WEAR OF CONTACT TIPS IN GAS-METAL ARC WELDING OF TITANIUM

by

Jerome Lee LaPointe

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1984

Signature of Author: ______________________
Department of Mechanical Engineering
June 4, 1984

Certified by: ______________________
Thomas W. Eagar
Thesis Supervisor

Accepted by: ______________________
Chairman, Department Thesis Committee

WEAR OF CONTACT TIPS IN GAS-METAL ARC WELDING OF TITANIUM

by

Jerome Lee LaPointe

Submitted to the Department of Mechanical Engineering
on June 4, 1984 in partial fulfillment of the
requirements for the degree of

Bachelor of Science

ABSTRACT

Wear in copper contact tips occurs much more rapidly in gas-metal arc (GMA) welding when titanium wire is used than when steel wire is used. This rapid wear necessitates frequent changing of contact tips, which is expensive. Experiments were run to understand the wear mechanisms and factors controlling wear in the contact tip. The results of the experiments reveal that titanium's low thermal conductivity causes melting of the wire at the contact tip-wire interface. Melted titanium can build up at the contact point and can lead to jamming of the wire in the contact tip or it can "freeze" to the moving wire and abrade the softer contact tip surface. Jamming of the wire in the contact tip did not occur in this experiment.

Thesis
Supervisor: Thomas W. Eagar
Title: Associate Professor of Materials Engineering

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to thank Professor Eagar for his advice and guidance in this thesis and in my UROP work. The other students and the lab techician, Bruce Russell, have made working in the welding laboratory enjoyable and rewarding.

Finally, I would like to thank my parents, Ernest and Margaret LaPointe, for their support and guidance during my studies at M.I.T.

This thesis work was financially supported by the Office of Naval Research.

LIST OF SYMBOLS

The following symbols were used in the sliding electrical contact system:

θ	Temperature rise
i_o	Total weld current
i_i	Weld current at point i $(i = 1,2,3)$
R_i	Resistance at point i $(i = 1,2,3)$
F_i	Contact force at point i $(i = 1,2,3)$
ρ_1	Bulk resistivity of copper
ρ_2	Bulk resistivity of titanium (or steel)
p	Penetration hardness
k_1	Thermal conductivity of copper
k_2	Thermal conductivity of titanium (or steel)

The following symbols were used in the temperature distribution of the filler wire:

θ	Temperature rise
T	Temperature
i_o	Total weld current
i_i	Weld current at point i $(i = 1,2)$
λ	$\rho c/2k$

ρ	Density
c	Specific heat
k	Thermal conductivity
A	Cross-sectional area
ρ_e	Electrical resistivity
V	Velocity
L	Electrode extension
ξ	Reference distance

1.0 INTRODUCTION

1.1 General Background

In the gas-metal arc (GMA) welding process, current passes through the contact tip to the electrode, and the electrode slides through the contact tip. This welding configuration, with a hole in the contact tip slightly larger in diameter than the electrode, can be described as a sliding electrical contact system (figure 1).

It is known that contact tips wear much more rapidly when titanium wire is used in GMA welding than when steel wire is used (1,2). An accompanying phenomenon which occurs when titanium wire is used is "burnback", which is the electrical arcing between the contact tip and base metal (1). It is a common practice when GMA welding with titanium wire to change the contact tip after every pass to avoid burnback. This is an expensive procedure, consuming up to 15 times more contact tips than when welding with steel wire (2).

The intention of this study is to better understand the wear mechanisms and factors controlling wear in the contact tip so appropriate changes in the GMA welding process and equipment can be made that will minimize contact tip wear.

