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Mechanical and Fatigue Properties of Stress Relieved Type 302 Stainless Steel Wire

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Type 302 stainless steel wire is manufactured using a cold extrusion process. The cold working increases the ultimate strength of the wire from approximately 690 MPa to 2070 MPa. However, the cold working process creates residual stresses and surface microcracks in the wire. The residual stresses and microcracks reduce the fatigue life of the wire considerably. Elimination or minimization of residual stresses and microcracks is necessary if longer fatigue life is required. Residual stresses or microcracks in a wire can be minimized by a heat treatment process, which could improve both its mechanical properties and fatigue properties.

Experimental evidence shows that the stress relieving process yields maximum mechanical properties between 316 and 482 °C (600 and 900 °F). The fatigue properties of the wire are optimum at a stress relieving temperature of 649 °C (1200 °F). However, the mechanical properties such as yield strength, modulus of resilience, modulus of toughness, and ultimate strength, etc., are reduced by as much as 30% if compared to the similar properties of 316 °C (600 °F) stress relieved wire.

1. Introduction

THE mechanical design data available for 0.84-mm-diameter type 302 stainless steel wire were limited, and fatigue design data for the wire did not even exist. Also, the proper stress relieving temperature required to eliminate or minimize residual stresses was not known. To further complicate matters, the cold working process used to increase the yield strength of the wire created surface cracks in addition to residual stresses, and these cracks suppressed the plastic deformation capacity of the wire. The cold working process also had a tendency to make the wire very brittle. Because brittle materials do not have the ability to suppress crack propagation, they are very weak under fatigue loads. Under such conditions, one must find ways to improve the fatigue life of a cold worked wire, without appreciably losing its high strength.

One method commonly used to minimize residual stresses and possibly close microcracks is to stress relieve the wire by heat treating it for a short period. The heat treatment is carried out by preheating the oven to the desired temperature and placing the wire to be stress relieved into the oven in straight form on a flat surface for 30 min to 1 hr. The oven contained air at atmospheric pressure, and no integrator or external treatment was given to the wire before it was placed in the oven. The time required for stress relieving depended on the mechanical properties, surface conditions, and the metallurgy of the wire. In this study, the stress relieving time was set at 30 min. After 30 min, the wire was taken out of the oven and air cooled for at least 1 hr before the tests were conducted on such wires.

A testing program was developed to study the monotonic tensile properties and tensile fatigue properties of the wire as a function of stress relieving temperature. The diameter of the type 302 stainless steel wire tested was 0.84 mm, and the surface conditions were unaltered.

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2. Test Procedure

The samples were stress relieved at a starting temperature of 38 °C (100 °F). The stress relieving temperature was increased each time by 55.6 °C (100 °F), and samples were obtained at each increment. The final stress relieving temperature was 704 °C (1300 °F). No test was conducted beyond 704 °C (1300 °F) because hydrogen embrittlement is high at such temperatures and the material has a tendency to anneal. Monotonic tests were also conducted on wire that was not stress relieved at 21 °C (70 °F). For each temperature level, at least three specimens were tested, and the average values of test results were obtained from such tests. This process was repeated for wire stress relieved at different temperatures. The same procedure was followed to test the wire under fatigue loads.

The monotonic test data were obtained using controlled crosshead speed. The crosshead speed was maintained at a rate of 0.03 mm/sec. Fatigue tests were conducted using an R ratio, *i.e.*, $\sigma_{min}/\sigma_{max}$ almost equal to zero because σ_{min} was nearly zero. The stress was varied sinusoidally, with the mean stress $\sigma_m = \sigma_{max/2}$ and the amplitude stress also equal to $\sigma_{max/2}$. The frequency of loading was 5 Hz. Maximum stress was maintained at about 80% of ultimate strength at each test temperature.

Special fixtures were made to attach 250-mm long wire samples for monotonic and fatigue study. These special fixtures minimized stress concentrations along the contact of the wire with the jig. The jig setup is shown in Fig. 1.

The universal tension and fatigue testing machine was used to test the wire under tensile and cyclic loads. The test data were collected and analyzed with the aid of computers. The variables used during testing were stress relieving temperature and stress level.

The monotonic tensile test results and fatigue test results were analyzed, and Table 1 was created to present the test results. Such results are shown graphically in Fig. 2 through 9.

The plots provide visual aids for determining fatigue life values as a function of stress relieving temperature.

