Model Equation for Predicting the Tensile Strength of Resistance-Brazed Joints

The tensile strength of resistance-brazed joints is predicted using a model equation based on the electric current variation

BY K. TAKESHITA

ABSTRACT. To ensure the quality of a resistance-brazed joint, a model equation for predicting its tensile strength is presented on the basis of the electric current variation during resistance brazing. The model equation derived considers changes occurring in a joint during resistance brazing and is subsequently expressed in a polynominal in three variables of i_1, $i_1–i_2$, and i_2/i_3: i_1 is the first maximum value, i_2 the minimum value and i_3 the second maximum value in the electric current measurement. The predicted tensile strength is discussed and compared with experimental data obtained from Ti-10 wt-% Zr alloy joints resistance brazed with Ti-20 wt-% Zr-20 wt-% Ni-20 wt-% Cu or Ni-50 wt-% Cu filler metal.

Introduction

In resistance brazing, the heat is obtained from dynamic resistance to the flow of electric current passing through a joint. The process is rapid, and the heating zones can be confined to very small areas. These characteristics provide the following advantages from a production viewpoint: 1) a high level of productivity, 2) suitability for automation and 3) decreased base-metal degradation. However, the dynamic resistance of each run can vary, which causes inconsistency in the joint. Thus, to ensure the quality of a resistance-brazed joint, its strength must be predicted without mechanical tests. Since the electric current during resistance brazing is inversely proportional to the dynamic resistance, it provides useful information on the changes that occur in a joint during resistance brazing.

The present paper proposes a model equation for predicting the tensile strength of a resistance-brazed joint on the basis of the electric current variation during resistance brazing. The efficacy of the model equation is subsequently determined in comparison with experimental data.

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Experimental Procedures

Ti-10 wt-% Zr alloy rods 4 mm (0.157 in.) in diameter were butt-joint resistance brazed with Ti-20 wt-% Zr-20 wt-% Ni-20 wt-% Cu or Ni-50 wt-% Cu filler metal foils of 50 µm (0.00197 in.) thickness under a protective argon gas atmosphere, as shown in Fig. 1A. The energizing AC voltage was set at 5.7 V, the energizing time at 0.8 s and the applied pressure at 0.63 MPa (0.0914 ksi). The Ti-10 wt-% Zr alloy rod was used as a base metal as cold drawn by a reduction in cross-sectional area of 60%; its tensile strength was 900 MPa (131 ksi). The physical properties of the materials used for resistance brazing are listed in Table 1. The surfaces of the base metal to be resistance brazed had an arithmetic average surface roughness of 0.4 µm (0.0000157 in). Before resistance brazing, the base metal and the filler metal foils were degreased in an ultrasonically agitated bath of acetone and then rinsed in distilled water.

The resistance-brazed joint was machined to form the tensile test specimen, the shape and size of which are shown in Fig. 1B. Tension tests were conducted at room temperature using an Instron-type test machine at a cross-head speed of 0.05 mm/s (0.00197 in./s).

During each resistance brazing, the electric current passing through the primary circuit of a transformer with an input voltage of 200 V of AC was recorded using an AC current/DC voltage transducer, with a response time of 0.25 s, and a storage oscilloscope, as shown in Fig. 2.

KEY WORDS

Resistance Brazing
Butt Joint
Quality Assurance
Tensile Strength
Electrical Data
Titanium Alloy
Titanium Brazing Filler Metal

Experimental Results

Tensile Strength of the Joints

Figure 3 shows the histogram for the measured tensile strength of 46 joints resistance brazed with Ti-Zr-Ni-Cu filler metal by a class interval of 30 MPa (4.35 ksi). The tensile strength varied from 260 to 485 MPa (37.7 to 70.3 ksi). The arithmetic mean value was 397 MPa (57.6 ksi), and the standard deviation was 39.7 MPa (5.76 ksi). Figure 4 shows the histogram for the measured tensile strength of 46 joints resistance brazed with Ni-Cu filler metal by a class interval of 40 MPa (5.80 ksi). The tensile strength varied from 138 to 508 MPa (20.0 to 73.7 ksi). The arithmetic mean value was 281 MPa (40.8 ksi), and the standard deviation was 83.6 MPa (12.1 ksi). These results demonstrate that, regardless of the filler metal, the tensile strength of the resistance-brazed joints varies over a wide range, even though the same brazing procedure was employed each time.