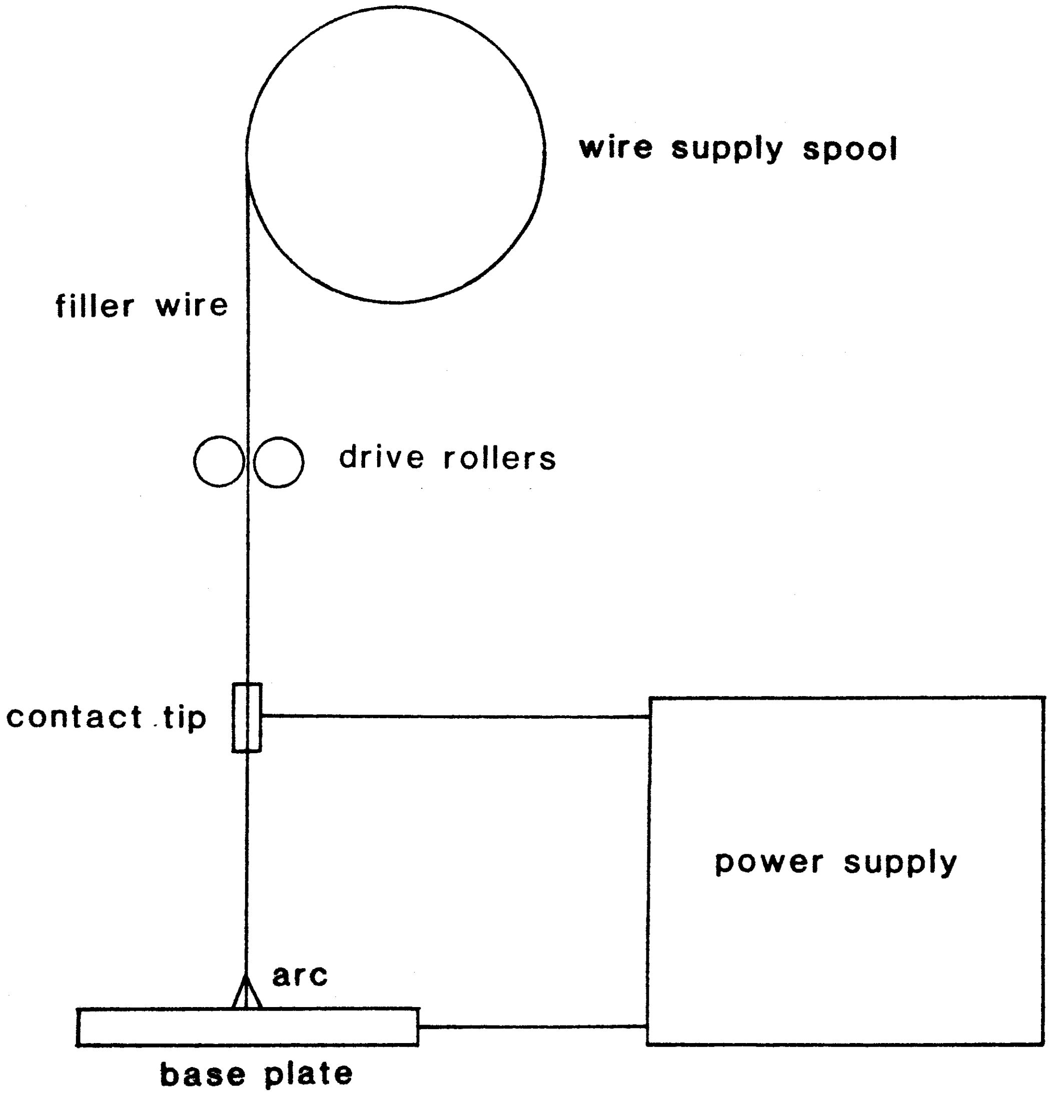

Figure 1 - Schematic of welding system

1.2 Prior Work

Ulrich looked at the problem of excessive contact tip wear in GMA welding of titanium (2). His study revealed that melting of the titanium electrode occured at points of contact within the contact tip where high interfacial temperatures developed due to titanium's low thermal conductivity. When the titanium wire melts, its contact resistance decreases, and the wire resolidifies. This "melting-freezing" of the wire, which is cyclic and forms a titanium "pad" on the inside of the contact tip, is the basis for the two types of wear encountered in the titanium wire-contact tip system. The first is the continued pad build up until the wire subsequently jams in the contact tip and the second occurs when the harder titanium pad breaks away from the contact tip, travels with the wire, and abrades the softer contact tip surface. The second type of wear is a form of adhesive and abrasive wear.

Ulrich developed an expression that predicts the temperature rise at a contact point. This equation suggests the use of bent contact tips in the GMA welding of titanium. Such a bent contact tip will produce higher contact forces and may reduce the contact resistance significantly so melting of titanium wire at the contact point will not occur.

2.0 THEORETICAL ANALYSIS

2.1 Contact Tip-Wire Configuration

As previously stated, a bent contact tip will produce larger forces at points of contact between the electrode and contact tip. Figure 2 is a drawing of the bent contact tip used in this study. The tip was bent at the tapered region, which constitutes the contact tip section. The wire, when passed through the tip, will touch the tip in at least three points. A Plexiglas model of the bent contact tip was made to determine the contact tip-wire configuration when wire is passed through it. The filler wire made contact with the tip at three points--at the bottom, at the bend, and above the bent section of the tip. See figure 3 for the configuration.

2.2 Temperature Rise at the Sliding Electrical Contact

In a sliding electrical contact system, such as the contact tip and electrode, wear is temperature related (3). Rabinowicz (3) states that in many sliding systems wear will increase rapidly when the interfacial temperature reaches a critical point known as the transition temperature. When the interfacial temperature becomes too great, one or both of the materials may soften or melt, and excessive wear will occur.

