TerraPower HT9 Mechanical and Thermal Creep Properties

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TerraPower has revitalized the manufacturing of HT9 and optimized its heat treatment for use as fuel claddings in the Traveling Wave Reactor. TerraPower initiated a comprehensive test program to compare the mechanical and thermal creep properties of the optimized TerraPower HT9 to historical data for HT9. The uniaxial tensile tests show TerraPower HT9 has improved yield strength compared to historical HT9 across all temperatures. Charpy impact toughness tests on TerraPower HT9 show lower upper shelf energy compared to historical HT9, but the ductile to brittle transition temperature (DBTT) between the steels remain similar. Three point bend tests between room temperature and 400˚C show comparable fracture toughness to those of historical HT9. Thermal creep test data indciates TerraPower HT9 has improved creep strength compared to historical HT9.

1. Introduction

HT9 is a 12Cr-1Mo-W-V ferritic-martensitic (FM) steel and is considered to be a first generation FM steel which has been supplanted by other more advanced steel alloys for use in the fossil industry. Although HT9 is not currently produced commercially, it is of great interest to TerraPower because of the relatively extensive irradiation performance database from EBR-II and FFTF showing excellent swelling and creep resistance relative to other materials tested. TerraPower has revived the commercial production of this steel and is actively conducting tests to compare the TerraPower HT9 to historical HT9.

Multiple heats of HT9 have been tested by different researchers in the past for their yield strength, fracture toughness, impact toughness, and thermal creep strength. Uniaxial tensile tests and Charpy impact tests conducted by Klueh [1] [2], Sandvik [3], Baek [4] and creep tests conducted by Chin [5], Sandvik [6], and Toloczko [7] made up majority of the historical HT9 database. Additional microstructural analyses conducted by TerraPower on the FFTF ACO3 duct have shown that the historical HT9 material can be further improved. Based on this information, TerraPower has developed an optimized formulation of HT9 that will be commercially produced and dedicated as structural material for the Traveling Wave Reactor (TWR). In the process of this development work, more than 12 tons of TerraPower HT9 have already been produced, some of which was used to test the mechanical and creep properties of the new HT9 for comparison to historical HT9.

2. Experimental

Mechanical properties testing and creep testing were conducted in accordance with the appropriate ASTM standards. Whenever possible, subsized specimens were used to maintain consistency with samples currently being irradiated, such that unirradiated and irradiated properties can be compared directly in the future.

The uniaxial tensile tests were conducted on standard tensile bars in air at a constant strain rate of 4×10^{-4} s^{-1}. The tensile tests were performed at temperatures between 25°C and 700°C. The total elongations were determined after completion of tensile testing by measuring the extension between locations marking the gage length of the sample. The initial gage length was defined as four times the sample diameter for the TerraPower tensile tests. Temperatures during testing were controlled to better than ± 3°C.

The Charpy impact toughness tests were performed on TerraPower HT9 plate material. The plate was machined into 10mm by 5mm subsized Charpy specimens with 2 mm v-notch. The tests were conducted between -100°C up to 200°C, and the temperatures were controlled within ± 2°C of the specified temperature for each test. The fracture toughness tests were conducted using miniature specimens that are 14 mm in length, 5 mm in width, and 3 mm in thickness with a 0.254 mm wide notch machined as crack initiation site. The experimental technique followed the pre-cracking and fracture toughness testing procedures developed specifically for miniature irradiated specimens. The detailed experimental setup and procedure are discussed in previous studies by T.S. Byun [8].

The creep tests were performed using subsized tensile specimens with 20 mm gage length and 4 mm diameter. The tests were conducted in an air environment at temperatures between 450°C – 650°C and stresses between 40MPa – 463MPa. The temperatures during testing were controlled to better than ±2°C throughout the test as measured by three type N thermocouples attached to the gage length of the sample.

3. Results

The results from uniaxial tensile tests on four heats of TerraPower HT9 show a significant increase in yield strength at all temperatures compared to historical HT9 while maintaining a similar temperature dependence. TerraPower HT9 shows an average of around 800 MPa yield strength at room temperature, and drops down to about 300 MPa at 650°C. This is higher than the historical HT9 room temperature yield strength of 650 MPa and 200 MPa at 650°C. Figure 1 shows the data comparison between historic and TerraPower HT9 yield strengths. The increase in yield strength between 300°C and 600°C is a significant improvement of HT9 materials property for the operating temperature of the TWR.