Electric Current during Resistance Brazing

Figure 5 shows a typical electric current curve recorded during resistance brazing with Ti-Zr-Ni-Cu filler metal in which the following four stages can be identified:

Table 1 — Physical Properties of the Materials Used for Resistance Brazing

Material	Ni-Cu	Ti-Zr-Ni-Cu	Ti-10Zr
Electrical Resistivity at 293 K (• m)	49 x 10^{-8}	174 x 10^{-8}	55 x 10^{-8}
Melting Point (K)	1573	1121	1910

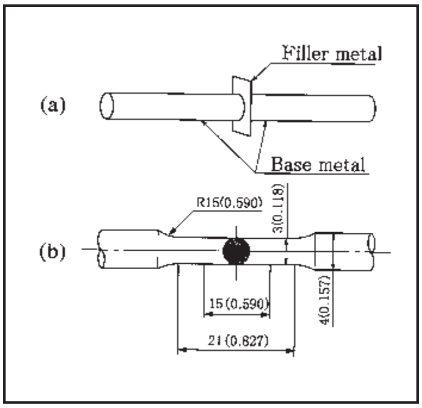

Fig. 1 — Schematic representation of (A) brazing procedure and (B) tensile test specimen. Dimensions are in millimeters (inches in parentheses).

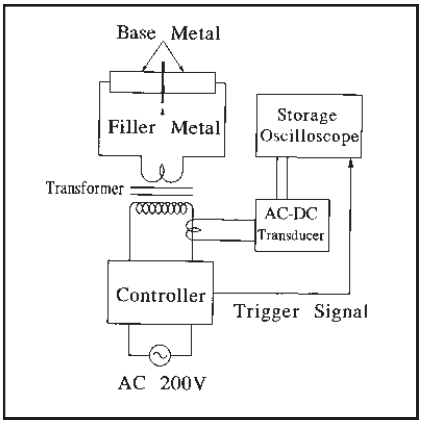

Fig. 2 — Schematic drawing of experimental setup for electric current measurement.

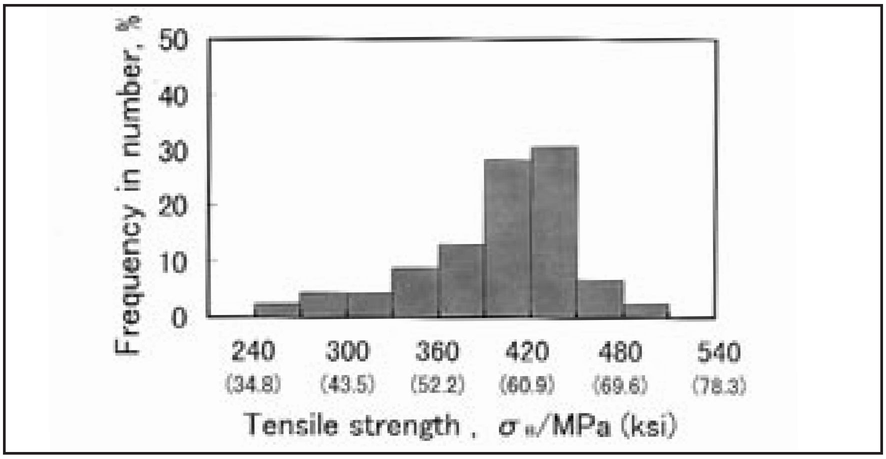

Fig. 3 — Histogram for measured tensile strength of joints resistance brazed with Ti-Zr-Ni-Cu filler metal.

1) Rapid increase to the first maximum value, i_1.

2) Gradual decrease to the minimum value, i_2.

3) Gradual increase to the second maximum value, i_3.

4) Rapid decrease to zero.

