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Gas-Tungsten-Arc Cathode and Related Phenomena†

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Abstract

A number of researchers have studied the gas-tungsten-arc cathode phenomena. This papers discusses their results with certain aspects of the electrode mechanisms and erosion which occur on refractory arc cathode containing oxides. Recommendations are made which enable a more rational approach to be made in selecting the optimum condition for particular application and production a new non-consumable electrode.

KEY WORDS: (Gas-Tungsten-Arc) (GTA Welding) (Tungsten Cathode) (Welding Arc)

(1) Definition of Arc:

Before entering into a discussion of arc welding, it is in order to consider a definition of a welding arc. In fact, there is no difinition which is generally or widely accepted for an arc of any kind. One of the references used by all workers in this field is the review of the literature presented by Spraragen and Lengyel[1] on physics of the arc and the transfer of metal in arc welding. Since the publication of this review, extensive literature has appeared which has referred specifically to the welding arc.

Even though the experts have not given a clear-cut definition of the welding arc, for our discussion, the following statement is proposed[2] "A welding arc consists of a sustained electrical discharge through a high temperature conducting plasma, producing sufficient thermal energy so as to be useful for the joining of metals by fusion".

Generally, in welding, one of the electrodes is the work piece while the second electrode is tungsten or a consumable metal. Since the conductivity of the plasma between the electrodes is maintained by thermal ionization, the temperature must be high. All experts agree that the conditions in the regions of electrical contact between the plasma and the electrodes are quite different from those in the plasma. In both the anode and cathode regions, since the temperature must drop from the high value in the plasma to the relatively low value at the electrode surfaces, high thermal gradients exist. The arc naturally, then, is divided into the plasma, cathode and anode regions. A concentration of charge carriers in the anode and cathode regions gives rise to a nonlineal potential or voltage distribution along the arc axis shown schematically in **Fig. 1**. Because of this space charge distribution,

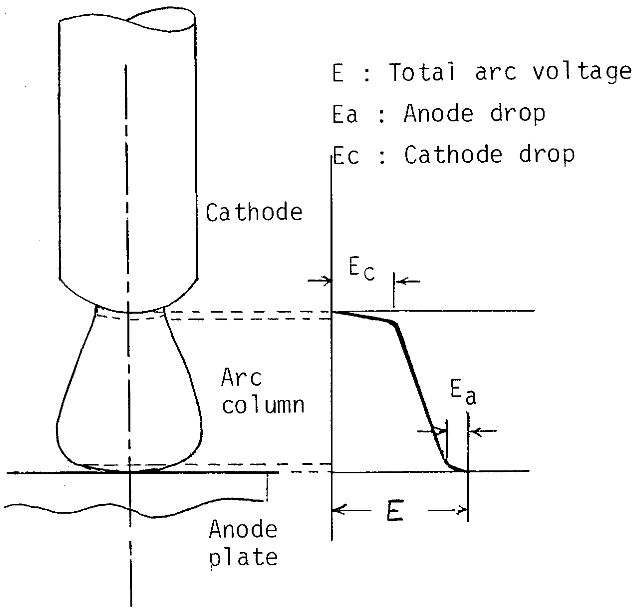

Fig. 1 Voltage relationship for typical tungsten-electrode arc.

high electric field strengths exist in the anode and cathode regions. Self-induced magnetic fields produced by the high currents encountered compress the plasma to the extent that appreciable radial and axial pressure gradients exist. The axial pressure gradient causes plasma streams which transport material and heat away from the electrode to the work piece.

(2) Tungsten-Electrode Welding Arc:

For the purpose of theoretical study, an arc with a direct-current power supply having a "point-to-plane" configuration, operating in argon at atmospheric pressure

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with a tungsten cathode and copper anode has been particularly useful. Since the anode plays little or no part in the arc mechanism except to serve as the positive electrode, the phenomena which exist are almost entirely dependt upon the behavior of the cathode.

Cathodes can be classified as:[3)]

(1) *Glow Cathodes*:
Where the current density is proportional to the square of gas pressure and only reaches about 10^6 to 10^7 A/m^2 at 1 atm., while the cathode voltage drop between 100 and 500 V. The current density of the normal glow discharge at a given gas pressure remains constant as long as any part of the cathode remains uncovered by cathode glow.