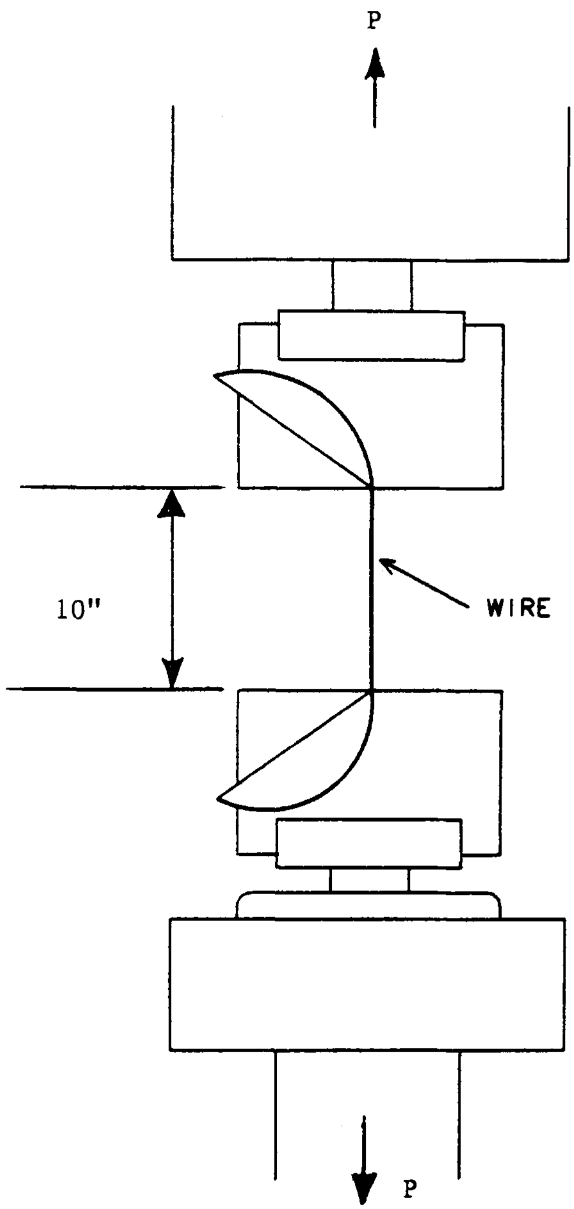

Fig. 1 Special fixture for tension testing in wire.

3. Discussion

The mechanical properties as a function of stress relieving temperature are shown in Table 1. The plots of various mechanical properties versus stress relieving temperature are shown in Fig. 2 through 9. All of the plots are normalized with reference to the 316 °C (600 °F) properties. The normalization with reference to 316 °C (600 °F) was carried out to compare the properties at various stress relieving temperatures, because this temperature was used by the sponsors as the stress relieving temperature for products made from such wire.

Figure 2 suggests that the ultimate strength (σ_{ult}) of type 302 stainless steel wire remains at a peak between a stress relieving temperature of 316 to 427 °C (600 to 800 °F). However, ultimate strength began to drop as the stress relieving temperature became equal to or greater than 482 °C (900 °F). The drop in ultimate strength compared to the 316 °C (600 °F) stress relieved wire was as much as 40% around 704 °C (1300 °F). A similar observation was observed for the ultimate strain, (ε_{ult}) except that the maximum ultimate strain was obtained at 427 °C (800 °F), as shown in Fig. 3. Figure 4 shows the relation of yield point stress versus stress relieving temperature. The peak value of yield strength ($\sigma_{y.p.}$) is at 316 °C (600 °F). However, it starts to drop as the stress relieving temperature is increased. The decrease in yield strength is as much as 55% from 316 to 704 °C (600 to 1300 °F). Figure 5 shows the relation of yield point strain versus stress relieving temperature. The peak value of yield point strain ($\varepsilon_{y.p.}$) is at 316 °C (600 °F), and the graph suggests that the yield point strain decreases continuously from 316 to 704 °C (600 to 1300 °F). The loss of yield point strain at 704 °C (1300 °F) is as much as 50% of the 316 °C (600 °F) value.

Because the modulus of resilience of the wire depends on the yield point stress and yield point strain, it can be seen from Fig. 6 that the peak value of the modulus of resilience is at 316 °C (600 °F). However, it decreases continuously as the stress relieving temperature increases. The modulus of resilience decreases to about 25% at 704 °C (1300 °F) compared to the peak value observed at 316 °C (600 °F).

The modulus of toughness as a function of stress relieving temperature is shown in Fig. 7. Here again, the peak values are obtained between 316 and 482 °C (600 and 900 °F), but they decrease continuously as the stress relieving temperature is increased. The modulus of toughness at 704 °C (1300 °F) is almost 45% of the 316 °C (600 °F) stress relieving modulus of toughness value.