Stage 1 corresponds to the increase in contact area between the filler metal and base metals due to fracture of the oxide films covering their surfaces. Stage 2 is associated with an increase in the specific resistance of the filler metal and base metals due to heating. Melting of the filler metal causes a decrease in spacing between the base metals due to the applied pressure resulting in the appearance of stage 3.

Tensile Strength Prediction

Model Equation

As stated above, the electric current during resistance brazing is associated with the changes that occur in a joint. Thus, the three extremum values in the electric current curve, i_1, i_2 and i_3, can be used to derive a model equation to predict the tensile strength of the joint if the following assumptions are introduced.

Assumption 1 (A1): The joint demonstrates its maximum tensile strength when the optimal interdiffusion between the filler metal and base metals occurs and when the joint has the optimal spacing between the base metals.

Assumption 2 (A2): Optimal interdiffusion is realized when the contact area between the filler metal and base metals and the temperature of the joint are both optimal. The contact area between the filler metal and base metal is proportionally related to the first maximum value in the electric current curve, i_1. The temperature of the joint is linearly related to the difference between the first maximum value and the minimum value in the electric current curve, i_1–i_2.

Assumption 3 (A3): The spacing between the base metals is linearly related to the minimum value divided by the second maximum value in the electric current curve, i_2/i_3.

Assumption 1 is based on the following points. Interdiffusion between the filler metal and base metals during resistance brazing changes the composition of the filler metal and consequently influences its solidified microstructure. The solidified filler metal generally has a heterogeneous microstructure consisting of soft and hard metallurgical phases. In addition, several experiments have shown the maximum strength of alloys with such a heterogeneous microstructure is related to the particular volume fraction of the hard metallurgical phase (Refs. 1, 2). Therefore, optimal interdiffusion is required to ensure the composition of the filler metal leads to the optimal solidified microstructure in terms of its strength. Furthermore, the tensile strength of a brazed joint is dependent upon the spacing between the base metals. Numerous investigators have confirmed a brazed joint demonstrates its maximum tensile strength when the joint has a particularly advantageous spacing between the base metals (Refs. 3, 4, 5).

The first part of Assumption 1 can be modified to allow derivation of the model equation and incorporate Assumption 2, discussed below. For a given brazing time, the extent of interdiffusion between the filler metal and base metal is proportionally related to the product of the contact area between the filler metal and base metals and the interdiffusion coefficient (Ref. 6). In addition, the interdiffusion coefficient is exponentially dependent upon temperature (Ref. 7). Therefore, optimal interdiffusion is realized when the contact area between the filler metal and base metals and the temperature of the joint are both optimal.

Since the contact area between the filler metal and base metals is presumably proportional to the first maximum value in the electric current curve, i_1, the requirement for the optimal contact area leads to that for the optimal value of i_1. The increase in temperature of the joint, as mentioned earlier, is associated with the difference between the first maximum value and the minimum value in the electric current curve, $i_1 – i_2$. If, for simplicity, the increase in temperature of the joint is assumed to be linearly related to the value of $i_1 – i_2$, the requirement for the optimal temperature of the joint leads to that for the optimal value of $i_1 – i_2$. Thus, the first part of Assumption 1 is modified to the following assumption (labeled A1-1) using the first maximum value, i_1, and the minimum value, i_2, in the electric current curve.

A1-1: The joint demonstrates its maximum tensile strength when the values of i_1 and $i_1 – i_2$ are both optimal.

The latter part of Assumption 1 can also be modified to allow derivation of the model equation and incorporate Assumption 3, discussed below. If it is assumed the spacing between the base metals varies from S_2 to S_3 in stage 3 and the resistance of the base metals, R_b, and the electrical resistivity of the filler metal, ρ_f, remain unchanged during stage 3, S_2 and S_3 are given by

$$S_2 = \frac{V_e - R_b \cdot i_2}{\rho_f \cdot i_2} \qquad (1)$$

$$S_3 = \frac{V_e - R_b \cdot i_3}{\rho_f \cdot i_3} \qquad (2)$$

where V_e is the voltage applied to the joint, i_2 is the electric current passing through the joint at the beginning of stage 3, identical to the minimum value in the electric current curve, and i_3 is the electric current passing through the joint at the end of stage 3, identical to the second maximum value in the electric current curve.

