Mechanisms of Power Dissipation in the Column of High Pressure Argon-Tungsten Arcs

Models are developed that predict the influence of main arcing variables on power dissipation over pressures ranging from 1 to 42 bars, or 1 to 41 atmospheres.

BY C. J. ALLUM

Abstract. Manual hyperbaric welding may now be regarded as a well established subsea repair and maintenance technique to water depths of at least 200 meters (≈650 ft). Manned trials do, however, indicate (Ref. 1) that physiological limitations will prohibit the fully manual use of this technique beyond about 400 meters (≈1300 ft). For such applications it appears presently that the role of the welder-diver will have to be supplemented by a degree of process automation. These developments will require a greater appreciation of process behavior than has hitherto been necessary.

In this paper, simple models are developed with the aim of understanding the influence of the main arc variables (with emphasis on ambient pressure) on power dissipation in a gas tungsten arc. Predictions are compared with experimental findings obtained by operating such arcs in pressure chambers over the range 1-42 bars, i.e., approximately 1 to 41 atmospheres.*

Introduction

Argon-tungsten arcs have long been used as heat sources for welding under normal ambient conditions. During the past ten years such arcs have also been used for underwater welding tasks. In this application the arc is usually operated in a dry high pressure (equivalent to water depth) environment constructed around the region to be welded.

The nature of the arc heat source and the suitability for use in welding is significantly influenced by ambient pressure. The influence of pressure on the characteristics of the column of such a heat source forms the basis of the present paper.

The most obvious influences of pressure are on arc appearance and operating voltage. It is generally observed that the column contracts and appears more luminous while voltage increases. These changes clearly mirror pressure-dependent energy exchanges. Experimental results presented here give details of the pressure dependence of arc voltage and radiative output, and a simple model is developed to explain many of these observations. Abbreviations and symbols for the terms used to describe the model during its development are defined in Table 1.

Experimental Results

Experiments have been performed in pressure chambers, such as shown in Fig. 1, over the range 1 to 42 bars. The principle arc form investigated was the free-burning gas tungsten arc in argon and helium environments. Such arcs were run on steel anodes (stationary and moving) and cooled-copper anodes.

Typical voltage characteristics obtained during these experiments are shown in Figs. 2 and 3. It can be seen that arc voltage (V) increases with pressure. However, the increase is such that the extrapolated zero arc length voltage ($V_0$) is largely independent of pressure. Changes in arc voltage are, therefore, due to pressure dependent phenomena in the column (voltage contribution, $V_c$). $V_0$ is also little influenced by arc current (at least for the 150 A > I > 75 A investigated).

Figure 3 shows that $V_0$ may be given by $9 - 10$ V for an argon-copper, gas-work piece combination. Other combinations not shown here (Ref. 2) give $8 ± 1$ V for Ar-Fe, $≈ 10$ V for He-Fe and $≈ 15$ V for He-Cu. It can also be seen from Fig. 3 that arc voltage has a substantially linear dependence on arc length (I) for short arcs. Thus $V_c = E L$ where $E$ is defined by the short arc gradient of the $V$-I characteristic. Values of $E$ obtained in this manner are shown in Fig. 4 for $I = 100$ A. It can be seen that $E$ may be quite well represented by a square root of pressure law for all arc conditions considered. The nature of the $V$-I characteristic (Fig. 2) is such that $E$ is not very

*1 bar = 0.987 atmosphere (atm).