(2) *Arc Cathode*:
Where the cathode voltage drop is only 10 to 20V, it is an arc cathode which may be thermionic with current densities of only about 10^7 A/m^2, or may be non-thermionic with current densities of 10^{12} A/m^2 or above.

Glow discharge occure more frequently at low pressure but they can occure also at ambient pressure, or at gas pressure of several atmospheres, although since the cathode current density increases with the square of gas pressure, the glow tends to change into an arc at high pressures.

It must be noted that glow discharges and arcs are not completely separable phenomena. It is possible to have a glow cathode with an arc plasma, or an arc cathode with a glow plasma.

(3) Theories of The Cathode Mechanism:

The cathode region of the arc at atmospheric pressure can be divided into three regions:

a- contraction zone.
b- high luminosity zone.
c- space charge zone.

The contraction zone is the transition region between the arc column proper, where the current density is relatively low, and the space charge zone, where it is relatively high. At the end of the transition zone there is a narrow region of intense luminosity which merges into the space charge zone. In the space charge zone their is a high potential gradient which accelerates electrons away from the electrode surface and accelerates ions towards the metal surface. The space charge region is a thin sheath covering the cathode spot surface.

3-1. The Thermionic Emission:

In the case of thermionic emission from an arc cathode made from a refractory material such as tungsten, the cathode can be heated to a very high temperature by the impacting positive ions which move towards the surface due to the electric field set up by their space charge. An additional possible source of heating is conduction and radiation from the hot plasma near the cathode.

The cathode-fall thickness λ_c may be of the order of an electron or ion mean free path so that many electrons cross this region without collision and excite ionise only at the end of it.

3.2. The Non-Thermionic Cathode:

At the non-thermionic cathode spot (or spots) the temperature is too low for thermionic emission of electrons.

Electron emission from a surface can occur due to an applied external electric field, provided that it is large enough.

Non-thermionic cathodes occur in welding

a- on non-refractory metals,
b- on refractory metals at low current and/or pressure.

There are at least three types of non-thermionic cathodes[4)]:

(1) *The Vapour Type*
Which forms on unfilmed metal.

(2) *The Tunnelling Type*
Which forms on thin oxide films (less than about 10 nm).

(3) *The Switching Type*
Which forms on thicker oxide films.

In the case of oxide – coated metals, it is suggested that positive ions condense on the oxide surface and set up a high electric field. In the case of thin films, if the field is higher than about 10^9 V/m electrons may tunnel through the film and generate an emitting site.

For thicker films, a phenomenon known as switching makes the film locally conducting. This allows relatively large currents to flow in filamentary channels through the oxide. Individual emitting sites are in the region of 1 nm. in diameter and have life times in the range 1 ns. to 1μs. The general effect is to strip oxide from the metal surface and generate very small but intense jets of metal vapour and debris. The sites may form wherever there is a supply of a positive ions. Formation of sites may however be inhibited by an inability to generate the required field across the oxide film; i.e. due to an excessive thickness of oxide or too low a density of ions, or a combination of the two.

The thermal balance at a non-thermionic cathode has not been studied in detail. The cathode drop is in the region 10–20V[5)] and the energy $V_c I$ is absorbed as heat in the work piece, chemical and electrical energy in dispersing oxide films, and kinetic energy (and possibly electrical energy) in the vapour jet emitted by individual cathode spots.

In the thermionic arc the cathode spot must be maintained at a high temperature in order for thermionic emission of electrons to occur, and there is an associated heat loss to the electrode and its surrounding. In the non-thermionic arc a high cathode spot temperature is not necessary for the mechanism described earlier.

It seems likely that cathode heat of a non-thermionic arc is a byproduct of the processes occuring in the cathode drop region, and until more is known of these processes, it would be futile to speculate as to the nature of the balance.

(4) Arc Modes:

Several investigators[4–8] noted five arc modes in a GTAW arc with a pure tungsten electrode. These are illustrated in **Fig. 2** and are described as follows:

(1) *Cathode-Spot Arc*
It has a bell-shaped envelope and an intense blue cone based on the cathode with a small dark spot in the centre of the base. This type was formed usually at currents above 150 A.

(2) *Unspoted Bell-Shaped Arc*
It is similar to the previous arc but without a dark spot. This type of arc occured usually between 50 and 150 A, rarely at higher currents.