Elimination of V_e from Equations 1 and 2 gives the following equation:

$$S_3 = \left(S_2 + \frac{R_b}{\rho_f}\right) \cdot \left(\frac{i_2}{i_3}\right) - \frac{R_b}{\rho_f} \qquad (3)$$

Because S_2 is approximately equal to the thickness of the filler metal, it can be regarded as a constant. If the value of R_b/ρ_f is assumed to be unchanged regardless of the joint temperature during stage 3 in each run, Equation 3 expresses Assumption 3 described above. The combination of the latter part of Assumptions 1 and 3 gives the following assumption:

A1-2: The joint demonstrates its maximum tensile strength when the value of i_2/i_3 is optimal.

A1-1 and A1-2 allow the model equation for predicting the tensile strength of the joint to be expressed in a dimensionless form, as

$$\hat{\sigma} = \left(1 + \beta x_1 + \alpha x_1^2\right) \cdot \left(1 + \delta x_2 + \gamma x_2^2\right) \cdot \left(1 + \xi x_3 + \eta x_3^2\right) \qquad (4)$$

where $\hat{\sigma}$ is the predicted dimensionless tensile strength defined by $\hat{\sigma}_B/\sigma_B^*$; x_1, x_2, and x_3 are dimensionless, independent variables defined by $x_1=(i_1/i_1^*) - 1$, $x_2 = (i_1 - i_2)/(i_1^* - i_2^*) - 1$ and $x_3=(i_2/i_3)/(i_2^*/i_3^*) - 1$; and α, β, γ, δ, ξ and η are unknown parameters. $\hat{\sigma}_B$ is the predicted tensile strength of the joint resistance brazed with the electric current curve having the three extremum values of i_1, i_2 and i_3. Symbols denoted with an asterisk, σ_B^*, i_1^*, i_2^* and i_3^*, are the reference standard quantities introduced for the dimensionless expression to the model equation. In the present work, σ_B^* was set at the highest measured tensile strength among the joints. In addition, i_1^*, i_2^* and i_3^* were set at the measured three extremum values in the electric current curve corresponding to the joint with the highest measured tensile strength, σ_B^*.

Modification of Model Equation

The values of the unknown parameters in Equation 4 may be determined by the least-squares method when experimental data are available. However, the calculation is too difficult to carry out because Equation 4 is nonlinear with respect to the unknown parameters. Thus, Equation 4 is modified to the linear form with respect to C_i, as

$$\hat{\sigma} = \sum_{i=0}^{26} C_i y_i \qquad (5)$$

where C_0 through C_{26} are unknown parameters, and y_0 through y_{26} are defined by

$$y_0=1,\ y_1=x_1,\ y_2=x_2,\ y_3=x_3,\ y_4=x_1^2,\ y_5=x_2^2,\ y_6=x_3^2,\ y_7=x_1x_2,\ y_8=x_2x_3,\ y_9=x_3x_1,\ y_{10}=x_1^2x_2,\ y_{11}=x_1x_2^2,\ y_{12}=x_2^2x_3,\ y_{13}=x_2x_3^2,\ y_{14}=x_3^2x_1,\ y_{15}=x_3x_1^2,\ y_{16}=x_1x_2x_3,\ y_{17}=x_1^2x_2^2,\ y_{18}=x_2^2x_3^2,\ y_{19}=x_3^2x_1^2,\ y_{20}=x_1^2x_2x_3,\ y_{21}=x_1x_2^2x_3,\ y_{22}=x_1x_2x_3^2,\ y_{23}=x_1x_2^2x_3^2,\ y_{24}=x_1^2x_2x_3^2,\ y_{25}=x_1^2x_2^2x_3 \text{ and } y_{26}=x_1^2x_2^2x_3^2. \qquad (6)$$

