# Effects of Pre-Strain and Heat Treatment on Properties of Selected Alloys

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The National High Magnetic Field Laboratory (NHMFL) in USA carries out extensive studies on the conduit alloys used for cable-in-conduit superconducting (CICC) magnets. Based on the demanding requirements of the conduit alloys for cable-in-conduit-conductors in high field superconducting magnets, a modified 316LN stainless steel (denoted as 316LLN, where LL indicates that the carbon content is below that in standard 316LN) and Haynes 242 were studied as conduit alloys for Cu-Nb-Sn wires. If the alloys are to be used it is also necessary to evaluate the microstructure and mechanical property evolution as a result of the processing because of the phase transformations that occur during the heat treatment. The maximum bending strain caused by coil winding is about 3%. The deformed conduit will then be heat treated with the $Nb_3Sn$ type conductors. A typical heat treatment schedule for $Nb_3Sn$ is in the temperature range of 650 °C -700°C for 50-100 hours. The deformation strain may or may not be removed by recovery during the heat treatment. If residual strain cannot be removed, the design of the CICC magnet has to take the residual strain into account. This work provides an insight to identify the pre-stress contribution to the performance of the conduit materials at -269 °C (4 K).

A special frame was designed to mount the tensile test samples. The frame and the samples were heat treated to simulate the pre-stress + heat treatment effects on the microstructure and mechanical properties of the conduit alloys. The pre-strain was measured by a clip-on extensometer and was nominally 3%. Tensile tests are performed with mechanical testing machines in the NHMFL. After the heat treatment under a pre-strain of about 3%, the cryogenic mechanical properties changed. Examples are shown in figure 1.

The base metal (denoted as B) of 316LLN shows a decreased yield strength and increased ductility after heat treatments under the strain of 3%. The tensile strength of the samples marginally increases when samples are exposed to S+H conditions. The high strength in the B+H samples can be partially attributed to the cold work introduced during the shaping of the conduits. The cold work hardens the 316LLN by introducing dislocations. Heat treatment between 650°C and 700°C introduces no grain size and twin density changes according to our recent studies on 316LLN [1]. This study indicates that the deformed 316LLN is not fully recovered by a heat treatment at 650 °C for 48 hours. Therefore, the major factor that contributes to the yield strength decrease is the dislocation density changes affected by the heat treatment in samples 316LLN B+H. The reduction of the yield strength and increase of the ductility in the B+S+H samples can therefore be attributed to the accelerated recovery or even recrystallizations when samples are exposed to both high temperatures and stresses. More research is required to clarify this issue in 316LLN.

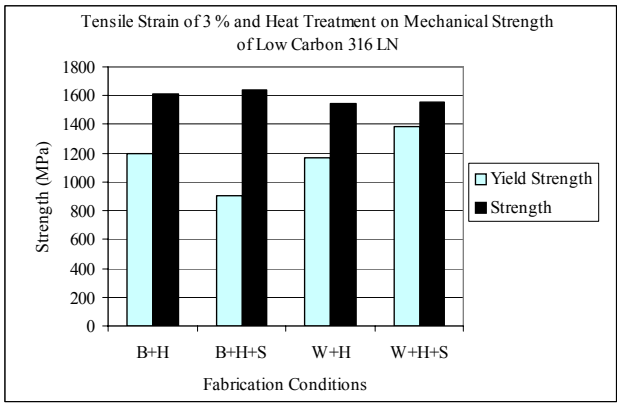


**FIGURE 1.** Comparison of the 4 K yield and tensile strength of the 316LLN conduit materials after the materials were heat treated with 3% strain. H denotes a heat treatment. The S denotes a heat treatment under a pre-strain of about 3%. B and W indicate base metal and welded metal, respectively.

The welded (denoted as W) 316LLN samples show increases of yield strength and reduction of the ductility after heat treatments under the strain of 3%. The yield strength of the sample W+H+S is the highest among all the samples is even higher than that of base metals. The tensile strength marginally increases. This indicates that hardening occurred in the process of heat treatment with the presence of the pre-stresses. The heat treatment plus stress reduces the ductility significantly. The mechanical property changes appear to be related to the formation of the precipitates.

Samples from Haynes 242 show different behaviors after the processing [2]. Thus, the pre-strain plus heat treatment affects mechanical properties by altering the microstructures. Further research will explore the more fundamental reasons for such phenomena.

**Reference:**

[1] Downey, S., *et al*., *Materials Science and Engineering A,* **480 (1-2)**, 96-100 (2008).
[2] Han, K., *et al., Advances in Cryogenic Engineering (Materials)* **54**, 84 (2008).