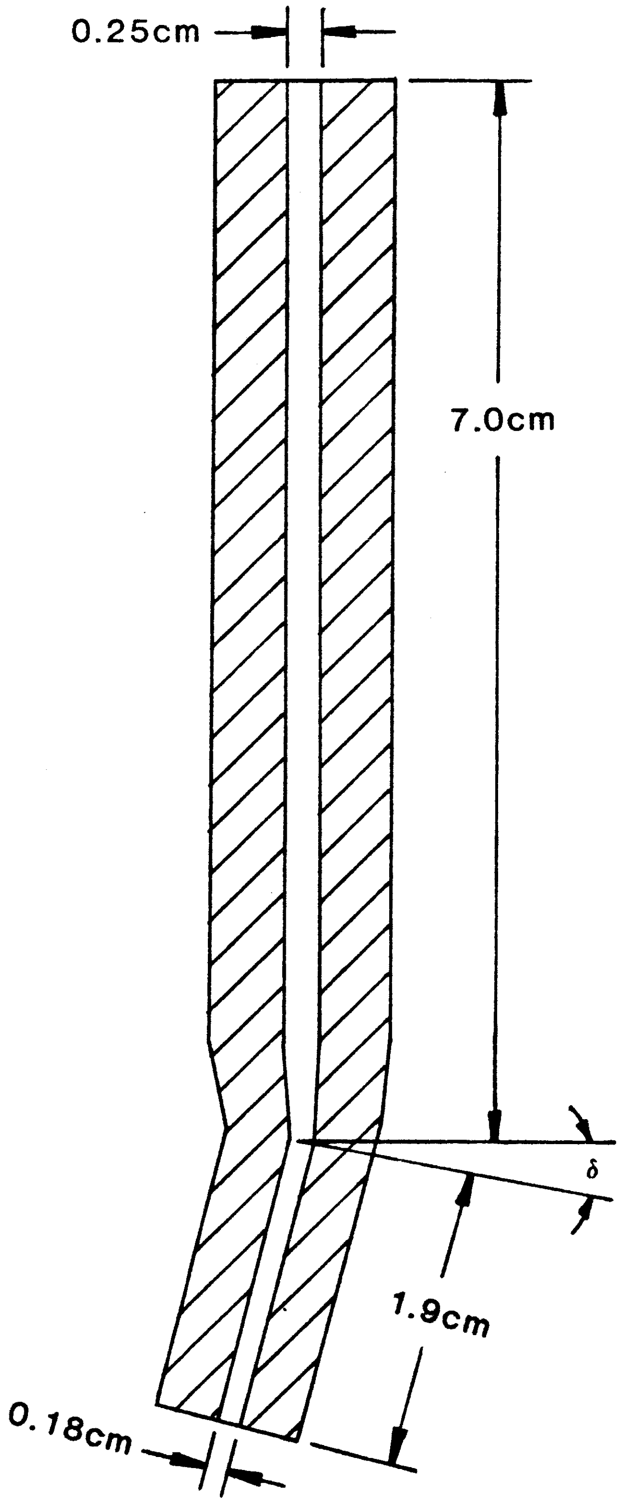

Figure 2 - Section view of bent contact tip

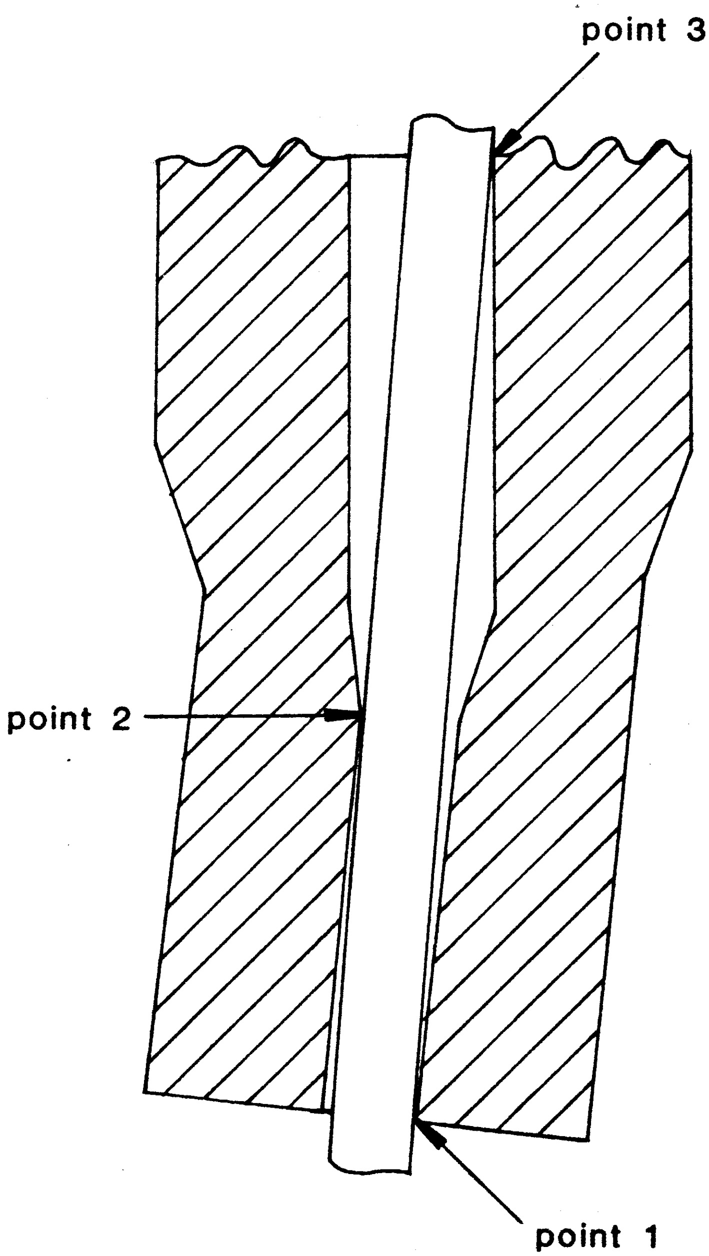

Figure 3 - Configuration of wire in contact tip

In a previous study of wear in contact tips in GMA welding of titanium, Ulrich established an expression for the temperature rise at a sliding electrical contact point which is given by:

$$\theta = \frac{(\rho_1 + \rho_2)\pi p i_o^2}{8F(k_1 + k_2)} \qquad (1)$$

This expression shows that the temperature rise at a contact point is dependent on the contact force and an increase in force will decrease the interfacial temperature, which should also decrease the rate of wear at that point.

Our bent contact tip has three contact points and equation (1) must be modified to account for this. This can be accomplished by using the relationship between resistance and force (2). The current passing through point 1 is:

$$i_1 = \frac{R_2R_3}{R_1R_2 + R_1R_3 + R_2R_3} i_o \qquad (2)$$

i_o is the total weld current (the subscripts 1-2-3 denote contact points 1-2-3 as seen in figure 3). Since force is inversely related to resistance, equation (2) can be expressed as:

$$i_1 = \frac{\sqrt{1/F_2}\sqrt{1/F_3}}{\sqrt{1/F_1}\sqrt{1/F_2} + \sqrt{1/F_1}\sqrt{1/F_3} + \sqrt{1/F_2}\sqrt{1/F_3}} i_o \qquad (3)$$

Substituting this into equation (1) results in as expression that predicts the temperature rise at point 1:

$$\theta_1 = \frac{(\rho_1 + \rho_2)\pi p i_o^2}{8(k_1 + k_2)(F_1 + F_2 + F_3 + 2\sqrt{F_1F_2} + 2\sqrt{F_2F_3} + 2\sqrt{F_1F_3}} \quad (4)$$

This expression is the same for point 2 and point 3 and suggests that the temperature rise will be the same at each point, yet the current passing through each point may not be equal.

The values of the forces were calculated from a simply supported beam representing the bending of the filler wire in the bent contact tip. See Appendix 1 for the beam configuration. Figure 4 shows the values of the forces calculated for various bent tip angles.

Using the forces calculated from the beam model, temperature rises at the contact points can be predicted. The temperature rises were predicted for various bent tip angles and the results are shown in figure 5. Table 1 shows the values for the constants used in calculating the results.

Ulrich calculated much larger temperature rises in his study. This is a result of much smaller contact forces he encountered in his system. The bent contact tip produced forces five to twenty times greater then the forces Ulrich encountered.

