A statistical study on tensile characteristics of stainless steel at elevated temperatures

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Abstract. This study describes the tensile test results of AISI type 304 deformed at room and elevated temperatures. It has been known that the normal distribution fits well with the strength of typical structural materials. The Weibull distribution has many characteristics in the reliability design. In this paper, we showed that the Weibull distribution can be used to describe the scattering of strength data as well as normal distribution by testing goodness of fit. It is found that the parameters of Weibull distribution have decreasing tendency for temperature rise and the coefficient of variation has increasing tendency for temperature rise.

1. Introduction

Stainless steel has become increasingly popular in structural and architectural applications due to its high level of resistance to corrosion, attractive appearance, structural and architectural qualities, as well as its ability to retain its strength at high temperatures [1]. Mechanical properties, such as yield strength, tensile strength, hardness, are not deterministic but statistical. Causes of scattering of the properties may be the incorrectness of test condition (specimen, equipment, etc.), the lack of test technique, chemical variations of test specimen, inhomogeneity of heat treatment conditions, the working method of specimen or the variation of residual stresses. These factors make mechanical properties more statistical. The quantitative distribution characteristics of mechanical properties are used for the reliability design of machine or structure and the basis data for quality control and design validation. Park et al. [2] showed that the normal distribution describes well the tensile and yield strength at various elevated temperatures from normal statistical paper. There are two statistical models of material’s strength. One is the weakest link model; the other is the averaged strength model. Generally, the defect dominant strength fits well with the extreme value distribution, and the deformation dominant strength (tensile strength and hardness of ductile material, etc) fits well with the normal distribution. On the normal statistical paper, the tensile strength, yield strength and hardness are shown linear [3]. Recently, many researchers have used the Weibull distribution to acquire a design parameter as well as fatigue life prediction [4-5].

Even though the strength follows normal distribution very well, in this study it is investigated by the Weibull distribution at wide range of temperatures. The aim of this study is to investigate which statistical distribution describes better for strengths of AISI 304 stainless steel and to get various
statistical distribution parameters at elevated temperatures and the variation of parameters with temperature.

2. Experimental method
An MTS 810 Universal testing machine of 100kN capacity was used for tensile tests. The MTS Model 653.02 high temperature furnace with a maximum temperature of 1400 °C was used for heating the specimens. The temperature of specimen was measured on the attached thermocouples, type-K, with a maximum measurable temperature of 1550 °C and attached on the specimen at 3 points (at the center of specimen and \( \pm 10 \text{mm} \) from the center) by strain gage welder.

The material used in this study is AISI 304 (18Cr-8Ni) austenitic stainless steel which is widely used in heat exchanger, transportation vessel, food container, rotor, blade, etc. The test specimens were prepared in accordance with the ASTM Standard E8 and E21 [6-7]. An MTS Model 632.53F-11 of axial extensometer was used to measure the strain of the middle part of the specimen. The gauge length of the extensometer was 25mm.

The temperatures specified in the temperature controller were 21 (R.T.), 100, 200, 350, 500, 650 and 800 °C. At each temperature, a steady state tensile test was conducted for 10 specimens. The specimen was heated up to a specified temperature and maintained for 30 minutes. Then the tensile load was applied to specimen. The strain control was used in the tensile testing machine. A tensile loading rate of 2mm/min was used, leading to an initial strain rate of \( 10^{-3} \text{s}^{-1} \), and the heating rate of the furnace is 1.9-2.0 °C/sec. The material properties, such as yield strength, ultimate tensile strength, modulus of elasticity, elongation, were obtained from the stress-strain curve.

3. Statistical analysis method
By a goodness of fit test, the best fitted model was chosen, which shows the minimum difference between the theoretical model (namely, normal distribution, Weibull distribution, etc.) and the cumulative distribution model. To choose the best fitted model to given strength data, we used three different kinds of goodness of fit methods in the commercial software Weibull++® 7: (1) modified Kolmogorov-Smirnov, (2) Correlation Coefficient \( \gamma \) and (3) Log-likelihood value. In this study, we considered the normal distribution and the (2-parameter) Weibull distribution function only for the competing distribution model for yield strength and tensile strength. Kang [8] used such goodness of fit test models to assess the statistical distribution of flexural strength of woven-fabric laminates with impact-induced damage. In his paper, the author summarized the use of three models briefly.

The coefficient of variation (C.V) is a normalized measure of dispersion of a probability distribution. It is defined as the ratio of the standard deviation (\( \sigma \)) to the mean (\( \mu \)). For the Weibull distribution, MTTF (mean time to failures) or MTBF (mean time between failures) is used as mean. So, the coefficient of variation of the Weibull distribution is as Eq. 1. Here, \( \Gamma \) is a gamma function and \( \eta \) and \( \beta \) are the scale and shape parameters in the 2-parameter Weibull distribution, respectively.

\[
C_v = \frac{\sigma}{\mu} = \eta \sqrt{\frac{1 + \frac{2}{\beta}}{\Gamma\left(1+\frac{1}{\beta}\right)} - \left[\Gamma\left(1+\frac{1}{\beta}\right)\right]^2} \eta \Gamma\left(1+\frac{1}{\beta}\right)
\]  

