CONTACT TIP WEAR IN GAS-METAL ARC WELDING OF TITANIUM

by

Karl Thatcher Ulrich

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING
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ABSTRACT

When titanium wire is used in gas-metal arc (GMA) welding, copper contact tips wear more rapidly than when steel wire is used. This wear is accompanied by arcing between the base plate and the contact tip instead of between the plate and the filler wire, a phenomenon called ''burnback.'' Burnback requires a complete shutdown of the welding operation and is therefore an expensive problem. Experiments were run to understand the mechanism of contact tip failure. The results of these experiments reveal that the low thermal conductivity of titanium causes melting to occur at the sliding electrical contact junction between the filler wire and the contact tip. Melting and subsequent freezing of titanium at the contact point can either build up and cause jamming of the filler wire in the contact tip or can cause adhesion of a chunk of titanium to the filler wire that then abrades the copper contact surface. The mechanism leading to the jamming of wire in the contact tip led to burnback in several of the experimental cases.

Thesis Supervisor: Thomas W. Eagar
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Since my first contact with the welding lab during the summer of 1979, my time spent there has been educational and fun. The work leading to this thesis is really only a small segment of a larger experience. Professor Eagar, who supervises the welding lab, is to a great extent responsible for the atmosphere of freedom and trust that has helped make my thesis and UROP work with him rewarding. I would like to thank him as much for that as for his technical advice. The other students in the lab and the lab technician, Bruce Russell, have been sources of support, friendship and advice.

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1.0 INTRODUCTION

1.1 General Background

Gas-metal arc (GMA) welding is a process in which a wire of filler metal, continuously fed from a supply spool, is the electrode for an electric arc. The current necessary to maintain the arc is applied to the wire a few centimeters above the arc through a copper contact tip. The filler wire slides through a hole in this contact tip that is slightly larger than the wire diameter. Current flows from a welding power supply through power cables to the contact tip, then flows to the filler wire at the points where the wire touches the contact tip. Since the wire is being fed through the contact tip, the wire and contact tip can be described as a sliding electrical contact system (figure 1).

When titanium wire is used in GMA welding, it has been found that contact tips wear much more rapidly than when steel wire is used (1). Ries (1) states that wear of contact tips is accompanied by poor electrical contact between the tip and the wire and that this poor electrical contact can cause arcing between the contact tip and the base plate instead of between the filler wire and the baseplate. This phenomenon is called ''burnback'' and requires a complete shutdown of the welding process and a replacement of the contact tip.

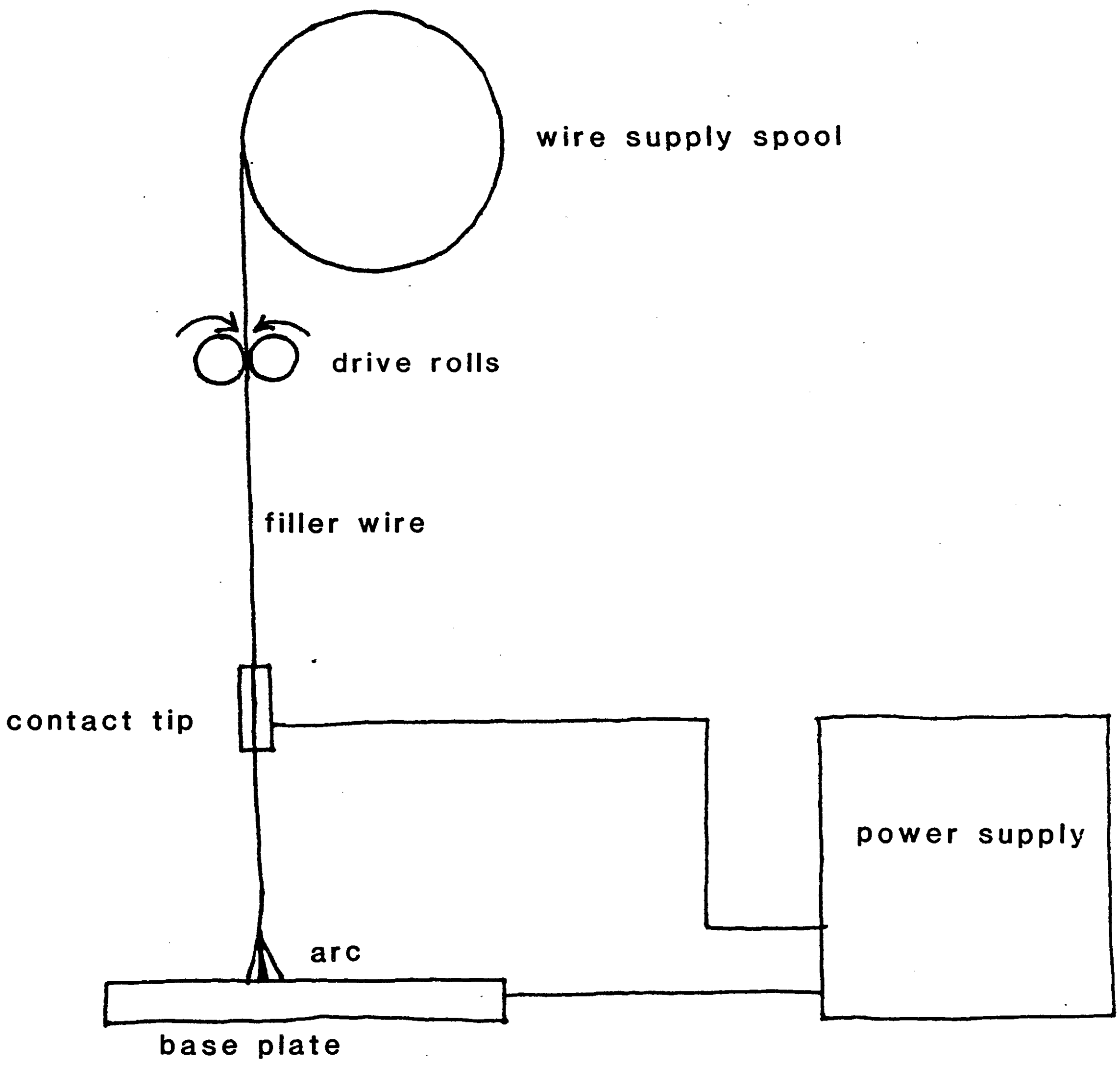

Figure 1 - Schematic of welding system

Burnback often necessitates the grinding away of weld metal that has been contaminated by the melted copper of the contact tip. The relatively rapid wear of contact tips in titanium GMA welding is an expensive problem. To avoid burnback welding machine operators, when welding titanium, typically replace the contact tips whenever they stop a weld. This practice consumes contact tips as much as 15 times faster than when welding with steel filler wire.

1.2 PRIOR WORK

The problem of contact tip wear has been noted during research at General Dynamics Electric Boat Division in Groton, Connecticut, and at the David Taylor Naval Ship Research and Development Center (DTNSRDC) in Annapolis, Maryland. Problems have also arisen in production of the ''Seacliff'' deep-sea submersible at Mare Island Naval Shipyard when using hot-wire gas tungsten arc welding. The solution at General Dynamics and Mare Island has been replacement of the tip after each welding pass. More recently, DTNSRDC has found that tips, bored out to diameters significantly larger than the wire diameter, wear much less rapidly than normal tips. While this solution is simple and inexpensive, the physics of this solution are not understood and it is not known whether the optimum contact tip bore diameter varies with the welding process parameters.