It should be noted that since the effect of load on

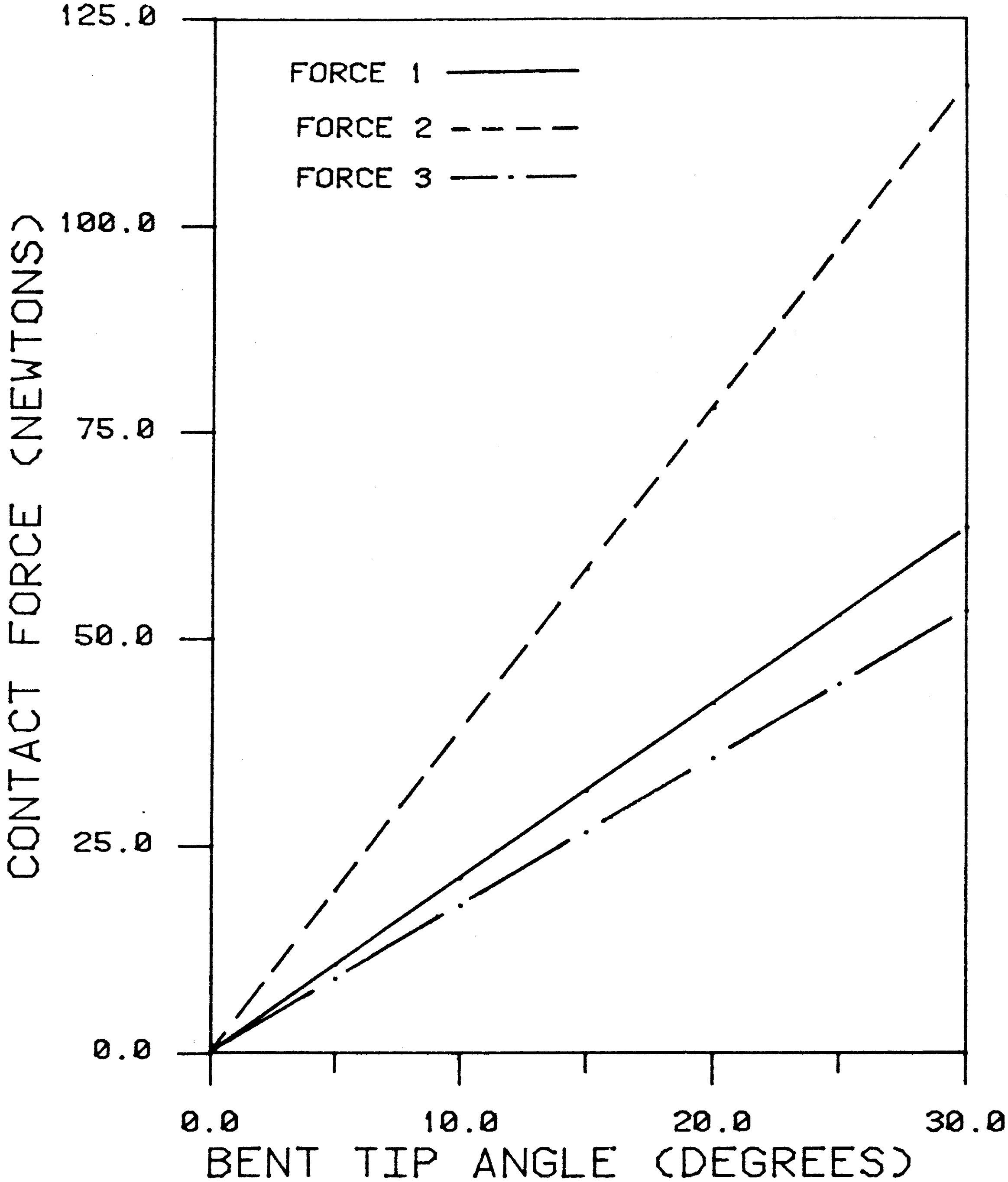

FIG. 4 - CONTACT FORCE VS.
BENT TIP ANGLE

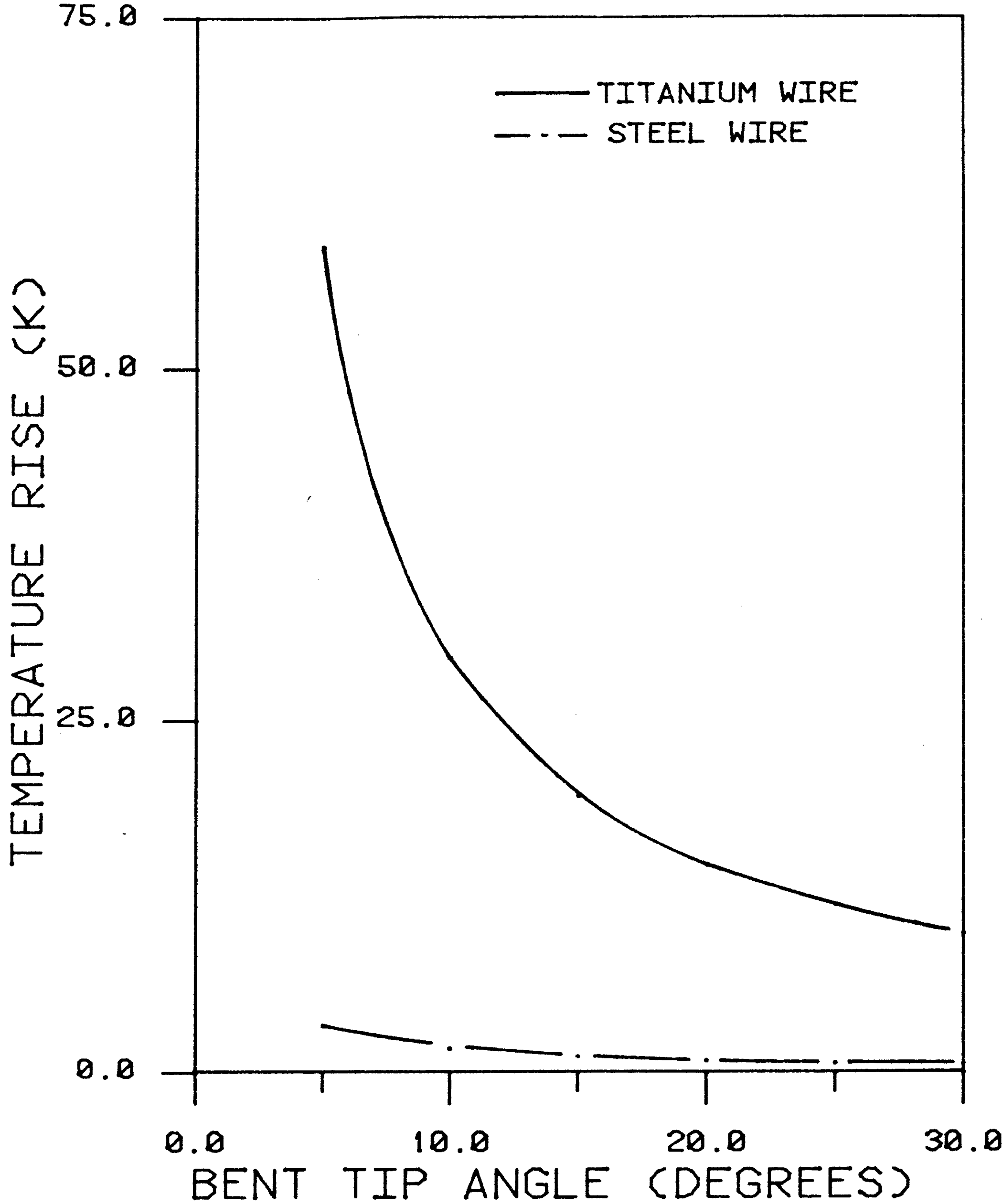

FIG. 5 - TEMPERATURE RISE VS.
BENT TIP ANGLE

Table 1 - Numerical values of constants used to predict temperature rises in the sliding electrical contact system.

constants	titanium wire	steel wire
ρ_1	1.7×10^{-8} m	1.7×10^{-8} m
ρ_2	42×10^{-8} m	10×10^{-8} m
p	2.4×10^{8} Pa	2.4×10^{8} Pa
k_1	378 W/m/K	378 W/m/K
k_2	8.4 W/m/K	50.4 W/m/K
i_o	250 A	250 A

temperature in a sliding contact system is not well known and since there are many uncertainties in these calculations, this model should only be used as a reference for materials under similar operating conditions. Wear is usually assumed to increase proportionally with load; but, our theoretical model of the sliding electrical contact system suggests that wear will decrease with increasing loads and that the load is an important parameter in controlling wear.