The modulus of elasticity was obtained from stress-strain curves using 0.2% offset. The modulus of elasticity as a func-

Table 1 Monotonic Tensile Properties for 0.844-mm-Diameter Type 302 Stainless Steel Wire

Physical property	Tensile properties at: 21 °C (70 °F)	316 °C 600 °F	371 °C 700 °F	427 °C 800 °F	482 °C 900 °F	538 °C 1000 °F	593 °C 1100 °F	649 °C 1200 °F	704 °C 1300 °F
$\sigma_{y.p.}$, MPa	1408	1932	1746	1711	1725	1325	1435	1125	1000
σ_{ult}, MPa	1911	2235	2243	2277	2194	2001	1760	1559	1332
$\varepsilon_{y.p.}$, m/m	0.0081	0.0105	0.0096	0.0093	0.0090	0.0069	0.0074	0.0058	0.0051
ε_{ult}, m/m	0.014	0.015	0.016	0.017	0.015	0.017	0.013	0.014	0.012
Modulus of toughness, MN·m/m^3	16.97	21.67	22.56	25.95	22.98	22.08	16.35	15.80	11.04
Modulus of elasticity, GPa	173.9	184.2	181.5	184.2	191.8	191.8	193.9	193.9	196.0

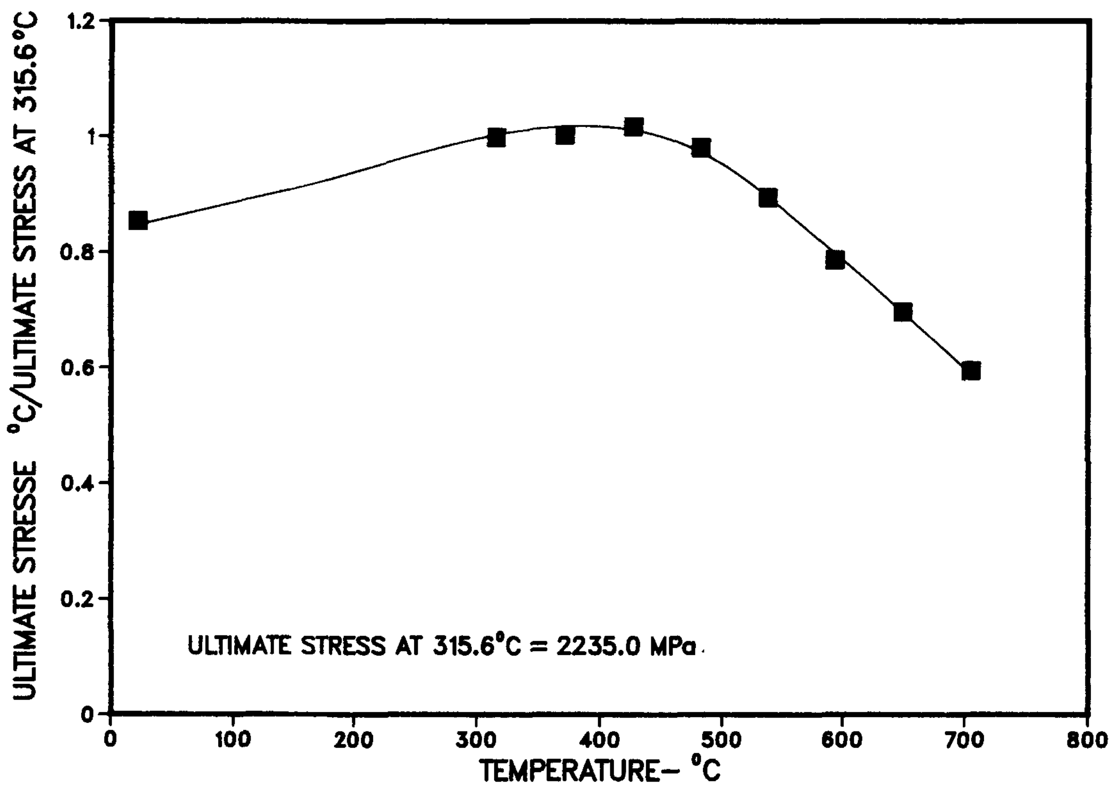

Fig. 2 Plot of normalized ultimate stress versus temperature for type 302 stainless steel wire (0.84-mm diameter).