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Fig. 1—Pressure chamber (operating range: 1–135 bars)
Table 1—Abbreviations with Definitions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>I</td>
<td>Arc Current</td>
</tr>
<tr>
<td>V</td>
<td>Total Voltage</td>
</tr>
<tr>
<td>$V_a$</td>
<td>Zero arc length voltage</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Column Voltage Contribution</td>
</tr>
<tr>
<td>E</td>
<td>Electric field strength (V/mm)</td>
</tr>
<tr>
<td>I</td>
<td>Arc length (mm)</td>
</tr>
<tr>
<td>P</td>
<td>Ambient pressure (bars)</td>
</tr>
<tr>
<td>Q</td>
<td>Total Power loss from column (Watts)</td>
</tr>
<tr>
<td>Q(cv)</td>
<td>Convective Power loss from column (Watts)</td>
</tr>
<tr>
<td>Q(R)</td>
<td>Radiated Power loss from column (Watts)</td>
</tr>
<tr>
<td>Q(t)</td>
<td>Conductive Power loss from column (Watts)</td>
</tr>
<tr>
<td>h</td>
<td>Enthalpy</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Electrical Conductivity</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Thermal Conductivity</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Average temperature difference between arc axis and boundary (k)</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>Plasma density at 1 bar</td>
</tr>
<tr>
<td>$\rho_{a,1}$</td>
<td>Density of cool surrounding atmosphere at 1 bar</td>
</tr>
<tr>
<td>$q(T)$</td>
<td>Average column radiative source strength (Watts/m$^2$)</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Permeability of free space</td>
</tr>
<tr>
<td>r</td>
<td>Arc radius at cathode</td>
</tr>
<tr>
<td>R</td>
<td>Arc radius near anode</td>
</tr>
<tr>
<td>$r = \frac{A}{I}$</td>
<td>Arc volume</td>
</tr>
<tr>
<td>$A = \pi R^2$</td>
<td>Arc cross-sectional area near anode</td>
</tr>
<tr>
<td>d</td>
<td>Dimensionless geometric factor</td>
</tr>
<tr>
<td>$I = \frac{1}{A}$</td>
<td>Arc current density</td>
</tr>
<tr>
<td>$B$</td>
<td>Magnetic field strength</td>
</tr>
<tr>
<td>$u$</td>
<td>Plasma flow velocity</td>
</tr>
<tr>
<td>$\bar{U}$</td>
<td>Radially averaged plasma flow velocity (m/s)</td>
</tr>
<tr>
<td>$\beta_m$</td>
<td>Value of $\beta$ when magnetic forces dominate</td>
</tr>
<tr>
<td>$\beta_b$</td>
<td>Value of $\beta$ when buoyancy forces dominate</td>
</tr>
<tr>
<td>$F$</td>
<td>Axial force (units of N)</td>
</tr>
<tr>
<td>$F_m$</td>
<td>Axial force (magnetic) (units of N)</td>
</tr>
<tr>
<td>$F_b$</td>
<td>Axial force (Buoyancy) (units of N)</td>
</tr>
<tr>
<td>$h$</td>
<td>Natural logarithm</td>
</tr>
<tr>
<td>$F = h(R/r)$</td>
<td>Stagnation pressure at anode (N/m$^2$)</td>
</tr>
<tr>
<td>$P$</td>
<td>Reynolds number of plasma flow</td>
</tr>
<tr>
<td>$\phi, \psi, \phi(cv), \phi(cv)b$</td>
<td>Thermodynamic functions defined in text</td>
</tr>
<tr>
<td>$\alpha, \beta, \gamma, \delta, \epsilon, \mu, \nu, \omega$</td>
<td>Dimensionless constants</td>
</tr>
</tbody>
</table>

Table 2—Percentage of Arc Column Power Radiated from an Argon Column (Bracketed Percentages for Helium), %

<table>
<thead>
<tr>
<th>Pressure, bars</th>
<th>Radiated arc column power for indicated arc currents, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>For 50 A</td>
</tr>
<tr>
<td>1</td>
<td>13.4</td>
</tr>
<tr>
<td>7.8</td>
<td>14.6</td>
</tr>
<tr>
<td>21.4</td>
<td>19.3</td>
</tr>
<tr>
<td>41.2</td>
<td>18.9</td>
</tr>
</tbody>
</table>

$^{(a)}$ 50 A results not included in averages.
than $E$, but for the present purposes the data are expressed as

$$Q(R) = (0.22 \pm 0.04) \cdot E \cdot I,$$

i.e., $22 \pm 4\%$ of $Q$.

\[ (2) \]

Discussion

An attempt is made to understand the voltage dependence on pressure, arc length and current by the use of a simple model describing the components of $Q$.

For helium arcs a much smaller fraction leaves the arc as radiation.

This model assumes that temperature conditions within the column are little influenced by pressure and that enthalpy ($h$) as well as the electrical ($\sigma$) and thermal ($\kappa$) conductivities are pressure insensitive.