Ries (1) addresses the problem of contact tip wear in titanium welding. He suggests that adhesive wear in the form of plowing and delamination control the wear of the tip, and he notes that melted wear particles and spatter collect at the tip exit. He makes a number of suggestions for improving the life of contact tips: water cooling of the copper tip to lower bulk temperatures, use of fully hardened copper beryllium alloys to provide a harder contact surface, the use of better wire straighteners to decrease the load at the wire-tip interface, the use of tungsten carbide inserts at the tip end, and the use of coating materials, such as silver, on the contact tip surfaces that would eliminate the possibility of titanium forming a low-melting point eutectic alloy with the copper.

A better understanding of the wear mechanism will be useful in determining the best method of solving this problem. The objective of this study has been to understand the factors controlling wear and the mechanism of wear in electrode contact tips. If this phenomenon can be understood, then appropriate changes can be made in the GMA welding process and in equipment that will minimize contact tip wear and the expense associated with that wear.

2.0 THEORETICAL ANALYSIS

2.1 Contact Tip-Wire Configuration

As stated in the introduction, the filler wire-contact tip configuration is a sliding electrical contact system. The first step to understanding the wear mechanism in this system is understanding the configuration of the filler wire as it slides through the contact tip. The filler wire is supplied to the contact tip from a 20 cm diameter spool. Although the wire passes through a three-roller wire straightener before it reaches the contact tip, it still has some cast. The cast, or diameter of a loop of wire, ranges from approximately 50 cm in the unstraightened case to over 5 m when the wire straightener is finely adjusted. A drawing of the contact tip used in this study is shown in figure 2. When this wire is forced through the small-diameter tube that constitutes the contact section of the tip, it can touch the tip at two or three points. To determine the exact configuration, a full-scale plexiglas model of a contact tip was made and a section of wire was fed through it. The wire made contact with the tip at two points--at the top and bottom of the constricted section of the tip. See figure 3. Once this configuration had been established, the problem of understanding the wear mechanism could proceed.

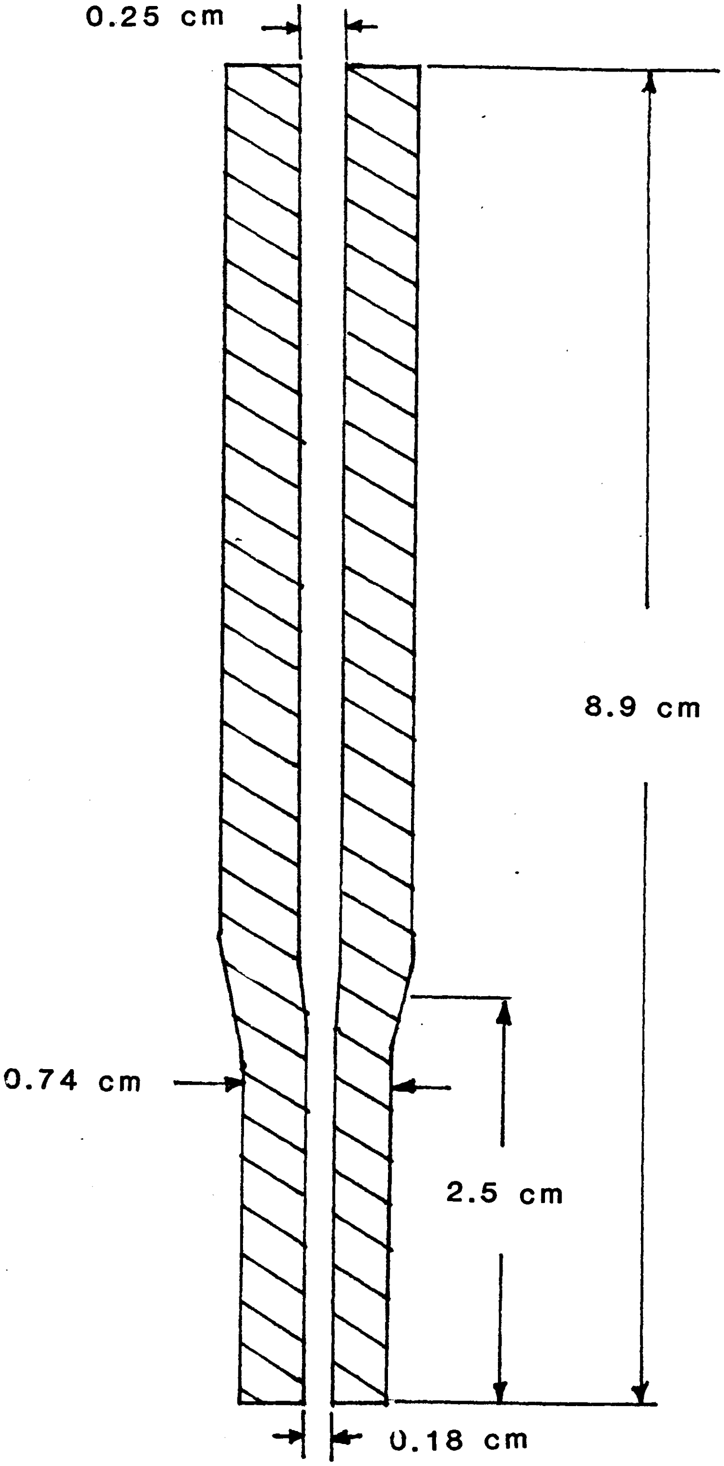

Figure 2 - Section view of contact tip

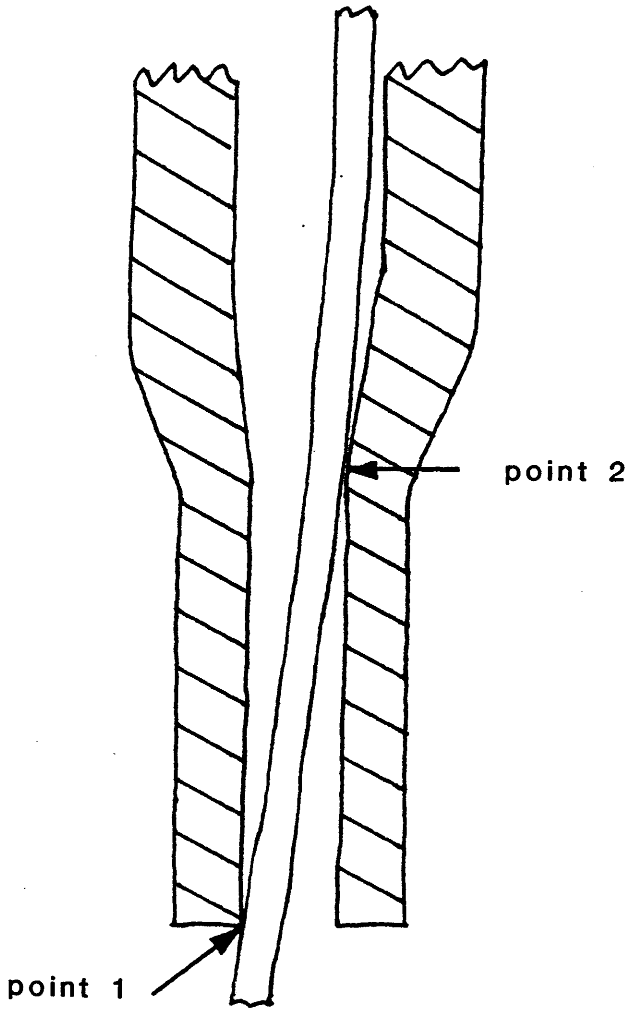

Figure 3 - Configuration of wire in contact tip

2.2 Temperature Rise at Sliding Electrical Contact

The first fundamental assumption made in approaching the problem of wear in contact tips is that wear is temperature related. This assumption is substantiated by wear literature (2). When a contact junction is heated, the electrical resistance of that junction increases and further heating takes place. As the temperature of the junction continues to rise, one or both of the contact surfaces softens or melts. Under these conditions wear is relatively rapid. Accepting this assumption, the problem of understanding wear in contact tips can be approached by understanding the temperature rise at the contact junctions between the filler wire and the contact tip.

