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Evaluation and Application of Super-Tough Steel for Use in Tank Cars Transporting Cryogenic Liquids

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Introduction

The goal of this project was to further develop and market advanced 70-ksi-yield strength super-tough steel (designated as NUCu70ST in the text) for use in tank cars transporting cryogenic liquids, like chlorine, for example. Fracture of these tanks resulted in a number of industrial accidents. One in 2005 in Graniteville, South Carolina led to nine deaths and at least 250 injuries (Figure 1).

This is a joint project with Union Tank Car Company (UTLX). Developed and investigated at Northwestern University by prior funding from ITI and CCITT, the super-tough cryogenic steel was included into the "Next-Generation Rail Tank Car Project", an innovative joint initiative of three companies (Dow, Union Pacific and UTLX), Association of American Railroads (AAR), and US and Canada Departments of Transportation that focuses on the design and implementation of a next-generation rail tank car with enhanced ability to safely transport hazardous chemicals. In preliminary mechanical and fracture studies performed at Northwestern University, UTLX and its contractors, NUCu70ST was shown to significantly outperform all other steels tested, including steels currently used in tank-cars as well as other high-performance steels on the market.

Figure 1. Tank car accident in Graniteville, South Carolina (2005)

Investigation of two new experimental steels for tank car application

During FYs 2010 and 2011, we continued our collaboration with UTLX in their mechanical, fracture testing, welding programs and interpretation of the results. UTLX purchased two more 300-lb experimental heats of NUCU70ST for further tests from Sophisticated Alloys, Inc. The steel was produced to our specifications, hot-rolled into ½-inch-thick plates and air-cooled. The compositions of steels (UTLX3 and UTLX4) are listed in Table 1.

Table 1. Chemical Composition, wt.%

Steel	C	Mn	Si	Cu	Ni	Nb	Ti	S	P
UTLX3	0.05	0.88	0.51	1.31	0.70	0.07	0.11	<0.005	<0.005
UTLX4	0.06	0.89	0.50	1.31	0.70	0.08	0.11	<0.005	<0.005

Tank car industry uses their current steel (TC 128) in normalized (heat-treated) condition; in general normalization increases fracture toughness of steels at low temperatures. Our steel does not need to be normalized because it possesses remarkable high low-temperature fracture toughness in as-rolled condition. However, to conform to UTLX current standards we normalized the steel and tested the strength in as-received and normalized (heated at 900°C for one hour and air cooled) conditions and fracture toughness in as-received condition.

The ultimate tensile strength (UTS) of the tank car steels should meet 80 ksi target. The UTS strength of both steels in as-received and normalized conditions exceeded this requirement (Table 2). The ductility of the steels was very high; elongation to failure exceeded 30%. The absorbed fracture energy of the steels in as-received condition was excellent; steel specimens did not fracture during the Charpy absorbed fracture energy tests down to -30°F (Figure 2). The absorbed fracture energy was high down to -80°F. The current standard for tank cars steels requires only 20 ft-lbs at -30°F.

Table 2. Tensile properties of UTLX3 and UTLX4 steels

Steel	UTLX3		UTLX4	
	As-Received	Normalized	As-Received	Normalized
Yield Strength (0.2% off-set), Ksi	73	67	81	71
Ultimate Tensile Strength, Ksi	88	82	89	81
Elongation to Failure, %	35	36	38	32