2.3 Temperature Distribution in a Moving Filler Wire

Since wear in an electrical contact system is temperature related, it would be useful to predict the temperature rise encountered within the contact tip and filler wire. Myers (4) has obtained a solution for the temperature distribution in a moving filler wire caused by electrical heating and it will be used in this study to estimate the temperature rise of the electrode in the contact tip. The physical situation considered is shown in figure 6. The filler wire has an extension L and is moving with a velocity V. The wire enters the contact tip with a temperature T_o (ambient) and has a temperature T_L (melting point of the filler wire) at the arc. Electrical heating of the wire is considered to take place at the entrance and exit regions of the tip, denoted by temperature rises T_1 and T_2 respectively. Myers'

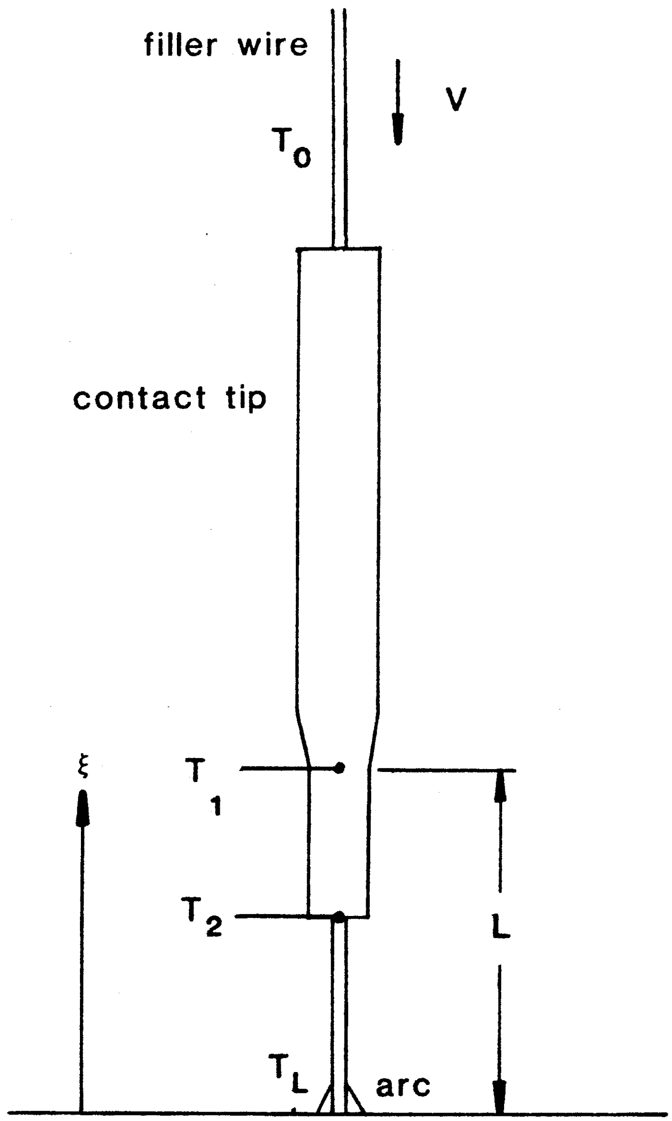

Figure 6 - Physical situation for temperature distributions in a moving feed wire

solution for this configuration is:

$$\frac{T_L - T}{T_L - T_o} = E + \frac{i_o^2 \rho_e L(-E + \xi/L)}{A^2 \rho c V(T_L - T_o)} \tag{5}$$

where

$$E = \frac{1 - \exp(-2\lambda V \xi)}{1 - \exp(-2\lambda VL)} \tag{6}$$

Assuming no heat loss in this situation, the temperature rise along the electrode extension due to electrical heating is:

$$T = T_o + \frac{i_1^2 \rho_e L}{A^2 \rho c V}(1 - \xi/L) \tag{7}$$

This is considering that point 1 is at a distance such that the effect of the arc temperature can be neglected. The temperature rise at point 2 may be obtained:

$$T_2 = \frac{i_1^2 \rho_e}{A^2 \rho c V} \Psi \tag{8}$$

where:

$$\Psi = L - \xi \tag{9}$$

Equation (9) can be expressed in terms of the current passing through point 2 and the total weld current by using the fact that the current passing through points 1 and 2 is the total weld current:

$$i_o = i_1 + i_2 \qquad (10)$$

The temperature rise of the filler wire in the contact tip then becomes:

$$\theta = \frac{(i_o^2 - 2i_o i_2 + i_2^2)\rho_e}{A^2 \rho c V} \Psi \qquad (11)$$

The temperature rise of the filler wire was calculated for various percentages of a total weld current of 250A passing through point 2. The results are shown in figure 7 and Table 2 shows the numerical values used in the calculations.

The result of the theoretical model suggests that the temperature rise of the titanium filler wire passing through the contact tip is significant; but, not high enough to cause melting of the wire. More importantly, the model suggests that the temperature distribution of the filler wire is controlled by the electrode extension. Decreasing the extension length will decrease the temperature rise of the filler wire passing through the contact tip. In GMA welding of titanium, the high temperatures and subsequent melting may be reduced

