PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Statistical analysis of tensile strength and elongation of pulse TIG welded titanium alloy joints using Weibull distribution

M. Balasubramanian

Abstract: In this study, the tensile strength of a pulsed current tungsten inert gas welded Ti-6Al-4 V plate has been statistically analysed by Weibull distribution. Titanium alloy of 1.6 mm thickness was welded with pulsed current tungsten inert gas welding. Testing of mechanical properties was done to understand the influence of pulsing current on the fabricated joint. But the result obtained has to be consistent and repeatable. Hence, this paper investigates a method for predicting the reliability of values obtained for tensile strength and elongation with consistency. The tensile strength results obtained vary between 975 and 1160 MPa and percentage elongation vary between 2.4 and 5.9%. Using Weibull technique in conjunction with the experimental data, we can predict the output more accurately. Using Weibull distribution, the welded joint reliability can be obtained. The probability distribution according to which the joint will fail is estimated with the help of Weibull analysis.

Subjects: Manufacturing & Processing; Metals & Alloys; Quality Control & Reliability

Keywords: Weibull distribution; titanium alloy; pulse TIG welding

ABOUT THE AUTHOR

M. Balasubramanian obtained his bachelor degree in Mechanical Engineering from Annamalai University, Tamil Nadu, India. His post graduation was in the area of Production Engineering from Annamalai University, Tamil Nadu, India. He obtained his doctoral degree in the area of material joining from Anna University, Tamil Nadu, India. He has 18 years of teaching experience including 8 years of research experience. He has more than 54 articles published in refereed journals. He has obtained various research projects and seminar grants from various funding agencies like BRNS, AICTE, ISTE, MNRE and CSIR across India to the tune of 40 lakhs. His area of specialization includes optimization, material joining and materials. One of his articles was ranked one among the top 50 articles in science direct. H index is the author level metric that attempts to measure both the productivity and citation impact of the publication of a scholar. His H index is 13 and I index is 14. To his credit, he has filed two patents in the area of friction welding and nozzle design in abrasive jet machining.

PUBLIC INTEREST STATEMENT

Experiments are conducted by the researchers to understand the effect of various factors on the outcome. Normally, researchers conduct three experiments and average the results obtained to pin down to a single number. Reliability analysis used in this study will help the researchers in understanding the number of trials to be done on the same experimental condition to accept the results obtained. Results obtained from two or three trials do not ascertain the results obtained. This study proves that the result cannot be averaged out and the probability of the results obtained can be understood from this analysis.
1. Introduction

Ti-6Al-4 V, titanium alloy most often used to fabricate structures, such as in the applications of defense vehicles and space vehicles (Reddy, Gokhale, & Rao, 1997, 1998). The preferred welding process for welding titanium alloy is more often GTAW due to its comparatively easier applicability and better economy (Yunlian, Ju, Quan, & Liying, 2000). Weibull distribution has the capability to model experimental data of very different characters. This is one of the reasons for its wide utilisation nowadays. The empirical data after transformation can be plotted on the Weibull probability plotting paper to estimate the parameters of the Weibull distribution. From those estimated parameters of Weibull distribution, the parameters of the extreme value distribution can be estimated easily by using transformation techniques (Dodson, 1994). Weibull distribution is a practical method used in the determination of 90 and 95% reliability values used in metal joining techniques. The variation of the tensile strength of pulse TIG welded titanium alloy has been modeled using Weibull distribution. Tension tests were performed and using the test data, the corresponding Weibull distribution was determined. Finally, the reliability of the welded joints in terms of its tensile strength was presented in graphical form. The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely less number of samples. Another advantage of Weibull analysis is that it provides a simple and useful plot of the failure results. The graph developed with the failure data is extremely valuable to the users. Ti-6Al-4 V also have excellent specific tensile and corrosion resistance, mainly used for aircraft structural and engine parts, material for petrochemical plants and surgical implants. Titanium (Ti-6Al-4 V) alloy has gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to-weight ratio, such as transportable bridge girders, military vehicles, road tankers and railway transport systems (Balasubramanian, Jayabalan, & Balasubramanian, 2008a, 2008b). So far Weibull distribution has not been used in the study of pulse current titanium alloy welding. Hence an attempt was made to study the reliability of the pulsed current welding of titanium alloy.