Similar to the yield strength, the ultimate tensile strength of TerraPower HT9 also shows an increase compared to the historical HT9. Figure 2 shows the ultimate tensile strength of TerraPower HT9 at room temperature is around 950 MPa and drops to about 400 MPa at 650°C. The relative increase in ultimate tensile strength of TerraPower HT9 compared to historical HT9 is less than the relative increase in yield strength, indicating that TerraPower HT9 undergoes proportionately less strain hardening before onset of plastic instability than historical HT9. Less potential for strain hardening usually indicates a reduction in ductility for the material, therefore the total elongation between the TerraPower HT9 and historical HT9 are also compared. Figure 3 shows the TerraPower total elongation compared to historic HT9 data. TerraPower HT9 data are demonstrated to have higher total elongation than historic HT9 at all temperatures. Although some of the observed difference could be attributed to systematic difference in elongation measurement procedures between the two data sets, it wouldn't account for the 50% increase in elongation observed at 600°C. Therefore, TerraPower HT9 have at least comparable, if not higher, ductility compared to historical HT9.

Fracture toughness and impact toughness testing were conducted to ensure the TerraPower HT9 has sufficient toughness to be used in design. Figure 4 plots the impact toughness curve for TerraPower HT9 and historical HT9 normalized by its cross sectional area. It is clear that TerraPower HT9 has slightly lower upper shelf energy compared to historical HT9. The ductile to brittle transition temperature (DBTT) remains unchanged at around 25°C for both variants of HT9. The lower shelf energy also appears unaffected, although testing at such lower temperatures carry large experimental uncertainties, making it difficult to differentiate small changes in the impact toughness.

The fracture toughness of TerraPower HT9 also showed slight reduction compared to historical HT9 at higher temperatures, as shown in Figure 5. The K_{JQ} values were determined by three point bend sample testing [8] technique developed for subsized specimens. The samples were tested in hot cells using manipulators in anticipation of similar tests on irradiated specimens in the future. Comparison with previous three point bend tests [4] shows HT9 fracture toughness values between historical and TerraPower HT9 are consistent at room temperature. TerraPower HT9 exhibits ductile fracture at all tested temperatures, indicating that HT9 shows no brittle fracture behavior in the unirradiated condition.

Thirty five thermal creep tests at various conditions are currently being tested on TerraPower HT9. Thirteen tests have reached completion, and the creep rates for each specimen in the secondary creep regime were calculated from their strain over time curves. Figure 6 plots the secondary creep rates of TerraPower HT9 in comparison to historical HT9. TerraPower HT9 consistently demonstrates lower secondary thermal creep rates at 600°C for all stress levels. The single data point available for TerraPower HT9 at 550°C also suggests a significantly lower thermal creep rate in comparison to historical HT9. Figure 7 plots the creep rupture of TerraPower HT9 compared to the combined creep rupture data from both uniaxial creep tests as well as biaxial creep tests. The creep rupture data show that TerraPower HT9 at 650°C fall well within historical values. TerraPower creep rupture at 600°C and 550°C have much higher creep rupture stress for a given time to failure compared to historical HT9. These observations confirm the results from secondary creep rate analysis that TerraPower HT9 with optimized microstructure has increased creep strength in comparison to historical HT9.