An expression for the temperature rise at a sliding electrical contact has been developed by Rabinowicz (2). The GMA welding system falls into what he terms the slow speed regime. This assumption is verified in Appendix I. In the Rabinowicz model the temperature rise is governed by:

$$\theta = \frac{\mu F v + i^2 R}{4r(k_1 + k_2)} \qquad (1)$$

where θ is the temperature rise above the bulk temperature, μ is the coefficient of friction, v is the velocity of the electrode, F is the force at the junction, i is the current flowing in the junction, R is the resistance of the junction, r is the radius of the contact area, and k_1 and k_2 are the the thermal conductivities of the two materials that constitute the junction. In the case of GMA welding, where sliding speeds are approximately 0.15 m/s and currents are approximately 250 A, the heat generated by sliding is insignificant compared to the heat generated by Joule heating (Appendix I). So equation (1) is reduced to:

$$\theta = \frac{i^2R}{4r(k_1 + k_2)} \tag{2}$$

The expression shows that the temperature rise at the sliding electrical contact is governed by the current, the resistance of the contact, the size of the contact and the conductivities of the materials.

Of the governing factors in equation (2), the thermal conductivities and the current are fairly easily determined. The thermal conductivities are known physical constants and the current can be measured by incorporating a shunt in the electrical welding circuit. The contact resistance and the contact radius are not so easily determined. The contact resistance is related to the contact radius and the contact radius is related to the contact force. Neither of these two quantities can be easily and accurately measured. However, approximate analytical expressions for these values do exist. The contact radius is approximately (3):

$$r = \sqrt{\frac{F}{\pi p}} \qquad (3)$$

where p is the penetration hardness. An expression for the contact resistance due to the constriction of the area of conduction at the contact point is given (4) by:

$$R = \frac{(\rho_1 + \rho_2)}{2r} \qquad (4)$$

where ρ_1 and ρ_2 are the bulk resistivities of copper and titanium. When these expressions for contact radius and contact resistance are substituted into equation (2), the following relationship is established:

$$\theta = \frac{(\rho_1 + \rho_2)\pi p i^2}{8F(k_1 + k_2)} \qquad (5)$$

This expression shows that the contact force is an important governing factor. The result is that temperature rise is decreased when the force is increased, which is the opposite of many common views of contact wear of welding tips.

Equation (5) is an expression for a single contact point. In reality, two contact points exist in the contact tip. Separate values for the two contact forces must be established to determine the radii at the two points which in turn determines the resistances at the two points. Once the resistances are determined, the division of current between the two points can be established. The subscripts 1 and 2 will refer to contact points 1 and 2 as shown in figure 3. The amount of current that flows through contact point one, for example, is given by:

$$i_1 = \frac{R_2}{R_1 + R_2} i_0 \qquad (6)$$

Where R_1 and R_2 are the resistances at the two contact points and i_0 is the total welding current. Since the value of the resistances at points 1 and 2 are inversely related to the forces at points 1 and 2, equation (6) can also be expressed in the following way:

$$i_1 = \frac{\sqrt{1/F_2}}{\sqrt{1/F_1} + \sqrt{1/F_2}} i_0 \qquad (7)$$

Substituting this information into equation (5) yields the following result that predicts the temperature rise at point 1:

$$\theta_1 = \frac{(\rho_1 + \rho_2)\pi p i_0^2}{8(k_1 + k_2)(F_1 + 2\sqrt{F_1 F_2} + F_2)} \qquad (8)$$

Note that the result will be the same for point 2. This model predicts that the temperature rise at the two points for a given configuration will be the same. However it does not imply that the currents at each location will be equal unless F_1 and F_2 are equal.

Approximate values for the contact forces were obtained by constructing a jig that simulated the contact tip-torch assembly and that allowed access to the filler wire at points directly adjacent to the contact points. The contact force values were determined by applying an increasing load to the wire next to the contact point until the applied load and the contact forces were equal and the wire pulled away from the contact point. A complete description of this apparatus is given in Appendix II. Using this procedure, values for contact forces were established for various wire casts. These values are shown in figure 4.

Using these forces, temperature rises were predicted for various wire casts. These predicted results are shown in figure 5. Table 1 shows the values for the constants used to calculate these results.

Since there are many uncertainties in these calculations, and since the exact relationship between temperature rise and wear is not known, this theoretical model is useful mainly as a figure of merit and for comparing various materials under similar operating