For many purposes these assumptions are not unrealistic over the temperature range encountered in GTA arcs. (The pressure insensitivity of $\sigma$ and $\kappa$ for argon near 12,000 K or 22,000°F is somewhat surprising. However, such results have been obtained by Devoto (Ref. 4), and more recently by Kannappan and Bose (Ref. 12). The pressure dependence is then almost entirely density ($p$) dependent. Convective dissipation can be written as

$$Q(CV) \approx p \cdot A \cdot \bar{u}$$

where $\bar{u}$ is the average axial velocity across an area $A (= \pi R^2)$ near the anode. $\bar{u}$ may be estimated from momentum flux ($F$) considerations. The behavior of $\bar{u}$ depends on the mechanism of momentum generation. If convection is generated by a $J \times B$ interaction, then:

$$F_m = \int_0^\infty \rho u^2 dA \approx \frac{\rho \bar{u}^2}{4 \pi R} \cdot \frac{R}{r}$$

where $r$ is the arc radius near the cathode. This enables a root mean square velocity $\bar{u}(rms)$ to be defined. Equating this to the mean value $\bar{u}$ gives

$$\bar{u} = \sqrt{\frac{\rho \bar{u}^2}{4 \pi p A}}$$

\[ (5) \]
Additional expressions are required for arcs in cross-flows (Ref. 6) or where swirl exists.
An estimate of \( Q(CV) \) may be obtained in an approximate manner from:

\[
Q(CV) = 2\pi \cdot \Delta T \cdot I
\]

where end effects are neglected and \( \Delta T \) is the temperature difference between arc axis and surface (assumed linear). For parabolic temperature profiles \( Q(K) \) is readily shown to be twice the value. However, this is not important to the present argument, because only qualitative predictions are made.

The most difficult behavior to justify with a simplistic description is net radiation from the column. As a first approximation it is assumed that radiative processes increase in proportion to the number of radiating particles. Referring to the literature (Ref. 7), it is also assumed that radiation leaving the arc increases in a similar manner:

\[
Q(R) = P \cdot \tau \cdot q(T)
\]

where \( q(T) \) is some function of temperature (Refs. 7 and 8) averaged over the temperature field of the arc volume \( r \) and \( P \) the absolute pressure in bars.

These equations may be combined to give:

\[
I \cdot V_c = \rho A 0 + 2\pi K \cdot \Delta T \cdot I / P \cdot \tau \cdot q(T)
\]

where \( \tau \) depends on the mechanism of momentum generation. \( V_c \) may be related to the relevant variables by Ohm's law:

\[
V_c = I \cdot \rho \cdot A
\]

Combining these expressions gives an equation that may be regarded as a fourth order in \( R \). For the present purposes it is sufficient to examine the general behavior of \( R \) when one mechanism dominates. The form of the equations is such that it is then possible to obtain relationships of the type:

\[
R = \Phi^b \cdot P^c \cdot P^P
\]

where \( \Phi \) and \( \Phi \) are principally thermodynamic functions and \( a, b, c, \alpha, \beta, \gamma \) are given in Table 3.

The predicted pressure dependence of these models is remarkably similar with the exception of the purely conductive arc, i.e., the pressure dependence of column voltage is between 0.33 and 0.50 which is in fair agreement with the observed pressure dependence of \( E \). Similarly, the column contracts from \(-0.17\) to \(-0.25\) which is precisely the range observed in practice. On this basis it is difficult to distinguish the dominant mechanisms in high pressure arcs.

Table 3—Dependence of Arc Voltage and Radius on Arcing Parameters for Different Arc Models

<table>
<thead>
<tr>
<th>( \Phi )</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM (magnetic)</td>
<td>( \Phi^{CV/m} )</td>
<td>+0.33</td>
<td>+0.33(a)</td>
<td>-0.17</td>
<td>+0.33</td>
<td>+0.33(b)</td>
</tr>
<tr>
<td>CV (buoyancy)</td>
<td>( \Phi^{CV/b} )</td>
<td>+0.50</td>
<td>+0.50</td>
<td>0.00</td>
<td>+0.50</td>
<td>+0.50</td>
</tr>
<tr>
<td>R</td>
<td>( \Phi^{R} )</td>
<td>+1.00</td>
<td>+1.00</td>
<td>0.00</td>
<td>+1.00</td>
<td>+1.00</td>
</tr>
<tr>
<td>k</td>
<td>( \Phi^{k} )</td>
<td>+1.00</td>
<td>+1.00</td>
<td>0.00</td>
<td>+1.00</td>
<td>+1.00</td>
</tr>
</tbody>
</table>

(a) Valid only for arcs long enough such that \( T \) changes slowly with \( \rho \).

where \( \Phi \) is a geometrical factor (e.g., \( 1 \) for a cylindrical column), \( \rho \) is the column density at 1 bar and \( \rho_{\infty} \), the cool ambient gas density.