2. Experimental procedure

The important factors which have greater influence on the tensile strength of pulsed current GTA welding process have been traced from the literature survey (Balasubramanian, Jayabalan, & Balasubramanian, 2008c, 2008; Sundaresan & Ram, 1999). They are peak current, background current, pulse frequency and pulse on time. The sheets of the Ti-6Al-4 V titanium alloy was made to square butt joint configuration as shown in Figure 1. The prepared specimen was fabricated by autogenous pulsed current GTAW process using the setup in Figure 2. Given that the plate thickness is 1.6 mm, the single pass welding procedure has been followed to fabricate all the joints. Necessary care was taken to avoid joint any distortion and the joints were made by ensuring suitable clamping. The required number of trial runs has been carried out using 1.6 mm thick sheets of titanium.
(Ti-6Al-4 V) alloy to identify the feasible working limits of pulsed current GTA welding parameters. Various combinations of pulsed current parameters have been used to carry out the test runs. The bead shape, bead look, and weld quality have been inspected to identify the working limits of the parameters. Details of observations made on trial runs and mathematical modeling are given by Balasubramanian, Jayabalan, and Balasubramanian (2006). Tensile specimens were prepared as per the ASTM E8 M-05 guidelines as shown in Figure 3. Fabricated specimens are displayed in Figure 4.

2.1. Weibull distribution

Weibull distribution is being used to model extreme values such as failure times and fracture strength. Two forms of this distribution are two and three parameter Weibull distributions. The cumulative distribution function of the three parameter Weibull distribution is as follows (Dirikolu, Aktas, & Birgoren, 2002).

\[
F(x; a, b, c) = 1 - \exp \left( - \left( \frac{x - a}{b} \right)^c \right)
\]

where the location, scale, and shape parameters are represented as \(a\), \(b\), and \(c\) respectively Abernethy (2006). When \(a = 0\) in Equation (1) the function of the two-parameter Weibull distribution is obtained. The three-parameter Weibull distribution is appropriate for situations in which an extreme value cannot take values less than \(a\). In this study, the two-parameter Weibull distribution is used to study the reliability of tensile strength results. The distribution function here can then be written as follows (Balasubramanian et al., 2006).
The parameters $b$ and $c$ of the function $F(x; b, c)$ are estimated from the following observations. Linear regression is a common method and will be used for estimation of parameters in this paper. In this method Equation (2) is transformed into $1 - F(x; b, c) = \exp\left(\frac{x}{b}\right)^c$ and taking the logarithms of both sides. Hence, a linear regression model in the form $Y = mX + r$ is obtained (Taljera, 1981).

$$
\ln\left[\ln\left(\frac{1}{1 - F(x; b, c)}\right)\right] = c \cdot \ln(x) - c \cdot \ln(b)
$$

2.2. Methodology

Two step procedure is followed in predicting the reliability of the mechanical properties under consideration. First, the parameters must be estimated. Then the estimates are used to predict subsequent failures.

Following are the step-by-step procedure for estimating the Weibull parameters. Although there are many techniques for analyzing the experimental data, the following requirements are common to each: an unambiguously defined time origin, a scale for measuring the passage of time, and a clear meaning for the failure. Many a time the Weibull distribution is expressed as three parameters in its most general form, it is commonly expressed as a two-parameter distribution. Since failure cannot occur until or after the value of the location parameter, the location parameter is mostly ignored.

The procedure for the estimation of the Weibull parameters is given below.

1. Define the scope of the experimentation.
2. Collect the data for analysis.
3. Plot the data on a graph.
4. Estimate the required parameters.

The first step in the estimation of Weibull parameters is to describe the scope. The next step is to obtain data on mechanical properties in the analysis.

The third step is to plot the data to verify that they conform to a Weibull distribution. Estimating the plotting positions for the failures involves approximating the true values of the Weibull cumulative distribution function. The plotted points are expected to fall in a relatively straight line if the data conform to a Weibull distribution. The Weibull parameters may be estimated after this condition is reached. Assemble the data in ascending order and tabulate it against the corresponding $F(t)$ values for 31 experiments conducted, obtained from the median rank tables (Suresh Babu & Jayabal, 2009). Now the Plot is developed using the tensile strength and percentage elongation ($t_i$) data on the horizontal axis against the corresponding $F(t)$ value on the vertical axis.

It was confirmed by experiment that this Weibull data treatment method is also valid for application in the dielectric failure of multilayer ceramic capacitors (MLCs) which have undergone screening. The Weibull modulus is found to be a useful parameter indicating the sharpness of the distribution of breakdown voltages and mechanical strength of MLCs. By Weibull analysis, the latest developed relax or-based MLCs are found to compare favorably with traditional barium-titanate based MLCs, implying that relax or MLCs are more attractive than generally realized (Wang, Chan, Gui, Webb, & Li, 1997). Increasing demand for reliable performance of materials requires that the strength should be measured accurately within the range of intended use. As it is well-known, due to the defects that may be present in the material, the mechanical test results may vary significantly depending on the size and population of these defects. Therefore, it is important to produce materials with minimal defects and more reliable mechanical properties. For this purpose, in engineering applications, Weibull distributions are widely used to study the distribution and magnitude of scatter.
of independent results obtained from experimental findings. The basic Weibull distribution is a plot between random variables, \( x \), and its cumulative probability, \( F(x) \); in such a way that the plot against \( x \) of its cumulative probability, \( F(x) \), appears as a straight line (Kirtayi & Dispinar, 2012).
3. Result and discussion