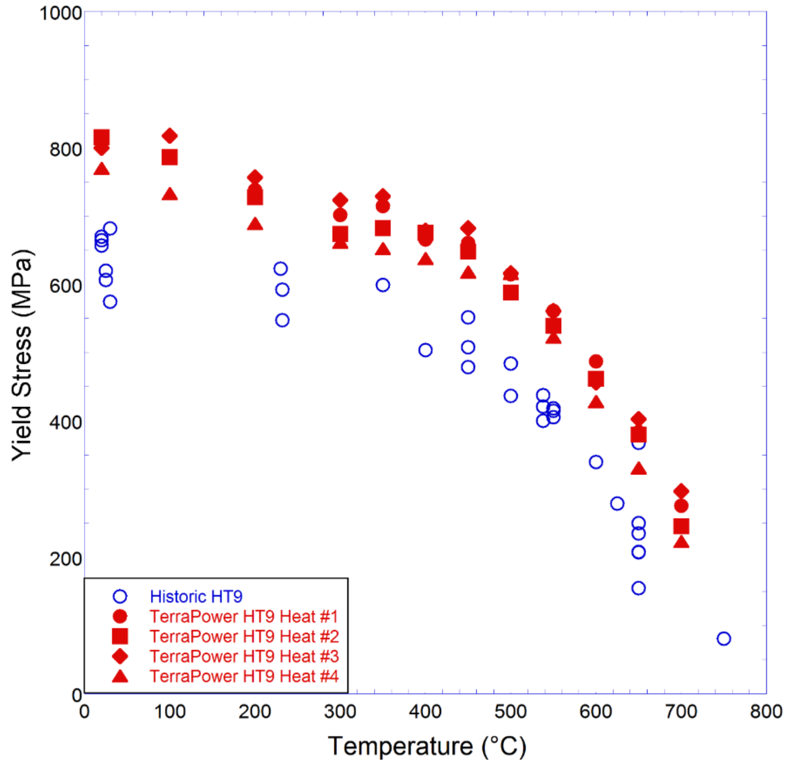

Figure 1: Yield stress of TerraPower HT9 compared to historical HT9

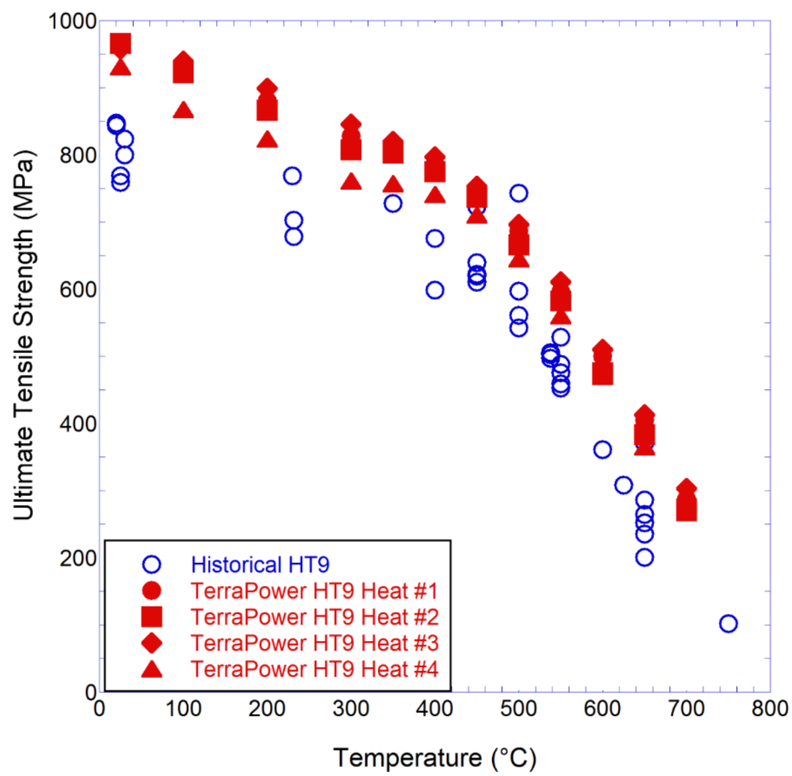

Figure 2: Ultimate tensile stress of TerraPower HT9 compared to historical HT9

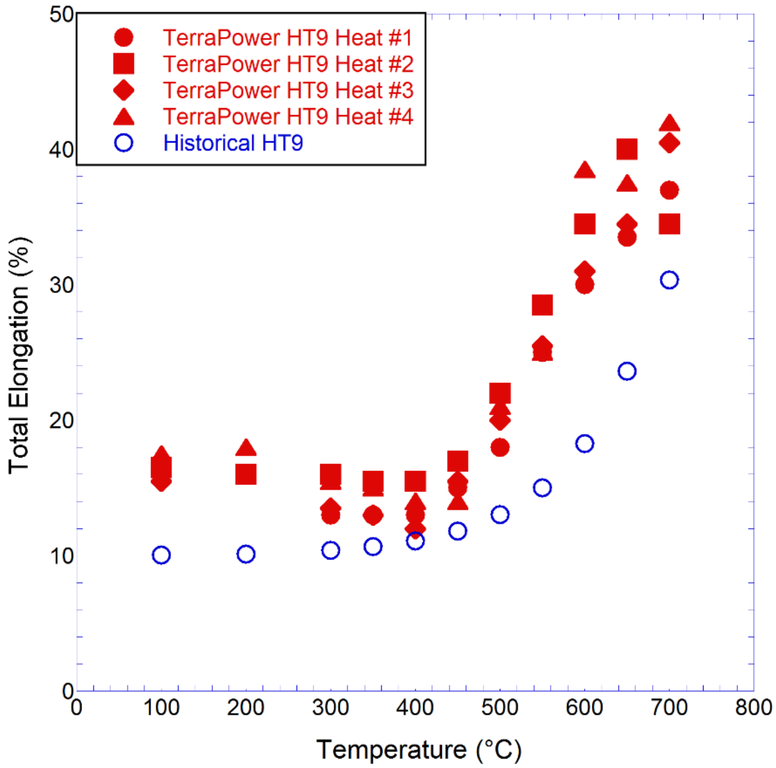

Figure 3: Total elongation at fracture of TerraPower HT9 compared to minimum total elongation recommended for historical HT9.