Table 3—Dependence of Arc Voltage and Radius on Arcing Parameters for Different Arc Models

<table>
<thead>
<tr>
<th>( \Phi^{CV/m} )</th>
<th>( \Phi^{CV/b} )</th>
<th>( \Phi^{R} )</th>
<th>( \Phi^{k} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.33</td>
<td>+0.33(b)</td>
<td>+0.33</td>
<td>+0.33(b)</td>
</tr>
</tbody>
</table>

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treatment given to this problem.

A firmer indication of the relative importance of the various mechanisms is given by the nature of the V-l characteristic. Only in convective arcs is a rising characteristic predicted. Indeed, weakly rising characteristics are often observed for argon arcs—Fig. 2. This explains why the effect of pressure on V diminishes as arc current is reduced, i.e., the conductive term diminishes.

Helium arcs exhibit negative characteristics indicating conductive behavior. Such behavior is complicated by the emergence of a powerful arc jet with increasing pressure (Ref. 9), thereby enhancing the pressure dependence of arc voltage. However, the low density and high thermal conductivity of helium ensures that conduction remains dominant—see equations (6) and (9).

The influence of turbulence may be incorporated by using suitable values for \( \kappa \). \( \kappa \) is known to increase dramatically under such conditions (Ref. 10). This appears to be required at high pressures if the observed dependence of arc voltage on shielding gas flow rate (Ref. 9) is to be explained. Further to this, the column is predicted to contract in turbulent flows, i.e., \( \mathrm{Re} \propto \kappa^{-0.5} \). This gives an explanation of the shielding gas flow dependence of arc radius observed experimentally.

It may be seen from Table 3 that only convective arcs diverge significantly between anode and cathode. Expansion is associated with entrainment and is strongest in /\( J \times B \)/ dominated columns. Table 3 also shows that radiative and conductive arcs are expected to have more or less linear arc voltage-arc length dependencies. Such a result is in agreement with the highly linear dependence of \( V \) observed in helium based (40 cfm He and 10폭/min or 21 cfm Ar) arcs—even at long arc lengths (Ref. 11).

Conclusions

The simple model developed here throws some light on the observed pressure dependence of arc characteristics. In particular it is shown that argon GTAW arcs undergo a slow transition from /\( J \times B \)/ convectively dominated at 1 bar to being strongly influenced by other factors (buoyancy, radiation, turbulence) at very high pressures. Similarly, helium arcs become increasingly influenced by convection with pressure, thereby explaining the observed pressure dependence of arc voltage.

Acknowledgments

The author wishes to thank the SERC for funding this work.

Appendix

Simple expressions introduced in the text may be used to indicate the influence of pressure on a range of arc properties. This is possible only because of the simple manner in which pressure dependence can be separated from other effects, i.e., it is generally possible to express this by a simple power law scaling factor of the form \( p^\alpha \). Values of \( \alpha \) are given in Table 4 in terms of \( n \) where arc radius \( (R) \) is proportional to \( p^{-n} \).

A full discussion of these results is not given here. However, it is interesting to note some implications for weld pool behavior. The increase in stagnation pressure, despite the insensitivity of \( J \times B \)/ force, should result in significantly greater pool depressions. Also, the increase in column Reynolds number should lead to enhanced heat transfer from the column to the pool. Weld pool geometry is also likely to change as a result of an increase in current density, i.e., indigenous /\( J \times B \)/ weld pool flow will be stronger and the arc will be a more point-like heat source.