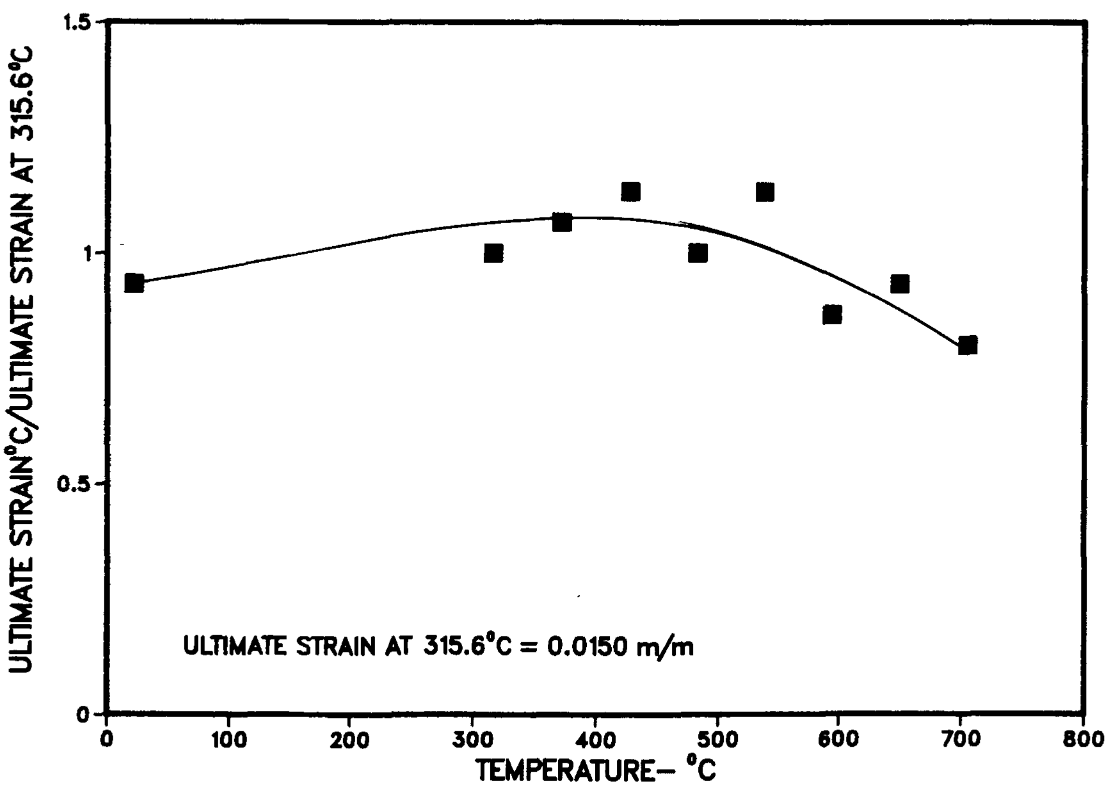

Fig. 3 Plot of normalized ultimate strain versus temperature for type 302 stainless steel wire (0.84-mm diameter).