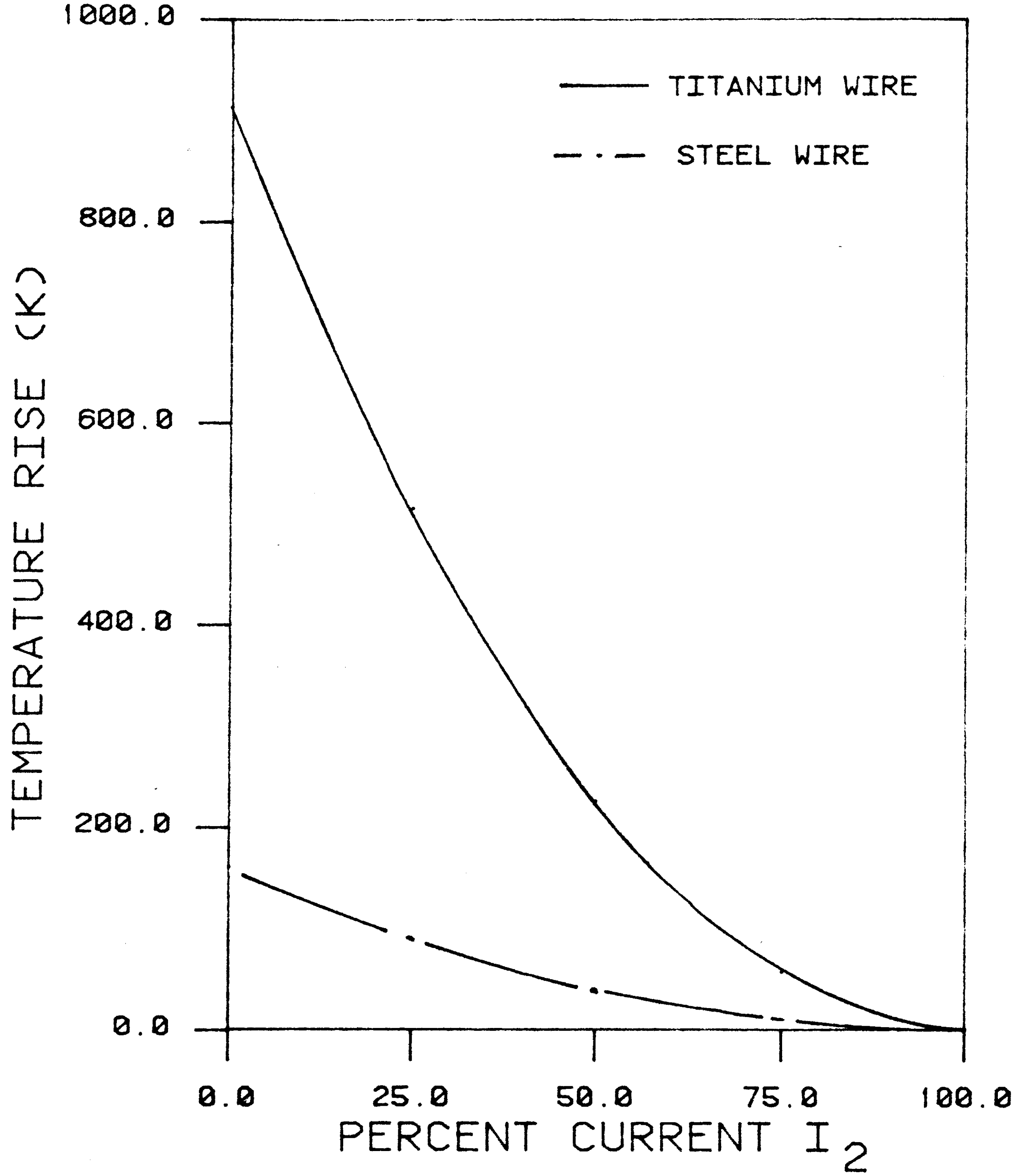

FIGURE 7 - TEMPERATURE RISE VS. PERCENT CURRENT I_2

Table 2 - Numerical values of constants used to predict temperature rises in the filler wire.

constants	titanium wire	steel wire
ρ	4539.5 kg/m^3	7750 kg/m^3
c	581.8 J/kg/K	460.4 J/kg/K
k	8.4 W/m/K	50.4 W/m/K
ρ_e	42 x 10^{-8} m	10 x 10^{-8} m
A	1.95 x 10^{-6} m^2	1.95 x 10^{-6} m^2
V	0.1 m/sec	0.1 m/sec
L	0.109 m	0.109 m
ξ	0.020 m	0.020 m
i_o	250 A	250 A

if small electrode extensions are used.

3.0 EXPERIMENTS

3.1 Apparatus

A commercially available GMA welding system was used in this experiment. The welding torch was a Linde ST-12. A Linde SCC-17A controller with a Linde J-Governor carriage drive was also used. Power was supplied by a Linde SVI-600 voltmeter was used to monitor the weld current. Figure 8 shows the experimental apparatus.

3.2 Procedure

Titanium wire and scrap steel were used to produce bead-on-plate welds. Producing satisfactory welds was not a consideration in this study since the objective was to study wear in contact tips. Two experimental parameters were used: weld time and weld current. The current was either 220A, 270A, or 350A and the weld time was either 5 min. or 10 min. in most experiments that were performed.