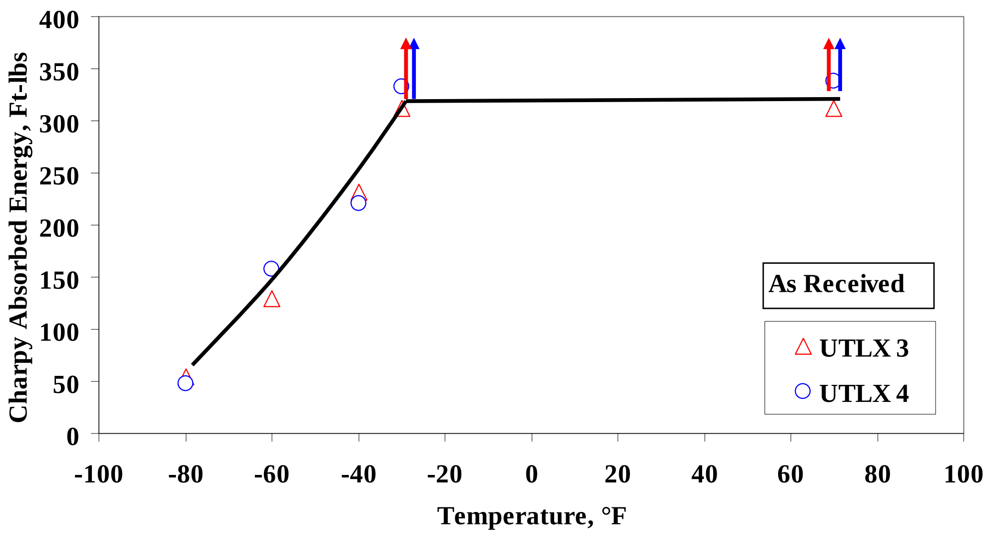

Figure 2. Charpy absorbed fracture energy for as received UTLX3 and UTLX4 steels

Since welding is very important during tank-car production, the welding of our steels was studied under laboratory (at Edison Welding Institute) and shop (at UTLX plant) conditions with welding consumables currently used for tank car construction. Two welding procedures were used: laser welding and submerged arc welding. The laser welding was done autogenously, i.e., no filler or flux were used. Different levels of heat input (as a function of laser power and laser travel speed) were used. The submerged arc welding employed the consumables (wire and flux) commonly used to weld the steel in tank car industry.

Table 3 shows the Charpy absorbed fracture energy of autogenously laser welded plate and weld in as-welded and stress-relieved (1 hr at 1200ºF) conditions. As received, the steel plate did not fracture in Charpy machine at -30ºF (Figure 2). After welding and stress relief the plate away from the weld had very high Charpy energy when tested at -30ºF (note that smaller, subsized specimens were used to test the plate that was welded). The weld prior to stress relief had very high fracture energy. However, the weld after the stress relief had very poor fracture energy.

Table 3. Charpy absorbed fracture energy (ft-lbs) at -30ºF of plate and welded UTLX3 steel (subsized Charpy specimens used)

Plate	Weld	
Stress-Relieved at 1200ºF	As-Welded	Stress-Relieved at 1200ºF
205	238	4

To investigate the reason for reduced fracture toughness of the steel after stress relief the welds before and after stress relief were examined at Northwestern University and ArcelorMittal Steel Company's Global R&D Center using optical and high resolution scanning electron microscopy, microhardness measurements and X-Ray diffraction. While there was a small (approximately 10%) hardness increase in welds after stress relief, there was no difference in the microstructure (up to 15,000X magnification) (Figure 3) and in crystal structure of as-produced and stress-relieved welds. Thus, while we suspect that copper precipitates in weld coarsen during stress relief and therefore affect the fracture toughness of the weld, these precipitates are very small to be observed by the high-resolution scanning electron microscope. Higher resolution transmission electron microscopy most likely is needed to detect the difference in size, morphology and location of copper precipitates in the welds before and after stress relief to explain the welds embrittlement. ArcelorMittal Global R&D on UTLX request is planning to perform such a study. UTLX is planning stress relief studies at lower than 1200ºF temperature to find out if the embrittlement is also observed at lower stress-relief temperatures.

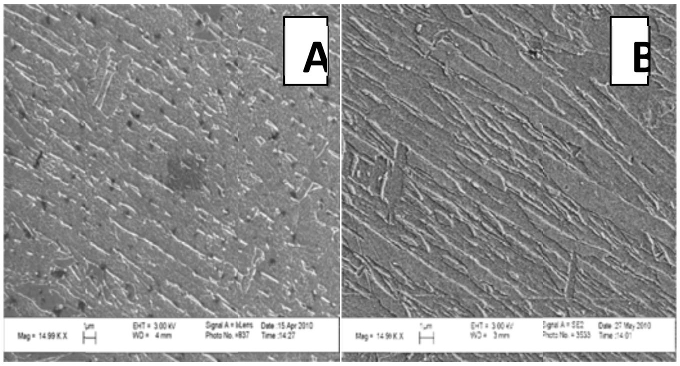

Figure 3. High-resolution SEM of a weld in the UTLX3 steel. A - as-welded; B – stress-relieved at 1200°F

In general, the stress relief is not needed for low-carbon steels such as our “super-tough” steel; however, the tank-car code requires the stress relief of welded steels. UTLX is working with American Association of Railroads Standard Committee on changes in the tank-car code for some of the tank cars to allow the use of welding without stress relief for construction of tank cars. Elimination of this procedure would result in significant energy savings in tank car industry. Then UTLX will build one or more experimental tank cars with our NUCu70ST steels.

Summary

- Two new experimental heats of our supertough steel were produced and tested by Northwestern University and UTLX. The mechanical properties met the tank car specifications while fracture toughness of the steel at low temperature significantly exceeded these specifications.
- The steel in as-welded condition has excellent fracture toughness. The stress relief heat treatment results in reduction in fracture toughness. The source of this reduction is under investigation.
- UTLX is working to change AAR Tank Car Code to eliminate stress relief after welding of the tank cars built with supertough steel since stress relief is not needed for low carbon steels. Elimination of this procedure would result in significant energy savings in tank car industry.