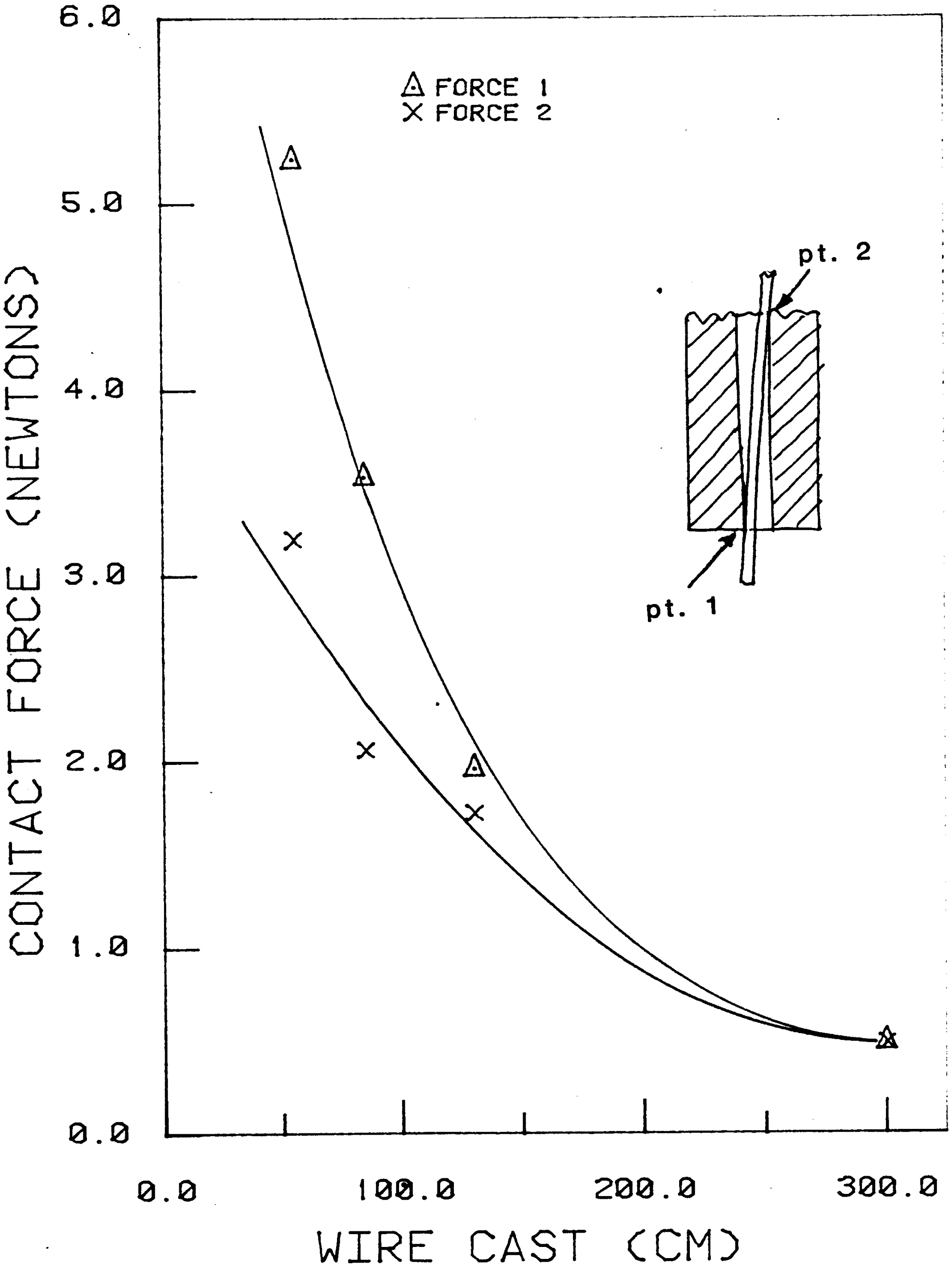

FIG. 4 - CONTACT FORCE VS. WIRE CAST FOR TI WIRE

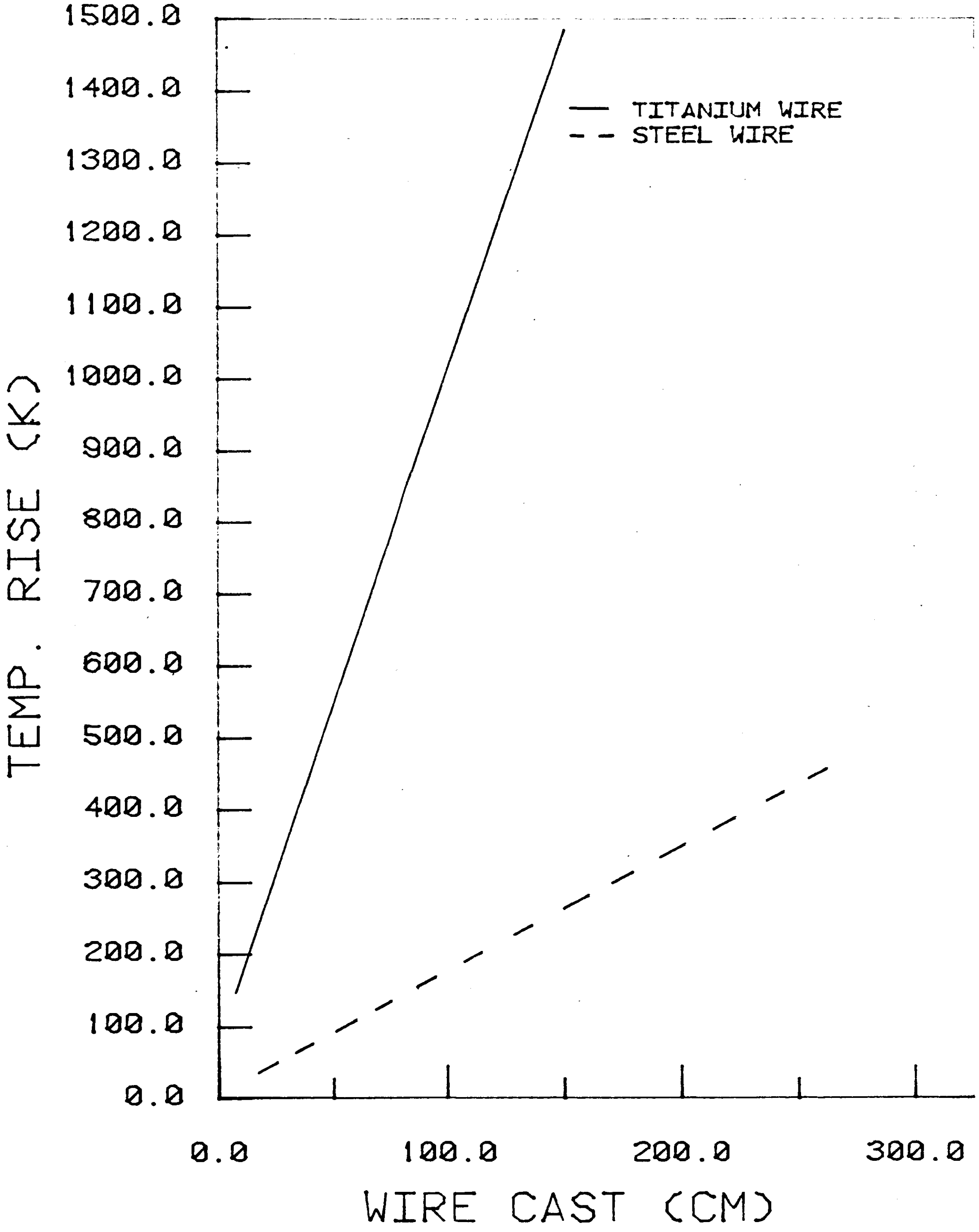

FIG. 5 - TEMP. RISE VS. WIRE CAST AT 250 A

Table 1 - Numerical values of constants used to predict temperature rises

constant	titanium wire	steel wire
ρ_1	1.7×10^{-8} Ω m	1.7×10^{-8} Ω m
ρ_2	42×10^{-8} Ω m	10×10^{-8} Ω m
p	2.4×10^{8} Pa	2.4×10^{8} Pa
i_0	250 A	250 A
k_1	378 W/m/K	378 W/m/K
k_2	8.4 W/m/K	50.4 W/m/K

parameters. Rabinowicz (3) states that wear is generally directly proportional to the load. But, in our sliding electrical contact system, temperature in inversely related to load, and wear is also temperature related. These factors suggest that, surprisingly, an increase in contact force could yield a decrease in wear by lowering contact temperatures. The theoretical model for this sliding electrical contact system, even if it does not provide precise predictions, identifies which process parameters may be important in controlling wear.

2.3 Metallurgical Considerations

Ries (1) raises the possibility that a low melting point eutectic may form between the copper contact tip and the titanium filler wire. He suggests that this phenomenon would encourage melting of the contact point once melting begins. A binary phase diagram for copper and titanium is shown in figure 6. The arrow in the diagram identifies the low melting point eutectic. Ries also suggests that if this eutectic formation is partially responsible for rapid wear of the copper titanium system, then substitution of a contact tip material that is more metallurgically compatible with titanium would help solve the wear problem. A contact tip material that exhibits good thermal and electrical conductivity but does not form a eutectic with titanium is silver. The binary alloy phase diagram for silver and titanium is shown in figure 7. Note that alloying of silver and titanium actually increases the melting temperature of the alloy. This phenomenon will help stop large scale melting of the contact junction as soon as it begins.

