Statistical Analysis and Prediction on Tensile Strength of 316L-SS Joints at High Temperature Based on Weibull Distribution

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Abstract. In this work, the prediction on average tensile strength of 316L stainless steel is statistically analyzed by Weibull distribution method. Direct diffusion bonding of 316L-SS was performed at high temperature of 550°C and 8 tension tests were carried out. The results obtained vary between 87.8MPa and 160.8MPa. The probability distribution of material failure is obtained by using the Weibull distribution.

1. Introduction
Diffusion bonding technology is a solid state bonding process, involving grinding and polishing the metal surface, and applying the appropriate amount of nominal pressure. It usually applied in micro heat exchangers and micro reactors [1]. With the development of bonding technology, diffusion bonding has become a preferred fabricating method due to its high processing precision and convenient manufacture [2,3]. As an austenitic stainless steel, 316L stainless steel (316L-SS) possesses more unique merits, such as excellent mechanical behavior and oxidation resistance at high temperature, therefore, it was selected as the base metal in the diffusion bonding technology. The research on room temperature performance of diffusion bonding joint between 316L-SS and heterogeneous material is relatively thorough. However, there are few studies about diffusion bonding connection of homogeneous material of 316L-SS, particularly about the design standard of high temperature performance [4-6]. Moreover, the predicted average tensile strength value of the direct diffusion bonding joints of 316L-SS has not been considered in the studies mentioned.

Weibull distribution is a theoretical basis of reliability analysis and life testing evaluation. and it is widely used in reliability engineering, the cumulative distribution of the form of failure. It can be easily inferred from the probability value of its distribution parameters, and it is also widely used in a variety of fatigue life test data processing [7-10].

In the present work, the tensile strength of the direct diffusion bonding joints was tested at a high temperature of 550°C. The validity of the Weibull distribution was confirmed and the reliability of the 316L-SS in terms of its tensile strength was analysed by experimental data, and the average tensile strength value of 316L-SS diffusion bonding joint is predicted.
2. Experiments and theoretical model

The chemical composition of 316L-SS is shown in Table 1.

**Table 1. Chemical composition of 316L-SS**

| element | wt % |
|---------|------|
| C       | 0.01 |
| Fe      | 67.10|
| Ni      | 12.43|
| Si      | 0.41 |
| Mo      | 2.16 |
| S       | 0.01 |
| Cr      | 17.84|
| P       | 0.04 |

The length of 50mm, 70mm diameter cylindrical blank made of 316L stainless steel rods. The bonded surface was polished to a roughness of 0.8µm and then cleaned in acetone prior to diffusion bonding. The tensile tests at 550°C are performed on the Shimadzu material tester with a temperature control in high temperature furnace according to national standards GB/T 228-2002 (entitled as Metallic Materials-Tensile Testing at Ambient Temperature) and GB/T 4338-2002 (entitled as Metallic Materials-Tensile Testing at Elevated Temperature). [11-13]. The result of tensile test was shown in Table 2.

**Table 2. Tensile strength of 316L-SS diffusion bonding specimens at 550°C**

| No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Tensile strength [MPa] | 87.8 | 102.4 | 122 | 123.9 | 140 | 149.1 | 159.7 | 160.8 |

Weibull distribution is being used to moderate extreme values in fracture strength and failure times. Two form of this distribution are two-parameter and three-parameter Weibull distribution. The distribution function and probability density function (PDF) in this case can be written respectively as follows [14]:

\[
F(x) = 1 - \exp \left\{ -\left( \frac{x - \gamma}{\eta} \right)^\beta \right\}, \quad \gamma \geq 0, \quad \eta \geq 0, \quad \beta \geq 0
\]

\[
f(x) = \frac{\beta}{\eta} \left( \frac{x - \gamma}{\eta} \right)^{\beta-1} \exp \left\{ -\left( \frac{x - \gamma}{\eta} \right)^\beta \right\}, \quad \gamma \geq 0, \quad \eta \geq 0, \quad \beta \geq 0
\]