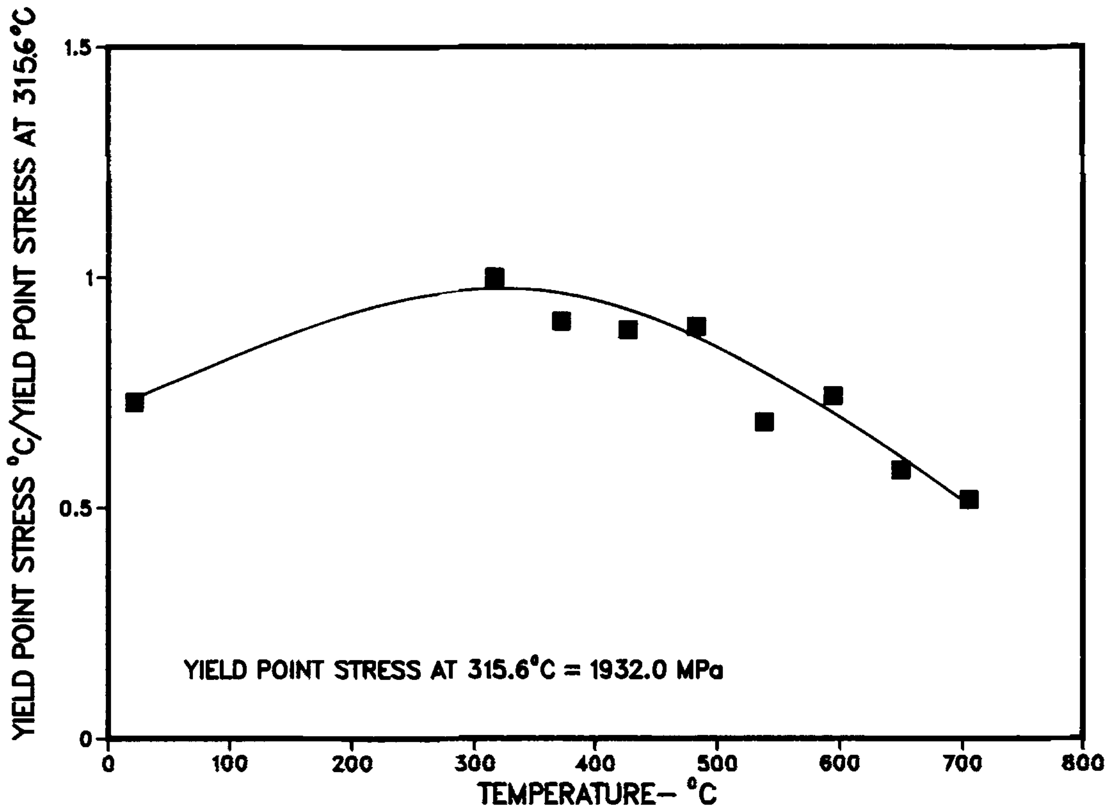

Fig. 4 Plot of normalized yield point stress versus temperature for type 302 stainless steel wire (0.84-mm diameter).

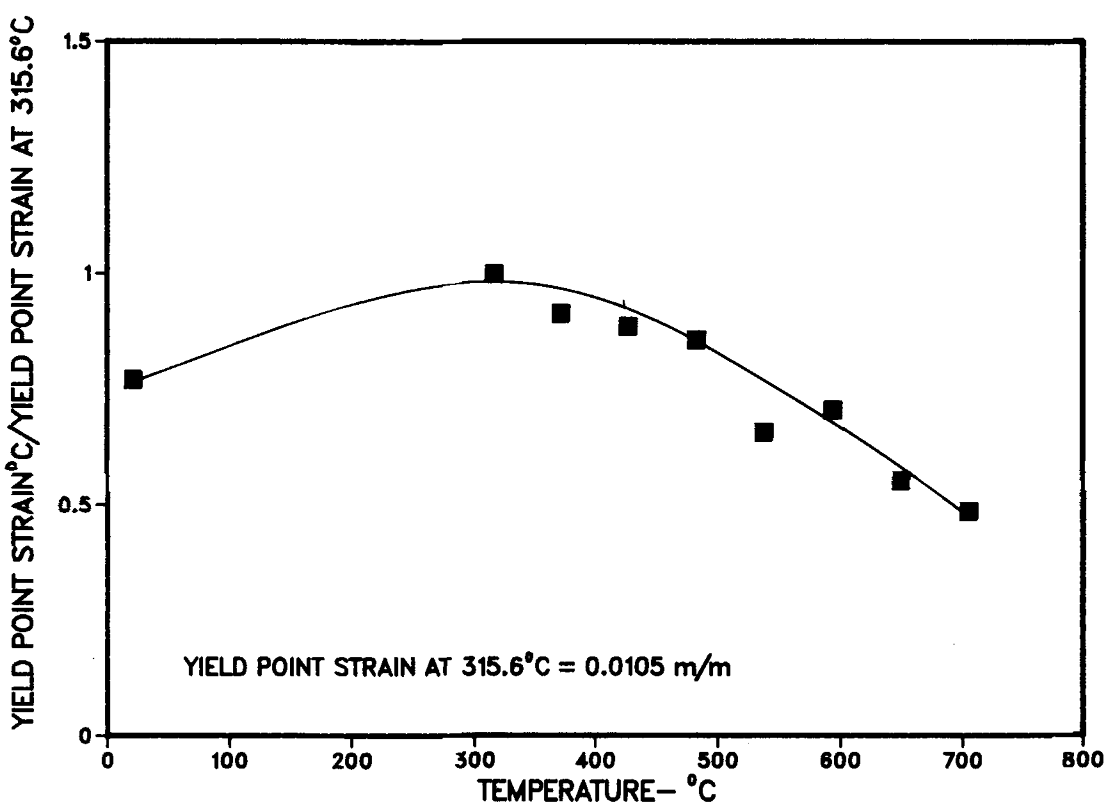

Fig. 5 Plot of normalized yield point strain versus temperature for type 302 stainless steel wire (0.84-mm diameter).