Six tips were run at the six possible combinations of

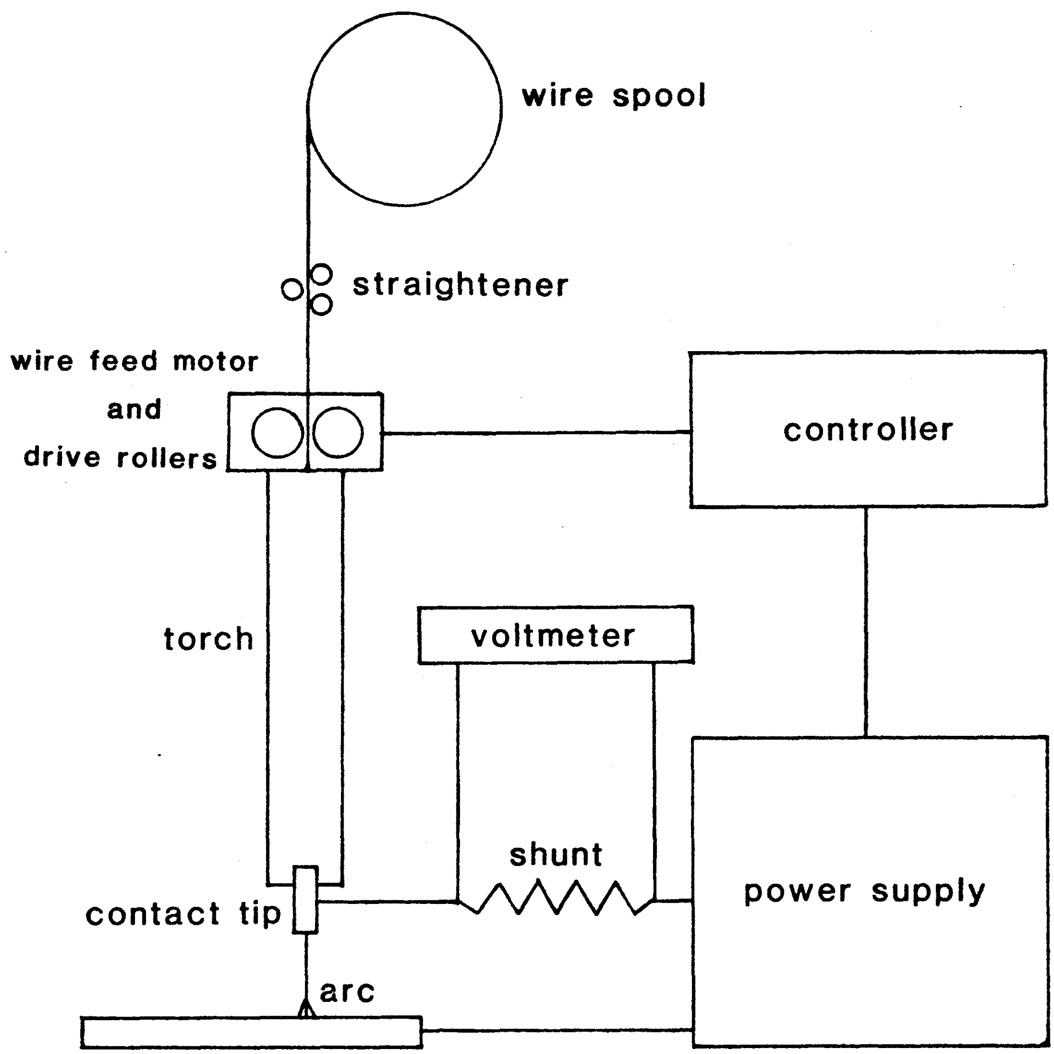

Figure 8 - Experimental apparatus

weld time and current mentioned above. An additional tip was run for 15 min. at 250A. Tips were run with steel wire for 10 min. at 350A and 15 min. at 250A. In total, 9 trials were made. All 9 trials were run with the contact tip bent at a maximum angle of 9 degrees. A greater angle would constrict the wire's movement through the contact tip or the wire would make contact with the torch nozzle.

It should be noted that wire speed and weld current are related. Higher weld currents will increase the wire speed and the amount of wire passing through the contact tip. Thus, a tip run for 10 min. at 350A had more wire passing through it than if it was run for 10 min. at 250A.

3.3 Analysis

In controlled studies, wear is usually quantified by measuring changes in weight or changes in physical dimensions of the object under study. In studying wear in GMA welding of titanium, the two methods proved useless. Weight loss measurements prove meaningless because of titanium spatter on the contact tip and measurements in changes in the inside diameter of the contact tip are prohibited because of titanium build up at the rim of the contact tip. Analysis was thus limited to examining the inner surface of the contact tip and examining the filler wire that passed through the contact tip for trends in the wear mechanisms. The contact tips were cut along the longitudinal axis with a hacksaw and examined with both an electron and an optical stereo microscope. The electrode was also examined in similar fashion.

4.0 RESULTS

4.1 Observations

The useful observations of the bent contact tips and filler wire were identical to the ones made by Ulrich in his study of wear in GMA welding of titanium. They are as follows.

The titanium wire melted at points of contact within the bent tip and this is characterized by smooth surfaces coated with titanium. Also, all the surfaces of the wire samples showed paths of melting and resolidifying.

Two broad characteristics can be made for all of the inner surfaces of the contact tips. All the tip surfaces showed titanium built-up at the exit of the tip with striations running the entire lenght of the constricted region and "pocked" areas near the tip exit without striations.

Ulrich noted during his experiment that the wire would jam in the contact tip and subsequently lead to burnback. Jamming of the wire did not occur in this experiment when the weld was restarted using the same tip.

Little abrasion and steel build up occured on the inner surface of the contact tip when steel wire was used as the electrode. Additionally, the steel wire samples showed no signs of melting.

4.2 Discussion of Results

The above theoretical analysis predicts that much higher interfacical temperatures in the sliding electrical contact system and much higher temperatures in the electrode will develop when titanium wire is used than when steel wire is used. This is due to titanium's low thermal conductivity and can explain why we see melting of titanium wire at contact points. The sliding electrical contact system is not valid when melting occurs. Even though it predicted high interfacial temperatures at low currents when titanium wire is used, the theoretical model was not validated in terms of the effect of load on the interfacial temperatures.

The two surface characteristics of the contact tip described above were also encountered in Ulrich's study and occur with a similar mechanism. When the weld is first started, melting occurs at the contact points between the titanium wire and copper surface. Once melting starts, the resistance at the contact point decreases, the interfacial temperature drops, and the titanium wire resolidifies. This process of melting-freezing is cyclic and is seen as melted and solidified ridges on the surface of the titanium wire. Figure 9 shows the melted surface of the titanium wire. Titanium begins to build up and forms a pad on the copper surface. Figure 10 shows the titanium pad on the contact tip surface. The two types of wear can occur after the pad is formed. The first is the continued pad build up until the wire fits tightly in the contact tip. This can lead to the wire jamming in the contact tip. Jamming of the wire in the contact tip did not occur in this study, but was encountered by Ulrich in his study. In the second case, the titanium pad adheres to the traveling electrode and abrades the copper surface. When the titanium pad breaks lose from the copper surface, portions of the copper surface adheres to the titanium wire. This is demonstrated by the "pocked" surface of the contact tip. In examining the titanium wire, chunks of copper can be observed adhering to the wire surface. The breaking away of the titanium pad is cyclic with the pad usually forming at a different point in the contact tip. The second example is a form of adhesive and abrasive wear. Adhesive because the titanium pad adheres to the moving electrode; and abrasive because the titanium pad is dragged along the contact tip surface. Figure 11 shows the abraded and pocked surface of the contact tip. The difference between the two mechanisms of wear characterizing the contact

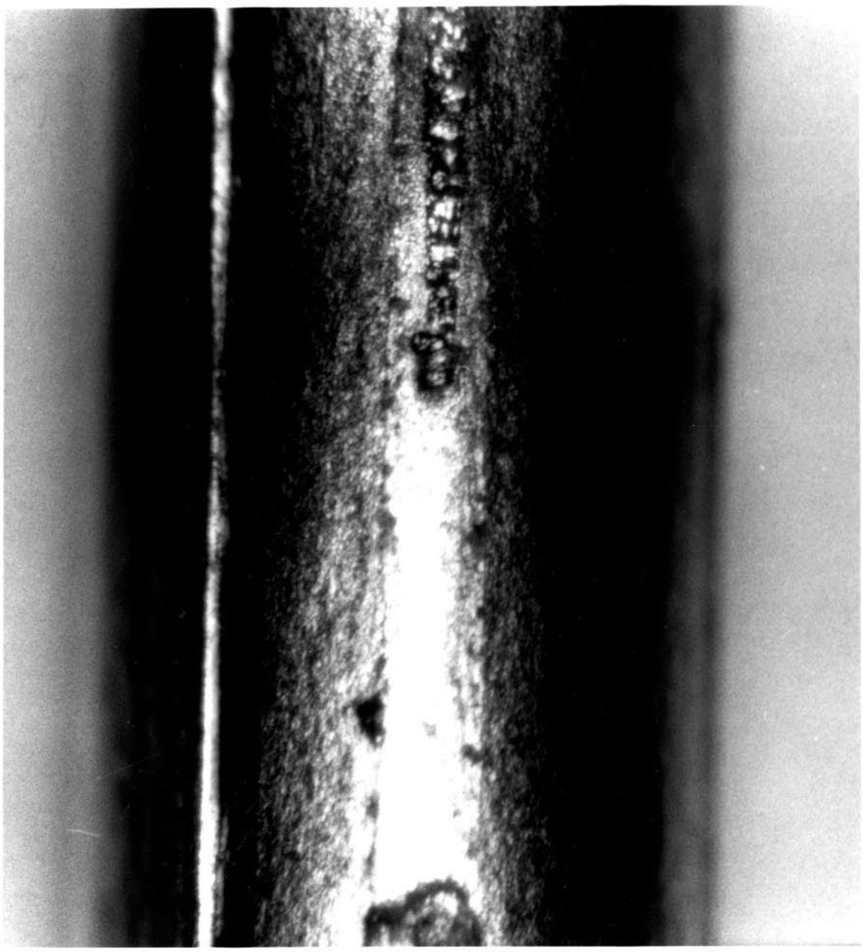

Figure 9 - Melted surface of titanium wire (40x)