Equation 5 can be derived by expanding Equation 4 and taking each term as an independent one. From the definitions of y_i, note that Equation 5 is a polynominal in the three variables of x_1, x_2 and x_3. To determine the values of C_i in Equation 5 by the least-squares method using experimental data, all the variables y_i must be independent of each other (Ref. 8). However, there is a strong correlation between y_1 and y_4, y_2 and y_5, y_3 and y_6, y_7 and y_{17}, y_8 and y_{18}, y_9 and y_{19} and y_{16} and y_{26}, as $y_4=y_1^2$, $y_5=y_2^2$, $y_6=y_3^2$, $y_{17}=y_7^2$, $y_{18}=y_8^2$, $y_{19}=y_9^2$ and $y_{26}=y_{16}^2$. These strong correlations may be considerably weakened by converting the variables y_i into the variables z_i, defined by the following (Ref. 9):

$$z_0 = 1,\ z_1 = x_1,\ z_3 = x_2,\ z_3 = x_3,\ z_4 = \left(x_1 - \bar{x}_1\right)^2,\ z_5 = \left(x_2 - \bar{x}_2\right)^2,\ z_6 = \left(x_3 - \bar{x}_3\right)^2,\ z_7 = \left(x_1 - \bar{x}_1\right) \cdot \left(x_2 - \bar{x}_2\right),\ z_8 = \left(x_2 - \bar{x}_2\right) \cdot \left(x_3 - \bar{x}_3\right),\ z_9 = \left(x_3 - \bar{x}_3\right) \cdot \left(x_1 - \bar{x}_1\right),\ z_{10} = \left(x_1 - \bar{x}_1\right)^2 \cdot \left(x_2 - \bar{x}_2\right),\ z_{11} = \left(x_1 - \bar{x}_1\right) \cdot \left(x_2 - \bar{x}_2\right)^2,\ z_{12} = \left(x_2 - \bar{x}_2\right)^2 \cdot \left(x_3 - \bar{x}_3\right),\ z_{13} = \left(x_2 - \bar{x}_2\right) \cdot \left(x_3 - \bar{x}_3\right)^2,\ z_{14} = \left(x_3 - \bar{x}_3\right)^2 \cdot \left(x_1 - \bar{x}_1\right),\ z_{15} = \left(x_3 - \bar{x}_3\right) \cdot \left(x_1 - \bar{x}_1\right)^2,\ z_{16} = \left(x_1 - \bar{x}_1\right) \cdot \left(x_2 - \bar{x}_2\right) \cdot \left(x_3 - \bar{x}_3\right),\ z_{17} = \left(x_1 - \bar{x}_1\right)^2 \cdot \left(x_2 - \bar{x}_2\right)^2,\ z_{18} = \left(x_2 - \bar{x}_2\right)^2 \cdot \left(x_3 - \bar{x}_3\right)^2,\ z_{19} = \left(x_3 - \bar{x}_3\right)^2 \cdot \left(x_1 - \bar{x}_1\right)^2,\ z_{20} = \left(x_1 - \bar{x}_1\right)^2 \cdot \left(x_2 - \bar{x}_2\right) \cdot \left(x_3 - \bar{x}_3\right),\ z_{21} = \left(x_1 - \bar{x}_1\right) \cdot \left(x_2 - \bar{x}_2\right)^2 \cdot \left(x_3 - \bar{x}_3\right),\ z_{22} = \left(x_1 - \bar{x}_1\right) \cdot \left(x_2 - \bar{x}_2\right) \cdot \left(x_3 - \bar{x}_3\right)^2,\ z_{23} = \left(x_1 - \bar{x}_1\right) \cdot \left(x_2 - \bar{x}_2\right)^2 \cdot \left(x_3 - \bar{x}_3\right)^2,\ z_{24} = \left(x_1 - \bar{x}_1\right)^2 \cdot \left(x_2 - \bar{x}_2\right) \cdot \left(x_3 - \bar{x}_3\right)^2,\ z_{25} = \left(x_1 - \bar{x}_1\right)^2 \cdot \left(x_2 - \bar{x}_2\right)^2 \cdot \left(x_3 - \bar{x}_3\right) \text{ and } z_{26} = \left(x_1 - \bar{x}_1\right)^2 \cdot \left(x_2 - \bar{x}_2\right)^2 \cdot \left(x_3 - \bar{x}_3\right)^2$$

where $\bar{x}_1$, $\bar{x}_2$ and $\bar{x}_3$ are the arithmetic means of x_1, x_2 and x_3, respectively.