References

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Klueh, R.L., King, J.F. and Griffith, J.L. — A Simple Test for Dissimilar-Metal Welds, 154-s to 159-s (June).
Kobayashi, M., Maki, S., Hashimoto, Y., and Suga, T. — Investigations on Chemical Composition of Welding Fumes, 190-s to 196-s (Jul).
Korolk, P.J. — Effects of Electrode Composition, Flux Basicity, and Slag Depth on Grain-Boundary Cracking in Electroslag Weld Metals, 63-s to 71-s (Mar).
Kujanpaa, V.P. — Weld Defects in Austenitic Stainless Steel Sheets — Effect of Welding Parameters, 45-s to 52-s (Feb).

Lathabai, S. and Stout, R.D. — Hydrogen-Induced Cracking in Flux Cored Electrode Welds, 58-s to 62-s (Mar).
Lippold, J.C. — An Investigation of Heat-Affected Zone Hot Cracking in Alloy 800, 1-s to 11-s (Jan).
Lippold, J.C. and Odegard, B.C. — Technical Note: Microstructural Evolution During Inertia Friction Welding of Austenitic Stainless Steels, 361-s to 364-s (Dec).
Odegard, B.C. and Lippold, J.C. — Technical Note: Microstructural Evolution During Inertia Friction Welding of Austenitic Stainless Steels, 361-s to 364-s (Dec).
Oshita, S., Saito, S. and Yurioka, N. — Determination of Necessary Preheating Temperature in Steel Welding, 147-s to 153-s (June).
Ovejero-Garcia, J., Morgenfeld, J.l. and Solari, M. — Technical Note: Metallographic Sulphur Determination by SEM in Austenitic Stainless Steel Weld Metal, 143-s to 146-s (May).
Owusu-Ofori, S.P. and Wu, S.M. — Signature Analysis of Contact Voltage of Resistance Welds, 185-s to 189-s (Jul).

Partz, K.D. and Lugscheider, E. — High Temperature Brazing of Stainless Steel with Nickel-Base Filler Metals BNI-2, BNI-5 and BNI-7, 160-s to 164-s (June).
Lugscheider, E. and Pelster, H. — Nickel Base Filler Metals of Low Precious Metal Content, 261-s to 266-s (Oct).
Maki, S., Hashimoto, Y., Suga, T., and Kobayashi, M. — Investigations on Chemical Composition of Welding Fumes, 190-s to 196-s (Jul).
Moon, D.W. and Metzbower, E.A. — Laser Beam Welding of Aluminum Alloy 5456, 54-s to 58-s (Feb).
Morris, Jr., J.W. and Kim, H.K. — The Development of a Ferritic Consumable for Welding Grain-Refined Fe12Ni0.25Ti to Retain Toughness at 4.2 K, 210-s to 219-s (Aug.)
Munson, W.H. and Bowmar, M.D. — Fatigue Behavior of Welded Steel Butt Joints Containing Artificial Discontinuities, 36-s to 44-s (Feb).
Nunes, Jr., A.C. — An Extended Rosenthal Weld Model, 165-s to 170-s (June).
Odegard, B.C. and Lippold, J.C. — Technical Note: Microstructural Evolution During Inertia Friction Welding of Austenitic Stainless Steels, 361-s to 364-s (Dec).
Oshita, S., Saito, S. and Yurioka, N. — Determination of Necessary Preheating Temperature in Steel Welding, 147-s to 153-s (June).
Ovejero-Garcia, J., Morgenfeld, J.l. and Solari, M. — Technical Note: Metallographic Sulphur Determination by SEM in Austenitic Stainless Steel Weld Metal, 143-s to 146-s (May).
Owusu-Ofori, S.P. and Wu, S.M. — Signature Analysis of Contact Voltage of Resistance Welds, 185-s to 189-s (Jul).

Partz, K.D. and Lugscheider, E. — High Temperature Brazing of Stainless Steel with Nickel-Base Filler Metals BNI-2, BNI-5 and BNI-7, 160-s to 164-s (June).
Lugscheider, E. and Pelster, H. — Nickel Base Filler Metals of Low Precious Metal Content, 261-s to 266-s (Oct).

The text contains a variety of research papers and technical notes on welding, metal properties, and material science. It covers topics such as arc welding processes, effects of welding parameters, chemical composition of fumes, solidification cracking, and the influence of nitrogen on weld metal microstructure.
Reichenecker, W.J. — Effect of Long Term Elevated Temperature Aging on the Electrical Resistance of Soldered Copper Joints, 290-s to 294-s (Oct).