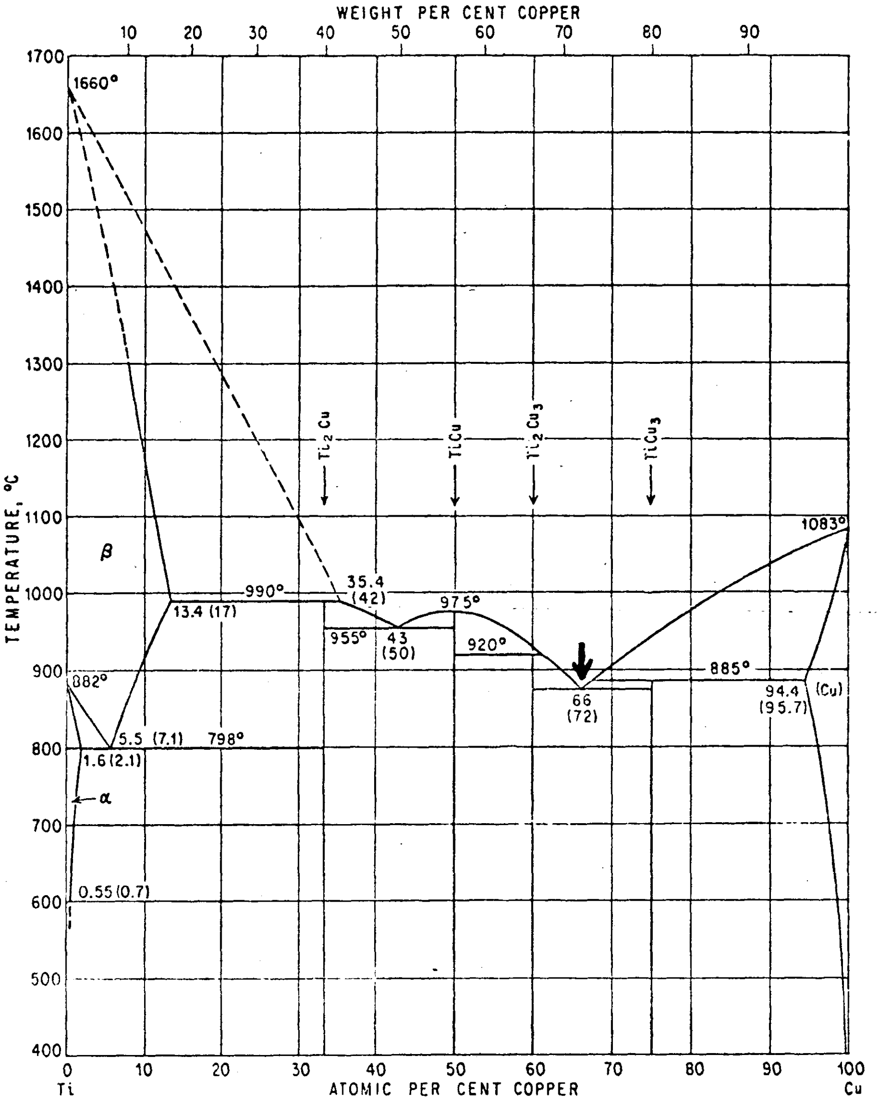

Figure 6 - Phase diagram for Ti-Cu

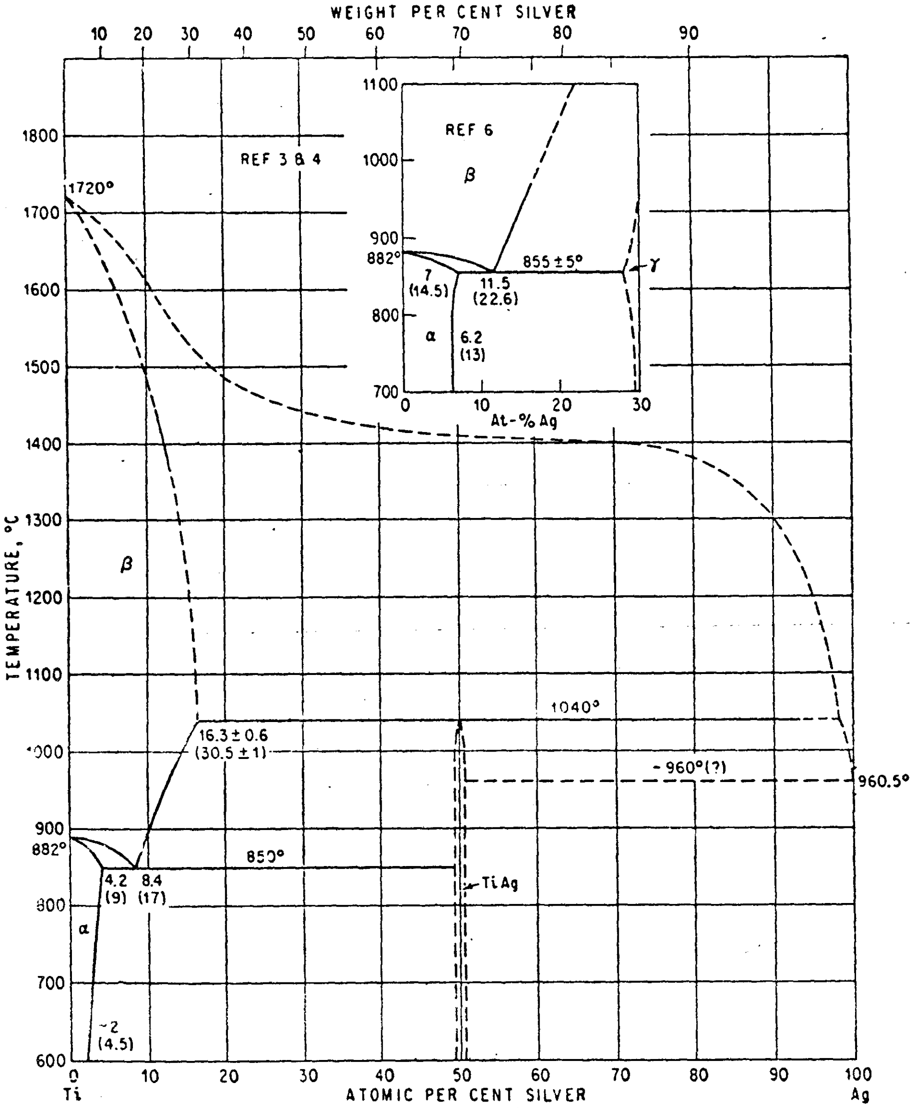

Figure 7 - Phase diagram for Ti–Ag

3.0 EXPERIMENTS

3.1 Apparatus

All of the experimental work for this project was carried out using standard commercially available welding equipment. The power supply was a Linde SVI-600 direct current unit. The controller was a Linde SCC-17A with a Linde J-Governor carriage drive and a Linde ST-12 torch. The weld current was measured with an in-line 1 milliohm shunt and a digital voltmeter. The wire feed speed was measured with a Shimpo digital tachometer. Figure 8 is a diagram of the experimental apparatus.

3.2 Procedure

Since the object of this study was to understand wear of contact tips and not to produce satisfactory welds, the welding time necessary to produce significant wear was spent making repeated bead-on-plate welds with titanium wire on scrap steel. Three experimental variables were used: weld current, feed wire cast, and weld time. Primarily only two different values for each of these variables were employed. For most of the tests, the current was either 220 A or 270 A, the wire cast was either 50 cm or 200 cm, and the weld time was either 5 min. or 10 min.