Equation 5 is further rewritten with the variables z_i as the following:

$$\hat{\sigma} = \sum_{i=0}^{26} C_i' z_i \qquad (7)$$

where C_0' through C_{26}' are unknown parameters, the values of which can be determined by the least-squares method using experimental data.

The coefficient of each similar term in Equation 5 should be equal to that of the corresponding similar term in the expansion equation of Equation 7. This requirement provides 26 equations connecting C_i in Equation 5 and C_i' in Equation 7. Thus, the values of C_i in Equation 5 are straightforwardly obtained using the 26 equations and the determined values of C_i' in Equation 7.

Calculated Results

The determined model expressed in Equation 5 is given by

$$\hat{\sigma} = 0.990267 - 5.40196y_1 + 0.349258y_2 - 20.5886y_3 - 128.124y_4 + 0.631925y_5 + 786.873y_6 + 3.70242y_7 - 47.0691y_8 + 568.712y_9 + 238.990y_{10} + 16.7892y_{11} - 93.2564y_{12} + 2371.87y_{13} - 18882.5y_{14} + 20536.1y_{15} + 880.058y_{16} - 249.690y_{17} + 862.649y_{18} - 857794y_{19} - 43648.6y_{20} -$$

$$1376.69y_{21} - 67812.3y_{22} + 52679.7y_{23} + 1863560y_{24} + 29622.9y_{25} - 1002250y_{26} \quad (8)$$

for the joints resistance brazed with Ti-Zr-Ni-Cu filler metal and

$$\hat{\sigma} = 0.471453 - 0.0706636y_1 + 0.0708294y_2 + 2.05003y_3 + 0.330522y_4 + 0.0459062y_5 - 31.3718y_6 - 0.776454y_7 + 7.90254y_8 + 10.0663y_9 + 1.32587y_{10} - 0.997871y_{11} - 2.57078y_{12} - 17.0537y_{13} - 397.840y_{14} - 33.8689y_{15} + 29.8881y_{16} + 0.805031y_{17} - 64.3148y_{18} + 1.94237y_{19} - 10.6362y_{20} - 0.190932y_{21} + 191.315y_{22} + 227.238y_{23} + 167.302y_{24} - 6.27958y_{25} - 237.479y_{26} \quad (9)$$

for the joints resistance brazed with Ni-Cu filler metal. The values of the reference standard quantities, σ_B^*, i_1^*, i_2^* and i_3^*, are 485 MPa (70.3 ksi), 33.3 A, 31.3 A and 32.2 A for Equation 8 and 508 MPa (73.7 ksi), 40.4 A, 34.1 A and 34.8 A for Equation 9, respectively. As mentioned previously, each set of values corresponds to the joint with the highest measured tensile strength among the joints. When the three extremum values in the electric current curve measured — i_1, i_2 and i_3 — are given, the values of the dimensionless variables of y_1 through y_{26} in Equations 8 and 9 can be determined using Equation 6 and the definitions of x_1, x_2 and x_3. Thus, Equations 8 and 9 enable prediction of the dimensionless tensile strength of the resistance-brazed joints. The predicted dimensionless tensile strength, $\hat{\sigma}$, can be transformed to the dimensional tensile strength, $\hat{\sigma}_B$, using the definition $\hat{\sigma}_B = \hat{\sigma} \cdot \sigma_B^*$.

Figure 6 shows the relationship between the tensile strength predicted by Equation 8 and the measured tensile strength for the joints resistance brazed with Ti-Zr-Ni-Cu filler metal. Figure 7 also shows the relationship between the tensile strength predicted by Equation 9 and the measured tensile strength for the joints resistance brazed with Ni-Cu filler metal. If the predictions are perfect, all data points plotted in Figs. 6 and 7 should lie on the solid straight lines drawn in these figures. However, these figures indicate there is some degree of variability. From the evaluation of the multiple correlation coefficient adjusted for the degrees of freedom, the efficacy of Equations 8 and 9 as a predictor can be assessed (Ref. 10). The closer the value is to unity, the greater the fitting quality and prediction accuracy of the equation. The calculations show the values are 0.883 for Equation 8 and 0.884 for Equation 9, indicating they are relatively close to unity. The root-mean-square error (RMSE) of prediction gives an estimate of standard deviation of prediction residual that can be used to evaluate the approximate confidence interval, explained below.