Renwick, R.J. and Richardson, R.W. — Experimental Investigation of GTA Weld Pool Oscillations, 29-s to 35-s (Feb).

Richardson, R.W. and Renwick, R.J. — Experimental Investigation of GTA Weld Pool Oscillations, 29-s to 35-s (Mar).

Roper, J., Stagner, R.T., Aden, R.J. and Heiple, C.R. — Surface Active Elements Effects on the Shape of GTA, Laser, and Electron Beam Welds, 72-s to 77-s (Mar).

Saito, S., Yurioka, N. and Oshita, S. — Determination of Necessary Preheating Temperature in Steel Welding, 147-s to 153-s (June).

Sakamoto, A. — Wetting in Vacuum-Inert Gas Partial Pressure Atmosphere Brazing, 272-s to 281-s (Oct).

Schaaf, Jr., B.W., Wilson, A.D., and Eberhard, B.J. — Friction Weld Ductility and Toughness as Influenced by Inclusion Morphology, 171-s to 178-s (Jul).

Schaereiter, H., Rabenstein, G. and Tosch, J. — Hot Cracking Problems in Different Fully Austenitic Weld Metals, 21-s to 27-s (Jan).

Schmatz, D.J. — Grain Boundary Penetration During Brazing of Aluminum, 267-s to 271-s (Oct).


Scott, M.H. and Cittos, M.F. — Tensile and Toughness Properties of Arc-Welded 5083 and 6082 Aluminum Alloys, 243-s to 252-s (Sept).

Seth, B.B. and Hattangadi, A.D. — Lamellar Tearing in Fillet Weldments of Pressure Vessel Fabrications, 89-s to 96-s (Apr).

Solari, M., Ovejero-Garcia, J. and Morgenfeld, J.I. — Technical Note: Metallographic Sulphur Determination by SEM in Austenitic Stainless Steel Weld Metal, 143-s to 146-s (May).

Stagner, R.T., Aden, R.J., Heiple, C.R. and Roper, J. — Surface Active Elements Effects on the Shape of GTA, Laser, and Electron Beam Welds, 72-s to 77-s (Mar).

Stout, R.D. and Kaufmann, E.J. — The Toughness and Fatigue Strength of Welded Joints with Buried Lamellar Tears, 301-s to 305-s (Nov).

Stout, R.D. and Lathabai, S. — Hydrogen-Induced Cracking in Flux Cored Electrode Welds, 58-s to 62-s (Mar).


Suga, T., Kobayashi, M., Maki, S., and Hashimoto, Y. — Investigations on Chemical Composition of Welding Fumes, 190-s to 196-s (Jul).


Tribau, R. and Bala, S.R. — Influence of Electroslag Weld Metal Composition on Hydrogen Cracking, 97-s to 104-s (Apr).

Thompson, A.W., Williams, J.C., and Brooks, J.A. — Variations in Weld Ferrite Content Due to P and S, 220-s to 226-s (Aug).

Thompson, R.G. and Genculu, S. — Microstructural Evolution in the HAZ of Inconel 718 and Correlation with the Hot Ductility Test, 337-s to 345-s (Dec).


Tosch, J., Schaereiter, H. and Rabenstein, G. — Hot Cracking Problems in Fully Austenitic Weld Metals, 21-s to 27-s (Jan).

Tsai, N.S. and Eager, T.W. — Temperature Fields Produced by Traveling Distributed Heat Sources, 346-s to 355-s (Dec).


Weiss, B.Z. and Grushko, B. — Effect of Strain Rate and Temperature on Yielding and Fracture Toughness of Brazed Joints of Inconel 718, 282-s to 289-s (Oct).


Wilson, A.D., Eberhard, B.J., and Schaaf, Jr., B.W. — Friction Weld Ductility and Toughness as Influenced by Inclusion Morphology, 171-s to 178-s (Jul).

Wu, S.M. and Owusu-Ofori, S.P. — Signature Analysis of Contact Voltage of Resistance Welds, 185-s to 189-s (Jul).


Yurioka, N., Oshita, S. and Saito, S. — Determination of Necessary Preheating Temperature in Steel Welding, 147-s to 153-s (June).