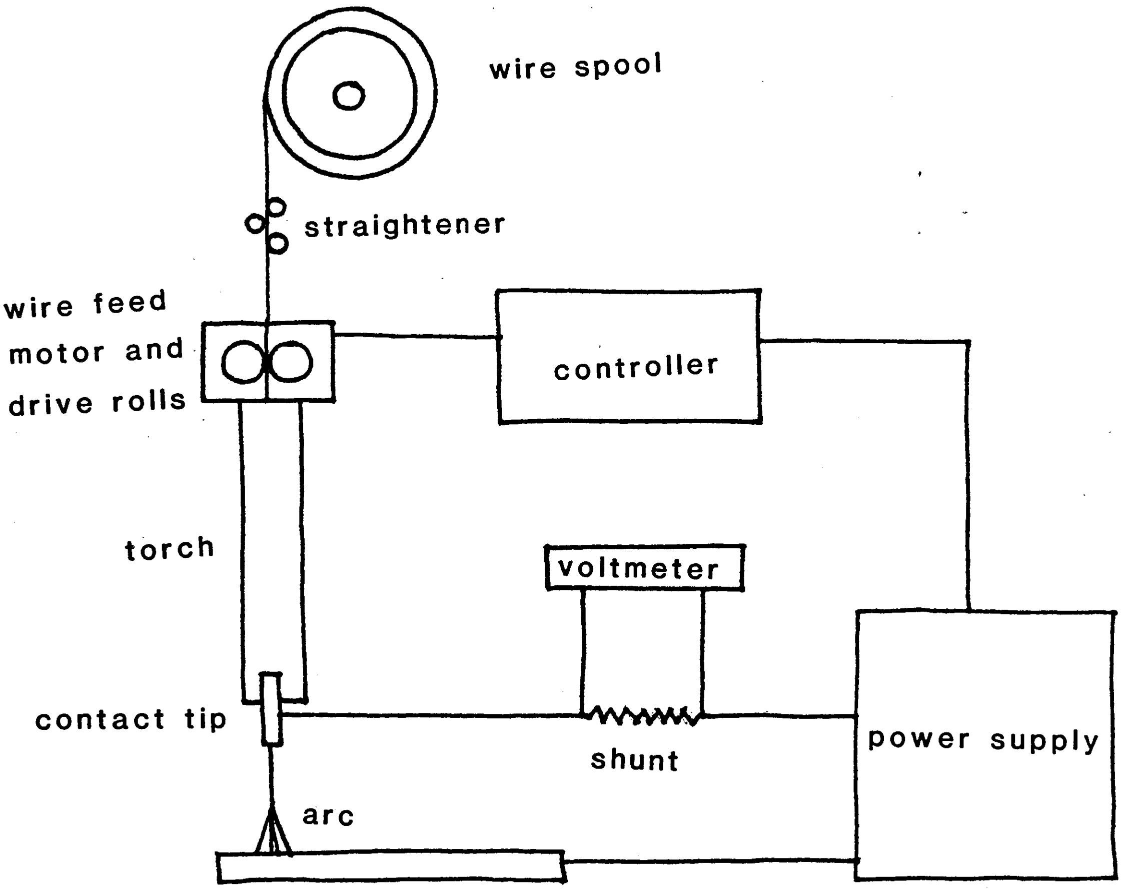

Figure 8 - Experimental apparatus

Eight copper tips were run with the eight different combinations provided by two variations in three variables. Two additional tips were run at medium current (250 A) for 15 minutes. Two tips were run at high currents (350 A) for 5 and 10 minutes. Two tips were run with steel wire at 350 A. Also, three silver tips were run at 250 A. In total, fourteen trials were made.

Note that time was used as a variable instead of total amount of wire passed through the tip. This was done because wire speed is related to welding current. Therefore, either the wire speed or the welding current can be controlled but not both. Because of this characteristic of the welding system, a tip run for 10 minutes at 270 A had more wire passed through it than a tip run for 10 minutes at 220 A. But, since wire feed speed varied from 9 cm/s to 14 cm/s, all of the tips run for 5 minutes had significantly less wire passed through them than all of the tips run for 10 minutes. Additionally note that the welding current when welding titanium is very unstable. Variations as high as plus or minus 25 percent were experienced during the weld time. The welding current values represent the operator's best efforts at estimating an average value.

3.3 Analysis

The wear phenomenon encountered in titanium GMA welding is very difficult to quantify. Two standard methods of wear quantification, measuring weight loss and measuring physical dimensions, were considered for analysing the contact tips. Neither of these approachs proved useful. Weighing is not a valid method because titanium spatter covers the end of the contact tip and alters the weight of the tip more than does wear. Measuring the diameter of the exit hole in the tip was not possible because titanium would build up on the rim of the hole making a diameter measurement meaningless. Analysis of the contact tips was therefore limited to cutting the tips along their longitudinal axis and examining their inner surface to identify trends in the wear mechanism. The tips were cut on a band saw and were examined with both an electron microscope and an optical stereo microscope. Additionally, the wire that protruded from the tips after the welds were finished was examined with the electron and optical microscopes.

4.0 RESULTS

4.1 Observations

Since no meaningful quantitative analysis of the contact tips was possible, all of the results are qualitative observations of the contact tips and the filler wire. Despite the lack of quantitative evaluation criteria, the following useful observations were made.

The most significant result yielded by the above experiments is that under every different set of experimental conditions examination of the contact tip and the filler wire reveals that melting of the titanium wire occurs at the contact points. The inside surfaces of the worn contact tips all had titanium coated areas with smooth surfaces, indicating melting. Additionally, most of the wire samples examined had a clearly defined path where the surface had melted and resolidified. Figures 9 and 10 show regions of melting for a contact tip and a section of filler wire respectively.

All of the contact tip inner surfaces can be described by two broad characterizations. The surfaces either show a built-up region near the tip exit composed entirely of titanium, or an abraded surface near the tip exit with clearly defined striations in the copper and ''pocked'' areas without striations. These two characterizations are typified by the photographs in figures 11 and 12 respectively.

During experimentation, one primary mode of failure was noted. The filler wire often would become jammed in the contact tip. This jamming led to kinking of the filler wire at the feed rolls and subsequently to burnback.

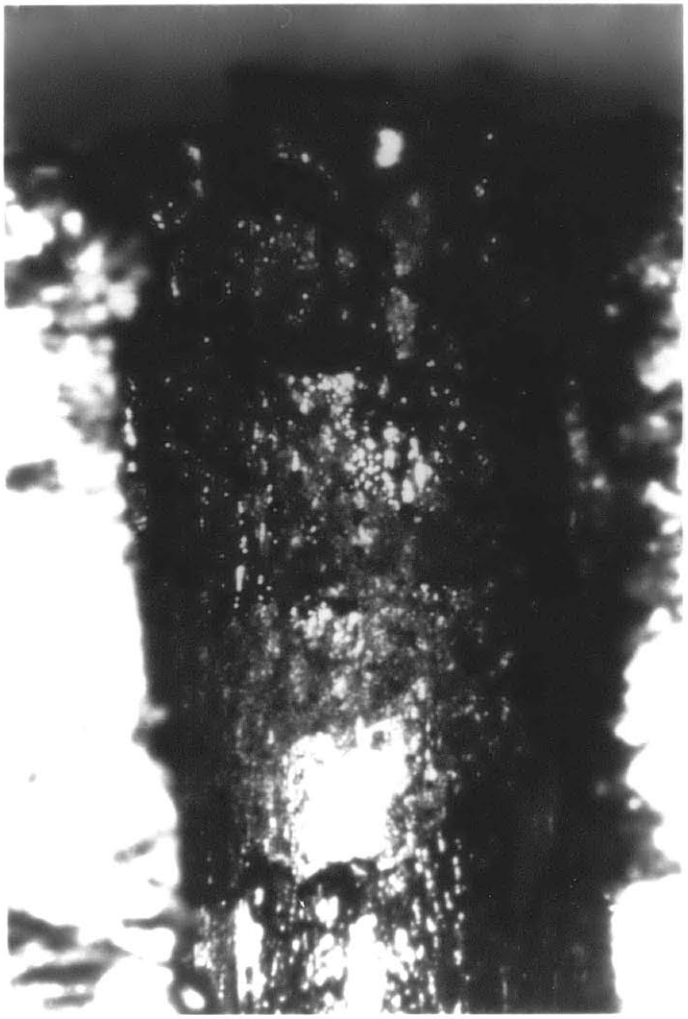

Figure 9 - Contact tip surface showing melting of titanium (32x)