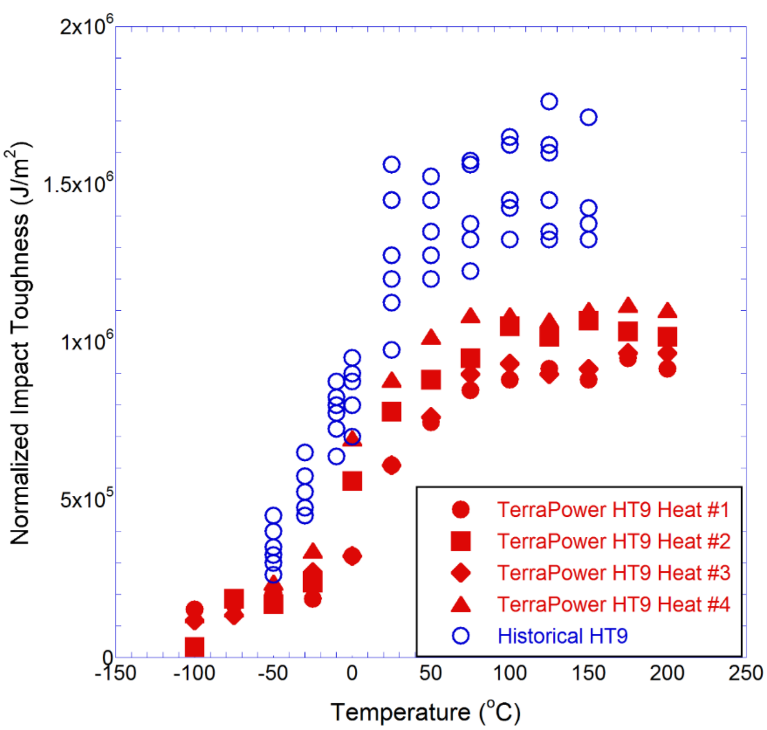

Figure 4: Normalized Charpy impact toughness of TerraPower HT9 compared to historical HT9