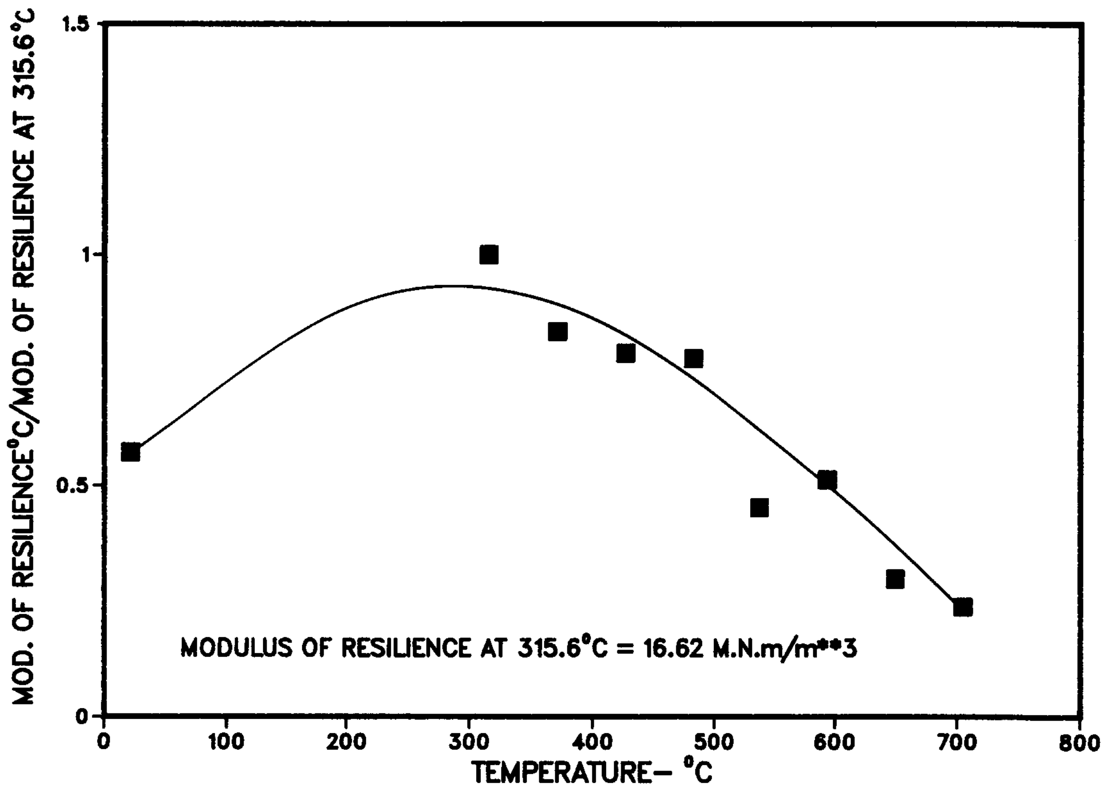

Fig. 6 Plot of normalized modulus of resilience versus temperature for type 302 stainless steel wire (0.84-mm diameter).