The tensile strength results obtained from the experimental investigation as per the input parameters listed in Table 1 is submitted in Table 2. For estimating the parameters b and c, they are rearranged from the smallest to the largest and (X, Y) values are computed. Regression analysis is most often used for prediction. The goal of regression analysis is to create a mathematical model that can be used to predict the values of a dependent variable based on the values of an independent variable. In other words, we use the model to predict the value of Y when we know the value of X. Regression analysis is most often used for prediction. The goal in regression analysis is to create a mathematical model that can be used to predict the values of a dependent variable based on the values of an independent variable. In other words, we use the model to predict the value of Y when we know the value of X. Then applying linear regression to these (X, Y) values, the linear regression model with the regression line is shown in Figures 5 and 6. The slope of the line is 61.205, which is the value of the shape parameter c. Scale parameter c < 1.0 indicates that the joint has a decreasing failure rate. Similarly, c = 0 indicates a constant failure rate and c > 1.0 indicates an increasing failure rate. The b value is computed as b = 1017.3. Therefore, c = 61.205 indicates that the joint tends to fracture with a higher probability for every unit increase in applied tension. The parameter b measures the spread in the distribution of data. As a theoretical property \( R(b; b, c) = 0.368 \). Therefore, \( R(1,017; 1,017, 61.205) = \exp^{-(x b)} c = 0.368 \), that is 36.8% of the tested specimens have a fracture strength of at least 1,017 MPa. The plot of \( R(x; b, c) \) is shown in Figure 7. Figure 7 brings out the reliability curve, which reveals that the tensile strength values less than 900 MPa are high to be reliable. For a more certain assessment, consider 0.90 and 0.95 reliability levels. When these values are used in Equation (3) and the equation is solved for \( x \), the fracture strength values 980 and 970 are obtained respectively. To be straight, this joint will fracture with 0.90 probability for a tension of 980 MPa and similarly will fracture with 0.99 probability for a tension of 905 MPa.

When we consider the percentage elongation of the pulse TIG welded specimen, the slope of the line is 5.934, which is the value of the parameter c. The b value is estimated as \( b = 3.529 \). Hence, \( c = 5.934 \) reveals that the joint tends to fracture with a higher probability for every unit increase in applied tension. The parameter b measures the spread in the measured data. By theory, the property \( R(b; b, c) = 0.368 \). Therefore, \( R(3.529; 3.529, 5.934) = \exp^{-(x b)} c = 0.368 \), that is 36.8% of the tested specimens have a percentage elongation of at least 3.529. The plot of \( R(x; b, c) \) is depicted in Figure 8. Figure 8 brings out the reliability curve, which reveals that the percentage elongation values less than 1.1 are high to be reliable. For a more certain assessment, consider 0.90 and 0.95 reliability levels. When these values are used in Equation (3) and the equation is solved for \( x \), the elongation values of 2.4 and 2.0% are obtained respectively. In other words, this specimen will fracture with 0.90 probability of an elongation value of 2.4%.
Figure 6. Regression line of response elongation.

![Regression line of response elongation](image)

$y = 5.9347x - 7.4836$

$R^2 = 0.9624$

$\log \text{of } y \text{ values}$

Figure 7. Weibull reliability distribution for tensile strength.

![Weibull reliability distribution for tensile strength](image)

Figure 8. Weibull reliability distribution of percentage elongation.

![Weibull reliability distribution of percentage elongation](image)
4. Conclusion

(1) Titanium alloy is generally required in strategically important applications, where failure due to variation in the material properties should be avoided. This study raises questions of assuming the tensile strength and percentage elongation as an average of the experimental results.

(2) In this respect, the Weibull distribution allows researchers to describe the experimental results in terms of a reliability function. In this investigation, the fracture statistics of the pulse TIG welded specimen are examined by plotting the survival probability of the specimen against the axial stress applied to the specimen.

(3) It can be concluded that the relation between the applied stress on the specimen and the survival probability can be described by the Weibull model. It also provides the engineers or the end users with a tool that will enable them to present the necessary mechanical properties with confidences.

(4) With 0.90 reliability level, we can conclude that the tensile strength of the Pulse TIG welded specimen will be 980 MPa.

(5) With 0.90 reliability level, we can ensure 2.4% elongation for the welded specimen.

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Author details

M. Balasubramanian
E-mail: manionmb@gmail.com
ORCID ID: http://orcid.org/0000-0003-3208-2613
1 Department of Mechanical Engineering, R.M.K. College of Engineering and Technology, Puduvoyal, Tiruvallur, India.

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