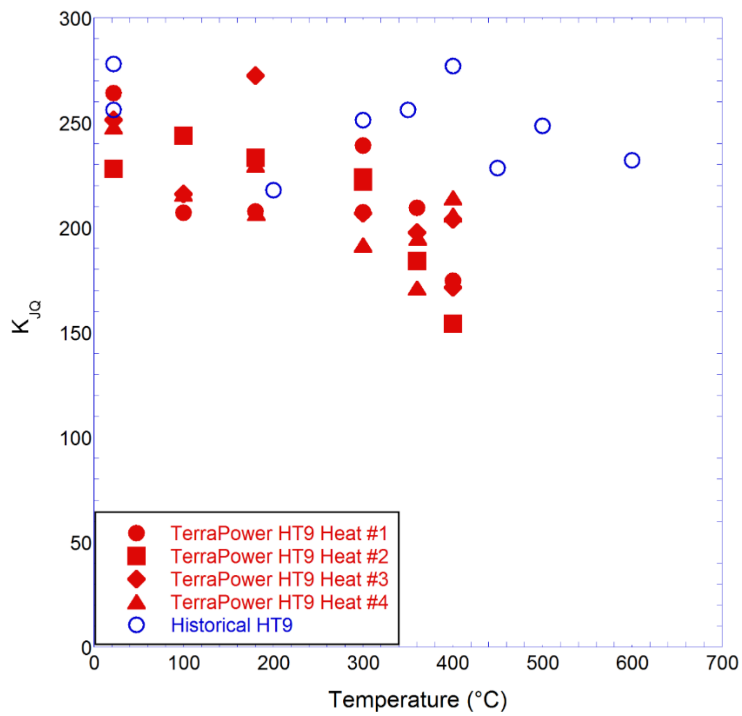

Figure 5: Fracture toughness of TerraPower HT9 compared to historical HT9

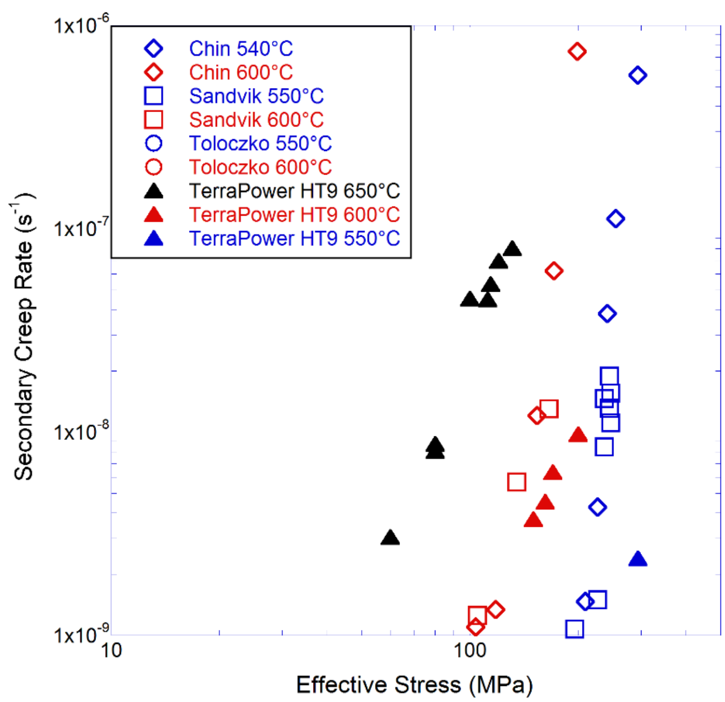

Figure 6: Secondary thermal creep rates of TerraPower HT9 compared to historical HT9

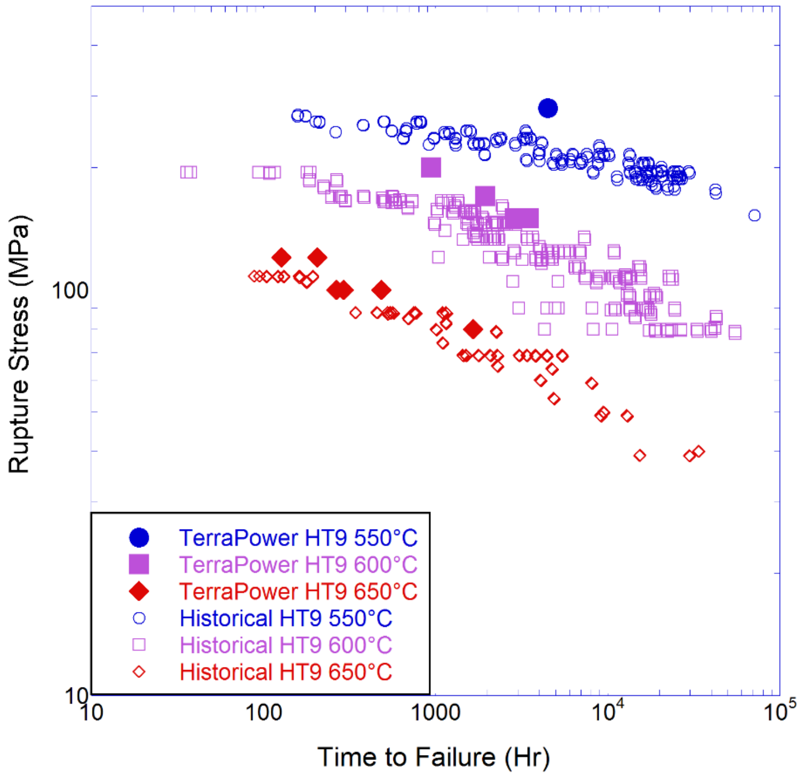

Figure 7: Creep rupture stress as a function of time to failure for TerraPower HT9 and historical HT9.

4. Conclusion

TerraPower has optimized and re-established the commercial fabrication of HT9. By demonstrating that the newly fabricated TerraPower HT9 provides comparable or improved properties compared to historical HT9, the combined mechanical properties database for HT9 can be used to commercially dedicate the material for fuel cladding and duct material in the TWR. Uniaxial tension, Charpy impact, fracture toughness, and thermal creep tests were conducted to confirm the mechanical properties of HT9 to ensure expected performance of the material. Uniaxial tensile testing showed a significant increase in both yield and ultimate tensile strength for the TerraPower HT9 compared to historical HT9 at temperatures between 25°C and 700°C. Charpy impact and fracture toughness testing showed no change in the DBTT, but a slight reduction in toughness in the unirradiated condition for TerraPower HT9 at higher temperatures that is not expected to affect its intended use. Thermal creep testing showed significantly improved creep strength for TerraPower HT9. The results from these tests demonstrate that the newly fabricated TerraPower HT9 has comparable performance to historical HT9 in the unirradiated condition.

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