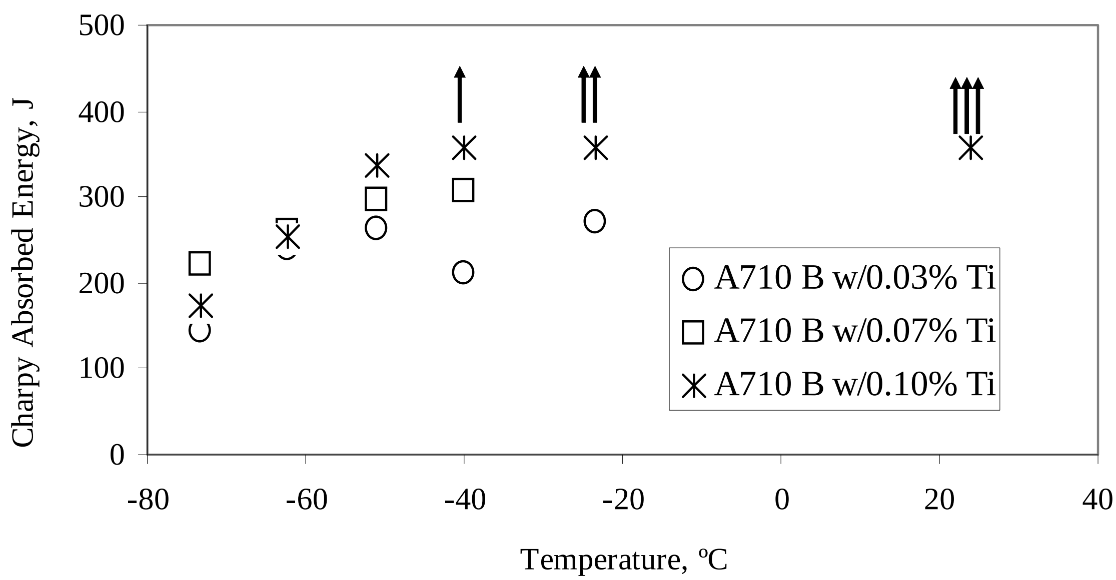

Figure 6. Charpy absorbed impact energy versus temperature for the three ASTM A710 steels modified by Ti

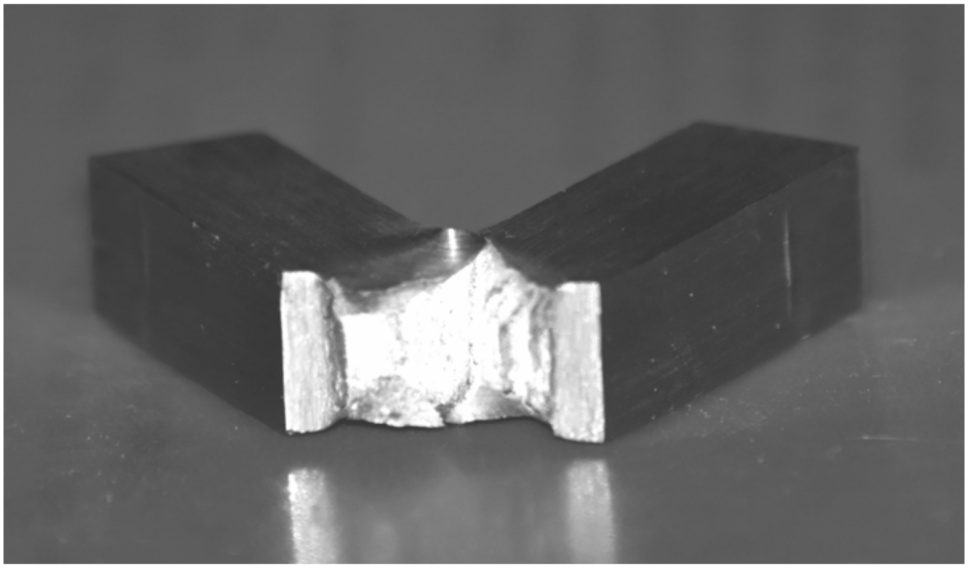

Figure 7. Charpy specimen of A710 Grade B with 0.10 % Ti tested at -40°C. The specimen stopped Charpy hammer without fully fracturing. Fracture surface is completely ductile

Final Discussion and Conclusions

The Ti modified Cu nanoscale precipitation hardened steels have remarkably high Charpy absorbed impact energies especially at cryogenic temperatures. This was attributed to Weertman's theory [2]. The interaction of slightly misfitting coherent coplanar low-nano-size Cu alloy precipitates with screw dislocations locally lowers the Peierls stress.

The addition of Ti to steel significantly reduced the cementite and pearlite in steel replacing them by small TiC particles raising the fracture stress.

Many applications for highly impact resistant steel particularly at low temperatures come to mind. Tank cars that carry refrigerated liquids and bridges in very cold climates are examples. The very high shelf fracture energy even at room temperature makes it a candidate for safety critical automobile components.

Acknowledgments

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