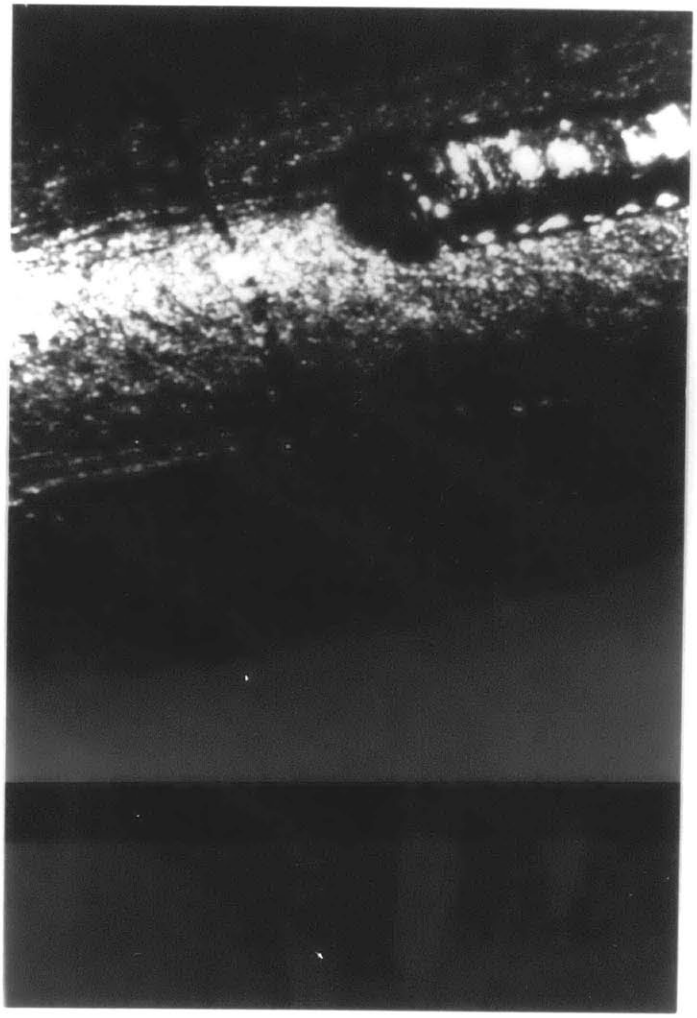

Figure 10 - Titanium wire showing melting (42x)

Figure 11 - Titanium "pad" on contact tip surface (32x)

Figure 12 - Abraded and pocked contact tip surface (40x)

The surface characteristics of the silver tips were indistinguishable from those of the copper tips.

The tips that were run with steel wire showed very little abrasion, very little build up of steel on the inside of the tips and no melting of the filler wire.

4.2 Discussion of Results

The above results indicate that the fundamental difference in contact wear between the steel and titanium wire cases is that when welding with titanium, the titanium melts at the contact points. In very general terms, the above theoretical analysis predicts this result. The low thermal conductivity of titanium causes the interfacial temperatures to be much higher than those experienced with steel wire. The theoretical model for a sliding electrical contact system does not apply once melting has begun. So, while the theoretical model predicts that titanium wire will melt at much lower currents than steel wire, the model was not validated in terms of the effect of wire cast on junction temperature.

Examination of contact tip surfaces indicates that the two surface characteristics described above occur with a similar mechanism. First, when the weld is started, melting occurs at the interface between the copper and the titanium. Since as soon as melting begins the contact resistance decreases, the temperature drops at the interface and the titanium freezes. Then the cycle begins again--melting and freezing. These cycles are shown on the filler wire by the ridged surface on the melted and resolidified region (figure 13). On the inside of the contact tip, titanium builds up to form a pad upon which the titanium wire rides. After the formation of this pad, two modes of wear can occur. In one case, the titanium continues to build up until the wire fits very tightly in the contact tip. At this point, the wire can jam in the tip. Additionally, if the weld is stopped at this point the melted regions will solidify and the wire may become permanently attached to the contact tip. In the other case, when the liquid titanium solidifies, the titanium pad may be more strongly bonded to the wire than to the contact tip surface. If this is the case, then the pad of titanium is ripped from the contact tip surface. When this happens, the harder titanium pad abrades the underlying copper surface. This phenomenon is a form of adhesive and abrasive wear. Adhesive because a chunk of titanium adheres to the moving wire rather than to the copper contact tip surface. And abrasive because this chunk of titanium is then dragged along the softer copper contact tip surface. After the breaking away of a titanium chunk, the whole cycle starts again with the build up of titanium--usually at a different point in the tip.

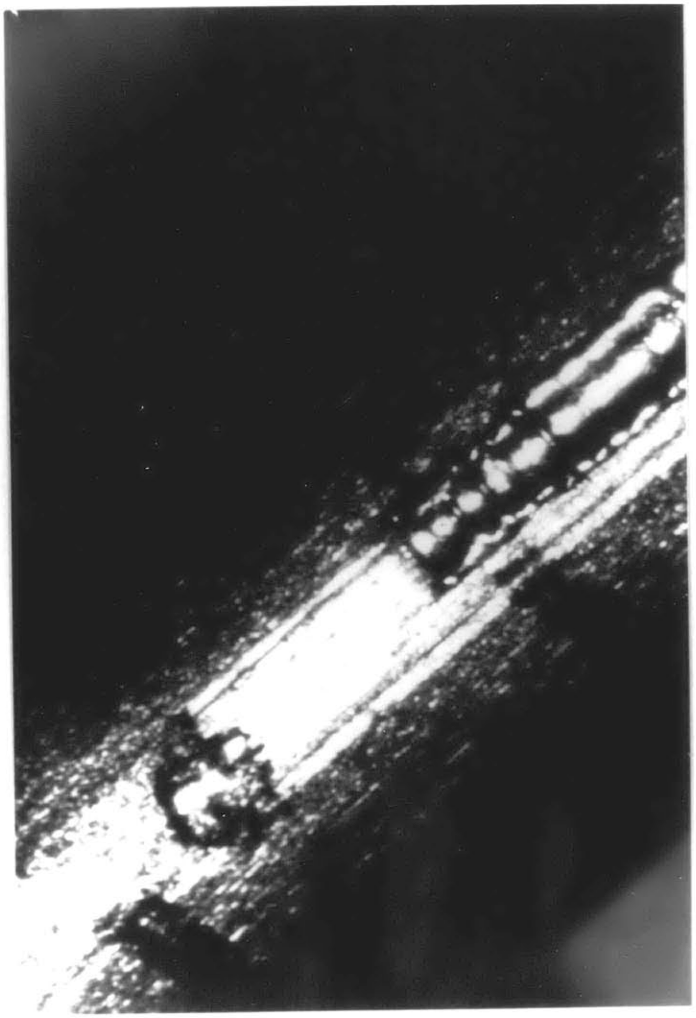

Figure 13 - Surface on titanium wire indicating melting-freezing cycles (40x)

This continual build-up and breaking away of chunks of titanium is demonstrated by the abrasion of the copper surfaces and by the ''pocked'' appearance of the surface. Also, chunks of titanium with copper adhering to them can be observed on the filler wire when the weld happened to be stopped as this part of the cycle was occuring (see figure 13). The difference between the mechanism for forming the two characteristic surface conditions is only that in one case the initial titanium pad breaks loose and abrades the copper surface, in the other case the titanium pad continues to build up.