Figure 10 - Titanium pad on contact tip surface (58x)

Figure 11 – Abraded and pocked surface of contact tip (36x)

tip surface is that the titanium pad breaks away and abrades the surface in the first case and continues to build up in the second case.

5.0 CONCLUSIONS

In GMA welding of titanium, melting of the electrode occurs in the contact tip. This melting is due to a combination of sliding contact point and electrical heating. Even though the sliding contact system model is not valid when melting occurs, it was useful in predicting higher interfacial temperatures in the titanium-copper system then for the steel-copper system. The model used for predicting the temperature rise of the electrode due to electrical heating indicates that significant temperatures develop in the titanium wire that passes through the contact tip; but, these temperatures are not high enough to cause melting of the wire. Increasing the load at the contact point does not seem to significantly lower the interfacial temperatures in the sliding electrical contact system. This may be due to the presence of the electrical heating, which is signficantly high.

The melting that occured was localized at the end of the tip and is cyclic and takes place at points of contact within the tip. The titanium pad that builds up may break away and abrade the contact tip surface of it may continue to build up, causing the wire to jam in the tip. Jamming of the wire did not occur in this study, but did in Ulrich's study. The build up of titanium and subseqent jamming of the wire can cause burnback, a noted problem in gas-metal arc welding with titanium.

6.0 RECOMMENDATIONS

The results of this study indicates that the electrical heating of the titanium wire passing through the contact tip is significant; but more importantly, it indicates that the effects of the electrical heating may be reduced by decreaing the electrode extension in the contact tip. Shorter contact tips with insulators would decrease the length of the electrode extension and ensure passage of current only within the constricted region. Reducing the electrical heating to a minimum would also give insight into the effects of the sliding contact system and the temperatures it produces on the melting of titanium in gas-metal arc welding.

REFERENCES

1. D. E. Ries, Gas Metal Arc Welding of Titanium, M.S. Thesis, Massachusetts Institute of Technology 1983, 179-209

2. K. T. Ulrich, Contact Tip Wear in Gas-Metal Arc Welding of Titanium, B.S. Thesis, Massachusetts Institute of Technology 1984, 5-38

3. E. Rabinowicz, The Temperature Rise at Sliding Electrical Contacts, Wear, 78 (1982), 29-37

4. P.S. Myers, O.A. Uyehara, and G.L. Borman, Fundamentals of Heat Flow in Welding, Welding Research Council, Bulletin 123 (1967), 1-46

5. N. Willems, and W.M. Lucas, Jr., Structural Analysis for Engineers, 1978, 456

APPENDIX I

The contact forces can be calculated from a simply supported beam representing the bending of the filler wire in the contact tip. Figure A12 is a drawing of the beam configuration. The expression for the beam in bending is (5):

$$\delta = \frac{-F_2 a}{6EIL}(2L^2 + a^2 - 6Lx_1 + 3x_1^2) \qquad (A1)$$

$$F_1 = \frac{F_2 b}{L} \qquad (A2)$$

$$F_3 = \frac{F_2 a}{L} \qquad (A3)$$

In these expressions, δ is the angle of deflection, F is the force, E is the elastic modulus, I is the moment of inertia, and L is the length of the beam.

The following values were used in the calculations:

$E = 1.16 \times 10^{11}\ N/m^2$

$I = 3.02 \times 10^{-13}\ m^4$ ($I = D^4/64$, $D = 0.062$ in.)

$L = 0.035$ m

$a = 0.016$ m

$b = 0.019$ m

$x_1 = 0.016$ m

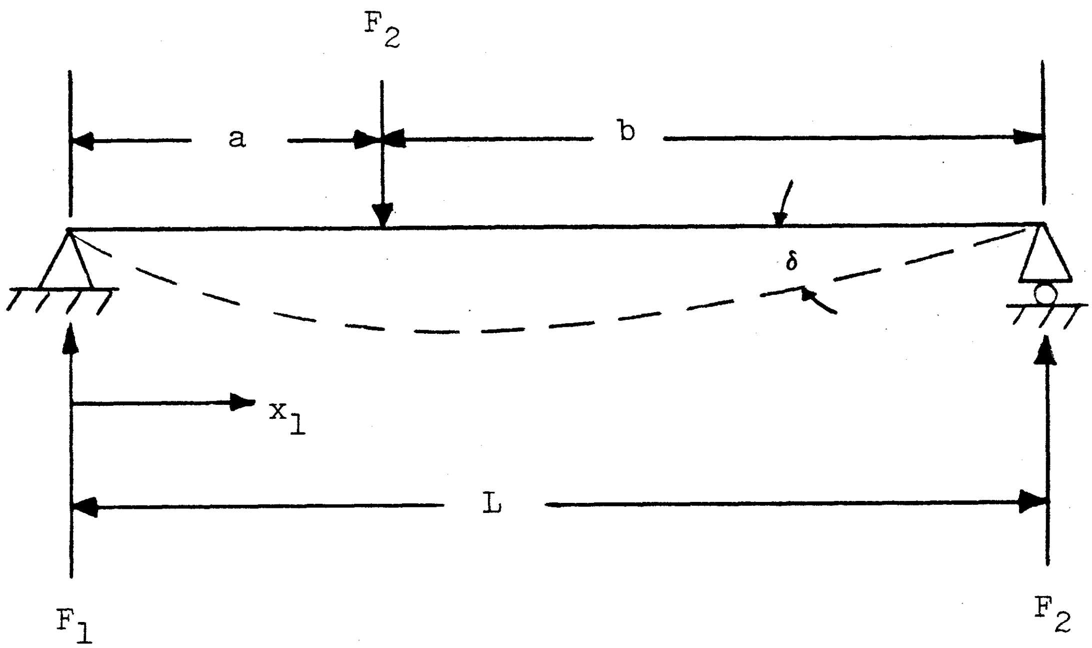

Figure 1A - Beam Configuration