4. Test and statistical analysis results
The details of test results are summarized in Ref. [2]. As the temperature rises, the tensile strength, yield strength and modulus of elasticity are decreased. But the elongation shows a different tendency for temperature. An elongation decreases as the temperature rises at below 650 °C, but it increases at above 650 °C.
The results of goodness of fit test for each statistical distribution model are shown in Table 1 for tensile strength and in Table 2 for yield strength. The correlation coefficient and Log-likelihood (L-K) value at each temperature for normal distribution are shown in parenthesis for a comparing purpose. Both Modified Kolmogorov-Smirnov (K-S) test and Chi-Squared test return the probability that the respective critical value is less than the value calculated. High values, close to one, indicate that there is a significant difference between the theoretical distribution and this data set. Depending on the sample size used, the K-S test and Chi-Squared test will return different results. For K-S as the sample size increases, D Critical becomes smaller thus increasing the probability that D Critical < D. On the other hand the Chi-Squared test is really not valid for smaller sample sizes, i.e. minimum of 35 [9]. In this study, the sample size at each temperature was 10. There might be some errors at modified K-S values and Chi-squared values, but the Weibull distribution seems to be more fitted to the data. The correlation coefficients and L-K values at various temperatures show that both normal and the Weibull distribution fits well with the data, but the Weibull distribution is slightly more fitted to the data than normal distribution.

### Table 1 Results of goodness of fit test for tensile strength

| Test Method   | 21°C     | 100°C    | 200°C    | 350°C    | 500°C    | 650°C    | 800°C    |
|---------------|----------|----------|----------|----------|----------|----------|----------|
| Modified K-S value(%) | 0.024    | 0.002    | 0.216    | 4.971    | 4.197    | 40.456   | 7.042    |
| Correlation Coefficient(%) | 98.743 (97.593) | 97.087 (97.555) | 96.824 (96.078) | 95.464 (90.189) | 95.653 (97.891) | 91.847 (85.502) | 94.247 (87.852) |
| Chi-Squared value(%) | 25.080   | 27.671   | 29.708   | 32.959   | 25.0119  | 41.932   | 33.981   |
| L-K value      | -32.128 (-31.951) | -19.649 (-18.689) | -23.949 (-23.438) | -33.115 (-34.153) | -31.110 (-37.749) | -37.228 (-43.419) | -29.701 (-35.580) |

### Table 2 Results of goodness of fit test for yield strength

| Test Method   | 21°C     | 100°C    | 200°C    | 350°C    | 500°C    | 650°C    | 800°C    |
|---------------|----------|----------|----------|----------|----------|----------|----------|
| Modified K-S value(%) | 9.3911   | 90.1507  | 37.7349  | 86.7418  | 85.0706  | 60.8708  | 26.9015  |
| Correlation Coefficient(%) | 94.7979 (89.163) | 85.5912 (79.650) | 93.1286 (89.103) | 81.6505 (73.998) | 86.3306 (86.481) | 88.1797 (81.308) | 94.7643 (91.327) |
| Chi-Squared value(%) | 36.4749  | 40.1061  | 20.9716  | 46.2782  | 27.7323  | 30.5425  | 34.8022  |
| L-K value      | -30.487 (-31.706) | -21.4977 (-23.526) | -27.2641 (-27.539) | -19.9399 (-22.691) | -25.5514 (-23.484) | -28.1770 (-30.409) | -28.9889 (-28.646) |

Fig. 3 is a plot of shape parameter and scale parameter of tensile strength at various temperatures. The shape parameter rises to the maximum at 100°C. Thereafter, it descends rapidly and remains almost constant above 650°C. The scale parameter of tensile strength descends to 200°C, remains almost constant to 300°C and falls rapidly to 800°C. The shape parameter of yield strength as shown in Fig. 4 rises to the maximum value as in the case of tensile strength. It descends rapidly to 200°C but rises to near the maximum value but rapidly drops to 650°C. Thereafter, the decreasing rate is low to the 800°C. The scale parameter of yield strength descends gradually as the temperature rises as shown in Fig. 4. The coefficient of variation was plotted against the temperature in Fig. 5 for tensile strength and yield strength. As the temperature rises, the coefficient of variation of tensile strength has tendency of rise. It is peculiar that the coefficient of variation at room temperature (21°C) is higher than that at 100°C. As the temperature rises, the strength decreases but its variation increases.
5. Conclusions
This paper aimed to statistically analyze the strength data of AISI 304 stainless steel at elevated temperatures. It is well known that the normal distribution describes well the distribution of tensile strength and yield strength. However, the Weibull distribution has many characteristics to life prediction so it might be used in various reliability design areas. In this study, we investigated the use of the Weibull distribution by a goodness of fit test. The following conclusions were obtained.

(1) On the basis of strength data at various temperatures and use of statistical criteria, the (2-parameter) Weibull distribution can be an appropriate statistical distribution as well as normal distribution.

(2) As the temperature increases, the shape parameter and the scale parameter of tensile strength and yield strength have a tendency of decrease. As the temperature increases, the coefficient of variation which is a normalized measure of dispersion has a tendency of increase.

6. References
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