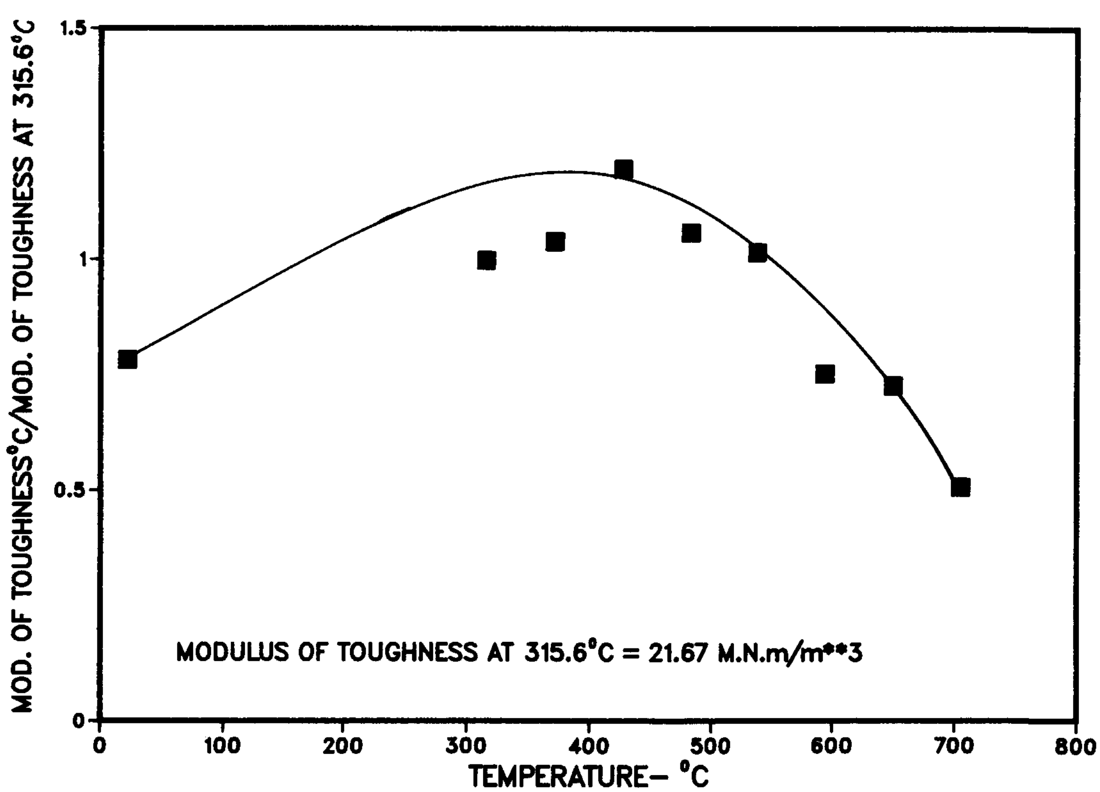

Fig. 7 Plot of normalized modulus of toughness versus temperature for type 302 stainless steel wire (0.84-mm diameter).

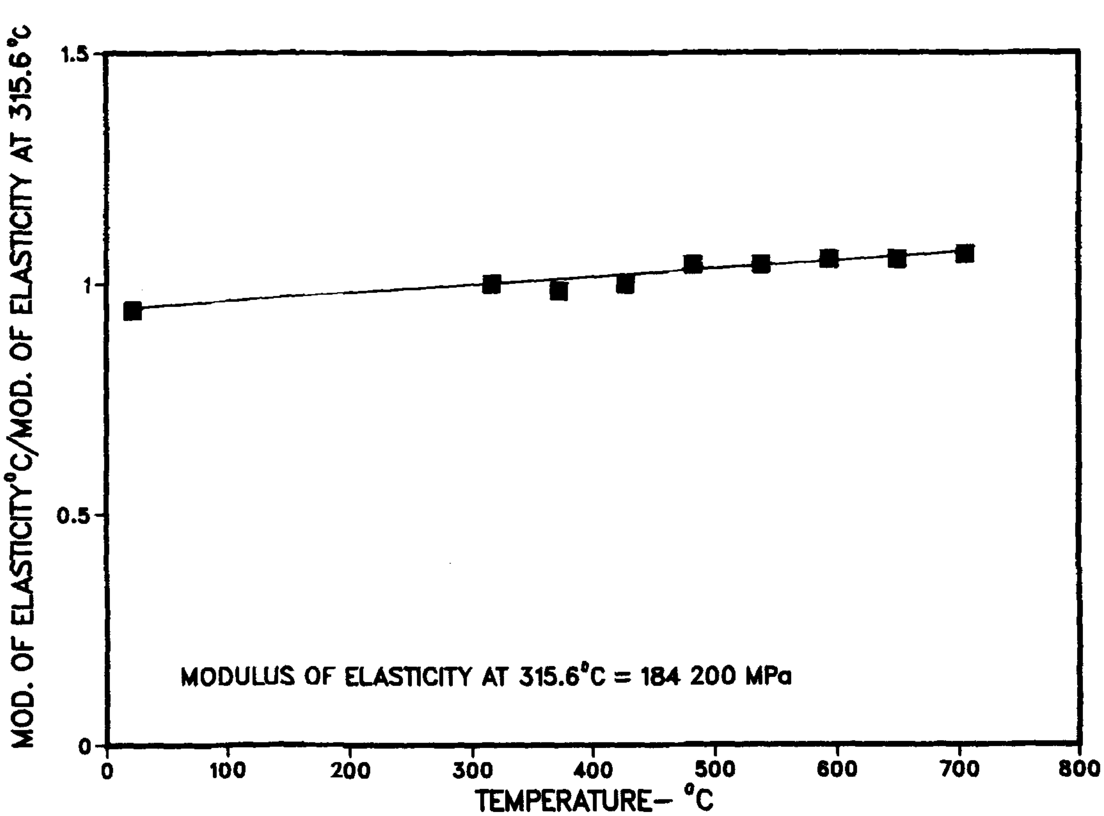

Fig. 8 Plot of normalized modulus of elasticity versus temperature for type 302 stainless steel wire (0.84-mm diameter).