Where \( \gamma \) is the position parameter, when \( \gamma = 0 \), the model degrade into two-parameter Weibull distribution; \( \eta \) is the scale parameter and \( \beta \) is the shape parameter. Three-parameter Weibull distribution applies to more data. In this study, the two-parameter Weibull distribution will be considered. The distribution function in this case can be written as:
\[ F(x) = 1 - \exp\left[-\left(\frac{x}{\eta}\right)^\beta\right], \quad \eta \geq 0, \quad \beta \geq 0 \]  

(3)

In the context of this study, \( F(x) \) represents the probability that the tensile strength is equal to or less than \( x \). Using the equality \( F(x) + R(x) = 1 \), the reliability \( R(x) \), that is, the probability that the tensile strength is at least \( t \), is defined as:

\[ R(x) = \exp\left[-\left(\frac{x}{\eta}\right)^\beta\right], \quad \eta \geq 0, \quad \beta \geq 0 \]  

(4)

If the natural logarithm of both sides of the Eq.(1) is taken, the following Eq.(4) can be written.

\[ \ln\left[\ln\left(\frac{1}{1-F(x)}\right)\right] = \beta \ln(t-\gamma) - \beta \ln \eta \]  

(5)

When the Eq.(5) is rearranged as linear equation, \( Y=\ln\left\{\ln\left[1/1-F(x)\right]\right\}, X=\ln(x) \), \( a=\beta \) and \( b = -\beta \ln \eta \) is written. Therefore, a linear regression model in the form of Eq.(6) is obtained as:

\[ Y = aX + b \]  

(6)

\[ \eta = \exp(-b/\beta) \]  

(7)

A good estimator of \( F(x) \) is Bernard’s Median Rank formula:

\[ F(x) = \frac{i-0.3}{n+0.4} \]  

(8)

where \( i \) is failure serial number and \( n \) is total test number of samples.

3. Results and discussion

The result of tensile test was shown in Table 2 and the linear regression model with the regression line in Figure 1 is obtained, then we can compute \( \beta \) and \( \eta \). The slope of the line is 4.68, which is the value of the shape parameter \( \beta \), according to Eq.(7), the scale parameter \( \eta \) value is computed as \( \eta=148.94 \). \( \beta<1:0 \) indicates that the material has a decreasing failure rate. Similarly \( \beta=0 \) indicates constant failure rate and \( \beta>1:0 \) indicates an increasing failure rate. Therefore, \( \beta=4.68 \) indicates that the 316L-SS tends to crush with higher tension. The scale parameter \( \eta \) measures the spread in the distribution of data. As a theoretical property \( R(x)=0.368 \), therefore, when \( x=\eta \), \( R(x)=0.368 \) that is 36.8% of the tested specimens have a tensile strength of at least 148.94 MPa.
The plot of $R(x)$ is shown in Figure 2. The reliability curve in Figure 2 shows that tensile strength value less than or equal to 50 MPa will provide high to be reliability. For a more certain assessment, consider 0.90 reliability levels. When this value are put as $R(x)$ in Eq.(4) and the equation is solved for $x$, the tensile strength value 92.08 is obtained. In another word, this material will crush with 0.90 probability for a tension of 92.08 MPa.

The cumulative distribution probability for the tensile strength data of 316L stainless steel diffusion welding joint is given in the following formula:
Where $\Gamma$ is the gamma function. And the reliability curve at high temperature is provided in Figure 3.

![Reliability of 316L-SS diffusion bonding](image)

**Figure 3.** Reliability curve at high temperature

Average tensile strength can be predicted by the formulation (9). The predicted average tensile strength value of 316L-SS diffusion bonding joint is 156 MPa

4. Conclusions

316L-SS is generally used in diffusion bonding, the tensile strength variation in the tension has been modeled using Weibull distribution. The Weibull distribution provides a way to predict the reasonable tension when the 316L-SS was working. It also allows researchers to describe the tensile strength of a material in terms of a reliability function. The length of 50mm and diameter of 70mm 316L-SS round bar test sample follows the Weibull distribution with scale parameter of 148.94 and shape parameter of 4.68 at high temperature; among which the average bonding life at normal temperature is tensile strength of 156MPa.

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