A 95% confidence interval = ±1.96 RMSE (Ref.11). The 95% confidence interval is ±58.0 MPa (8.41 ksi) for Equation 8 and ±45.5 MPa (6.60 ksi) for Equation 9. From Figs. 6 and 7, it can be seen all data points lie within the 95% confidence interval. Thus, the model equation expressed in Equation 5 appears to be effective for predicting the tensile strength of resistance-brazed joints.

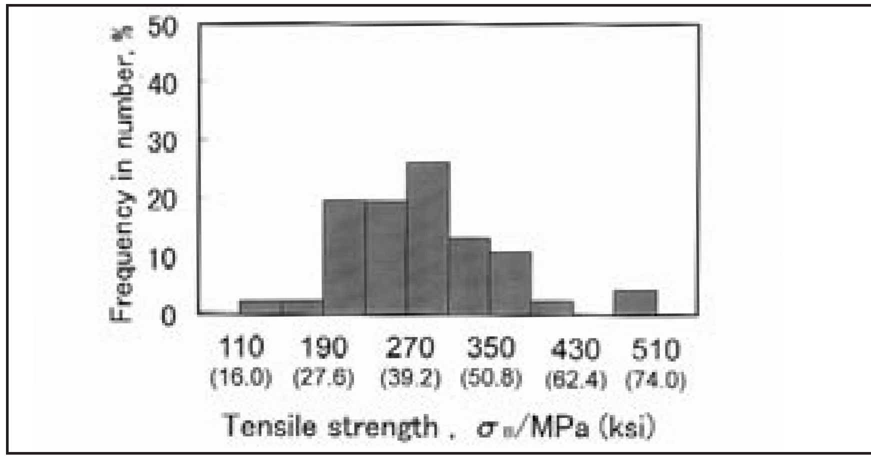

Fig. 4 — Histogram for measured tensile strength of joints resistance brazed with Ni-Cu filler metal.

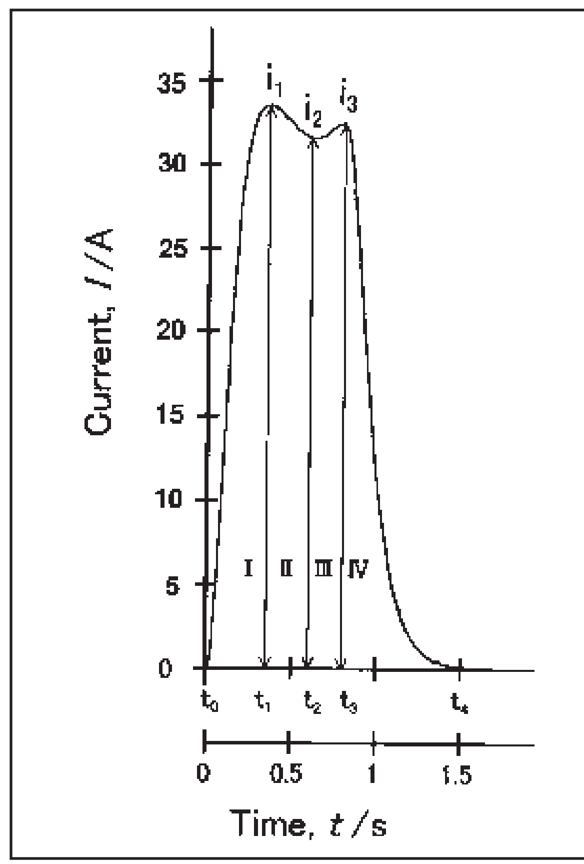

Fig. 5 — Typical electric current curve.

Results and Discussion

Improvement of Prediction

Although the calculated results using the model equation expressed in Equation 5 show good agreement with the experimental data, further experiments and modeling should be performed to improve prediction methods of the tensile strength of resistance-brazed joints.