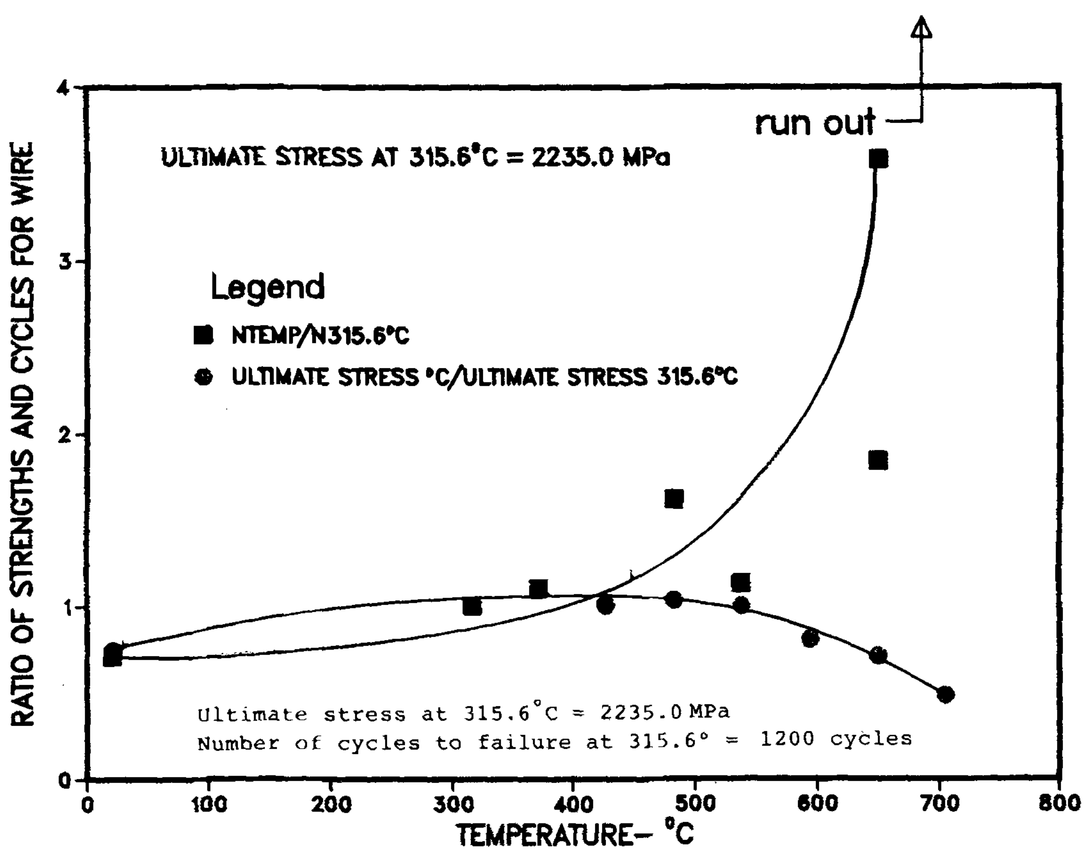

Fig. 9 Plot of normalized number of cycles and ultimate stress versus temperature for type 302 stainless steel wire (0.84-mm diameter)

tion of stress relieving temperature is shown in Fig. 8. It is interesting to note that the modulus of elasticity gradually increases as the heat treatment temperature increases. The increase in the modulus of elasticity is about 13% of the 316 °C (600 °F) modulus of elasticity. This increase shows the tendency of the material to become stiff as the stress relieving temperature is increased.

The wire specimens that were stress relieved at various temperatures also were tested by applying cyclic loads to determine fatigue life. A cyclic axial load was applied at 5 Hz to the wire specimen, and the life cycles to failure were obtained for each stress relieved wire specimen. Figure 9 shows the relation between ultimate strength and the number of cycles to failure with respect to various stress relieving temperatures. It is very interesting to observe that the ultimate strength continuously decreased as the stress relieving temperature was increased. However, the fatigue life of the wire continuously increased as the stress relieving temperature was increased. In fact, the fatigue life at the 649 °C (1200 °F) stress relieving temperature was at its peak, whereas the fatigue life for the 704 °C (1300 °F) wire began to decrease.

4. Conclusions

The mechanical properties at room temperature for a type 302 stainless steel wire are at their peak in the range of 316 to 427 °C (600 to 800 °F) stress relieving temperature, except for the modulus of elasticity. The capacity of the type 302 stainless steel wire to stretch elastically continuously decreases at room temperature as the stress relieving temperature is increased beyond 316 °C (600 °F). The modulus of elasticity of the type 302 stainless steel wire at room temperature increases modestly as the temperature is increased from 316 to 704 °C (600 to 1300 °F).

The fatigue life of the type 302 stainless steel wire is at its peak value at room temperature if the material is stress relieved at 649 °C (1200 °F) for 30 min and air cooled. The reduction in mechanical properties as the stress relieving temperature is increased has no effect on the fatigue life of the material. In fact, the fatigue life at room temperature for the stainless steel type 302 wire increases if the stress relieving temperature is increased to 649 °C (1200 °F). This may be attributed to the elimination or minimization of surface microcracks and residual stresses formed during the cold working process.

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