The fact that silver contact tips exhibit surface characteristics that are identical to those of copper contact tips indicates that metallurgical incompatability is not a significant factor in the explanation of rapid wear of contact tips when welding titanium.

6.0 CONCLUSIONS

The theoretical model for the sliding electrical contact system was useful only in indicating that higher interfacial temperatures are expected for a titanium-copper system than for a steel-copper system due to the lower thermal conductivity of titanium. The validity of the model for the titanium-copper system was limited because it does not apply when melting occurs. Melting does in fact occur in the sliding electrical contact system in titanium gas-metal arc welding.

This melting is part of a melting-freezing cycle at the contact points. The freezing part of this cycle can cause the built-up titanium to break away from the copper thus abrading the contact tip surface. When the titanium does not break away, it builds up until the wire jams in the contact tip. This jamming can cause the burnback that has been identified as a symptom of wear and poor electrical contact in the prior work on this problem. If the built-up titanium does break away periodically, then enough copper could possibly be abraded away to cause poor enough electrical contact to cause burnback. In the tests run for this study no tips burned back as a result of this mechanism.

7.0 RECOMMENDATIONS

The results of this study indicate that what has been previously identified as wear leading to poor electrical contact and burnback may really be a build-up of titanium within the tip that leads to jamming of the wire in the tip and subsequent burnback. This result explains why investigators at DTNSRDC found that a larger diameter contact tip hole increased the useful life of the tip. A larger tip simply provides more room for the titanium to build up before the wire jams in the tip. Further work must be done with a variety of contact tip designs, including those used at DTNSRDC, before this statement can be validated completely.

Titanium, because of its low thermal conductivity, will cause melting and subsequent tip failure in conventional welding torch designs. Enlarging the contact tip may provide an extension of the life of a contact tip. Other methods of passing the weld current to the filler wire need to be developed for gas-metal arc welding of titanium. These methods need to incorporate high enough forces to make the contact resistances low enough that melting will not occur. Such a design might use a curved contact tip although with sliding systems the requirements of high contact forces and yet low enough friction to prevent kinking and jamming of the filler wire seem incompatible. Other schemes should be investigated such as nip rollers that exert high contact forces yet provide a wire path with relatively little friction.

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APPENDIX I

Rabinowicz states (2) that when the following non-dimensional expression is less than 2, the sliding system falls into the slow speed regime and is governed by equation 1.

$$\frac{vr\delta c}{k} \qquad \text{(A1)}$$

In this expression, v is the velocity, r is the radius of the contact area, δ is the density of copper, c is the specific heat of copper and k is the thermal conductivity of copper.

The folowing values where used to calculate the value of A1.

$v = 0.1$ m/s
$r = 5 \times 10^{-5}$ m
$\delta = 9000$ kg/m^3
$c = 386$ j/kg/K
$k = 378$ w/m/K

Expression A1 is equal to 0.05 with the above values, substantially less than 2.

The following calculation shows that Joule heating dominates the power input to the contact junction.

Average values for operating parameters:

$i = 250$ A
$R = 0.005$ Ω
$\mu = 0.3$
$L = 5$ N
$v = 0.1$ m/s

Joule heating:

$i^2R = (250)(250)(.005) = 312.5$ watts

Frictional heating:

$\mu Fv = (0.3)(5)(0.1) = 0.15$ watts

APPENDIX II

Figure A1 shows the apparatus used to calculate the contact forces in the tip. Ball bearings were used as weights applied at points 1 and 2. Bearings were added to the basket until the weight exactly equaled the force exerted by the wire on the contact point, indicated by the separation of the wire from the contact tip section. When the force at point 2 was determined, the wire was rotated 180 degrees from the position shown in figure A1. The apparatus in figure A1 was designed to simulate the configuration of the wire in a Linde ST-12 welding torch.

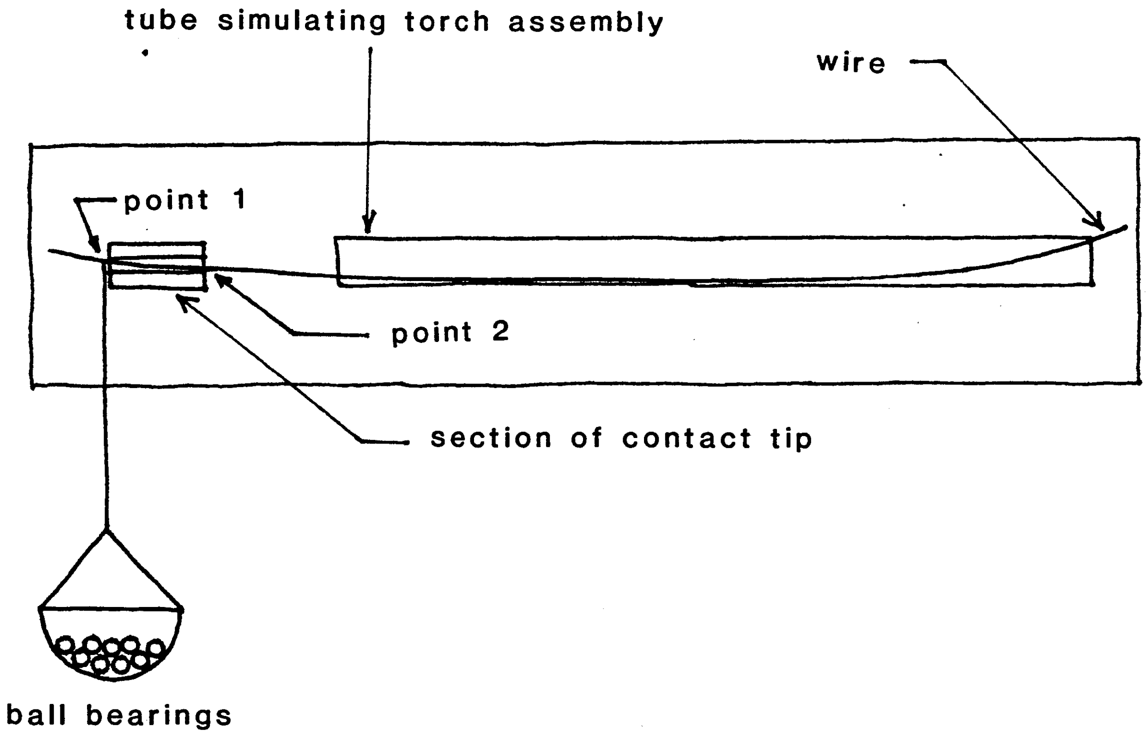

Figure A1 - Jig for measuring contact forces