The response time of the transducer used in the present work was 0.25 s. Since this response time is not sufficiently short to be compared with the energizing time of 0.8 s, there will be some degree of error in the electric current measurement. As stated previously, the unknown parameters in the model equation were determined using experimental data, including this error. Therefore, if the degree of error in the experimental data can be reduced using a transducer with a shorter response time, the prediction model equation could be greatly improved.

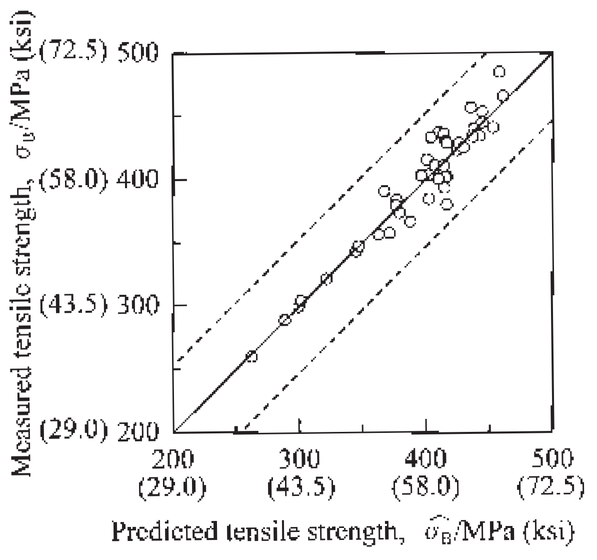

Fig. 6 — Relationship between measured and predicted tensile strength of joints resistance brazed with Ti-Zr-Ni-Cu filler metal. Two dashed lines indicate an approximate 95% confidence interval.

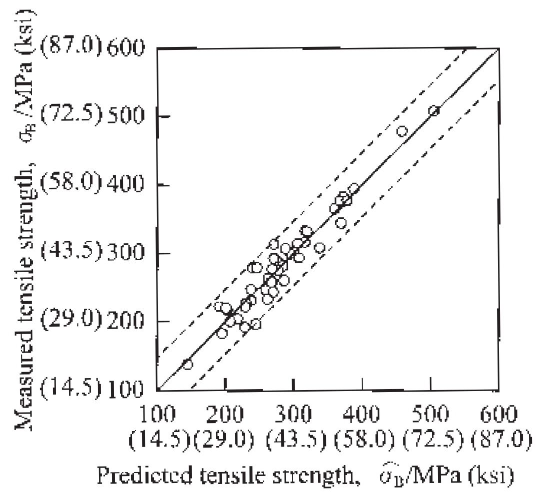

Fig. 7 — Relationship between measured and predicted tensile strength of joints resistance brazed with Ni-Cu filler metal. Two dashed lines indicate an approximate 95% confidence interval.

The model equation expressed in Equation 5 was derived by making some assumptions. To improve the prediction model equation, these assumptions should be confirmed experimentally by examining the compositional change in the solidified filler metal and by measuring the spacing between the base metals. These experimental results may enable a better model equation to be derived with respect to the three extremum values in the electric current during resistance brazing, leading to improved prediction of the tensile strength of resistance-brazed joints.

Conclusions

The results of the present work provided the following conclusions.

1) During resistance brazing, the electric current passing through the primary circuit of the transformer changes in relation to the three extremum values, i_1, i_2 and i_3. The electric current rapidly increased to the first maximum value, i_1, then gradually decreased to the minimum value, i_2, and finally gradually increased to the second maximum value, i_3.

2) The tensile strength of resistance-brazed joints was predicted using a model equation expressed in the form of a polynominal in three variables of i_1, i_1–i_2 and i_2/i_3. The predicted tensile strength of Ti-10 wt-% Zr alloy joints resistance brazed with Ti-20 wt-% Zr-20 wt-% Ni-20 wt-% Cu or Ni-50 wt-% Cu filler metal agreed well with experimental data. The values of the multiple correlation coefficient adjusted for the degrees of freedom were 0.883 for Ti-20 wt-% Zr-20 wt-% Ni-20 wt-% Cu filler metal and 0.884 for Ni-50 wt-% Cu filler metal.

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