(3) *Coneless Bell-Shaped Arc*
It has neither cone nor spot. It usually occured between 100 and 150 A.

(4) *Normal Mode with A Blue Cone*
It has an axe-shaped envelope but no spot. It was formed in transition from the unspotted bell-shaped to the normal mode and was observed usually between 30 and 90 A.

(5) *Normal Mode*
It is an axe-shaped arc without any spot or blue cone. This type exists over a wide current range.

In practical GTA welding the cathode spot mode of operation is almost invariably used, since this gives better directional properties.

From Olsen's results for the gas tungsten arc, it will be seen that the total arc voltage is higher in the cathode spot mode than in the normal mode, and that the increased voltage is mainly due to an increase in the sum of the anode and cathode drops. As would be expected, the axial current density in the arc volumn near the cathode is also higher of.

The electrical conductivity of the arc plasma near the cathode is independent of current and arc length within the given range.

Generaly, the normal mode can be produced in a pure-argon atmosphere with a pure-tungsten cathode shaped initially to a hemispherical tip. The true cathode spot mode can usually be produced with a pure tungsten cathode by grinding it to a sharp conical tip.

This arc, however, is semistable and may transform spontaneously to a normal mode after a short period of operation.

In 1965 Yamamoto et al.[9–11] found that a spherical zone formed at tungsten electrode tip in low pressure atmospheres and reported it behaviour and practical appli-

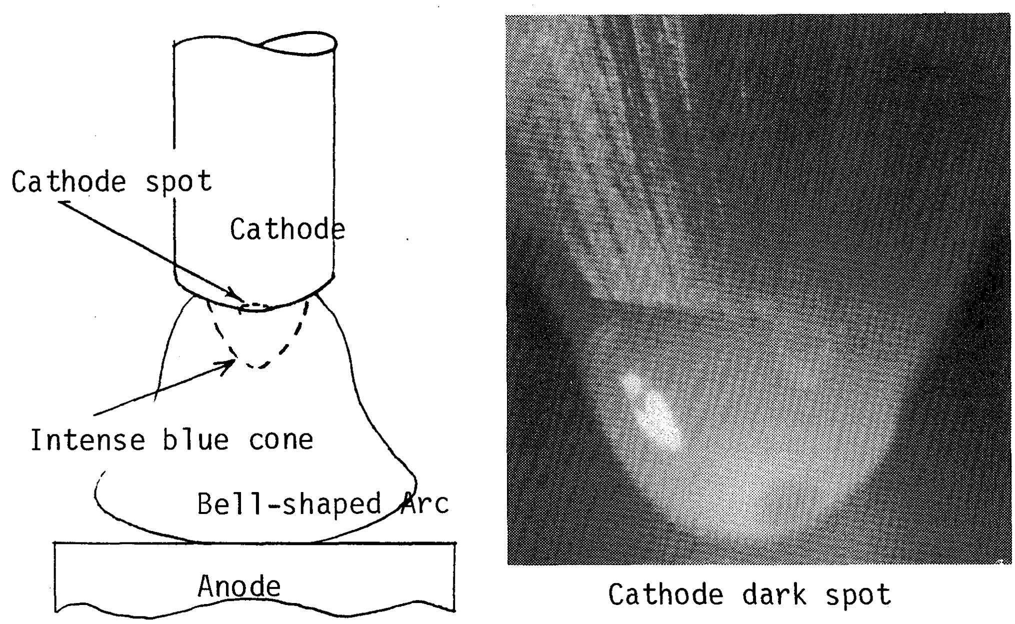

Fig. 2 Schematic representation of the tungsten/argon arc and photograph of cathode dark spot.

Table 1 Physical properties of cathode materials of low pressure argon arcs (4.0 Pa, 60 A)[12].

Cathode material and diameter, mm		Work function Φ, V	Cathode fall, V_C, V	Electron energy, $V_C - \Phi$, V	Length of CPB d_p, mm
W	6	4.54	16.8	12.3	3.9
W	4	4.54	12.6	8.1	3.6
Ta	6	4.13	11.0	6.9	3.3
Nb	6	4.01	9.5	5.5	1.4
Mo	4	4.15	9.2	5.1	0.9
Th.W	4	2.63	6.8	4.2	3.1

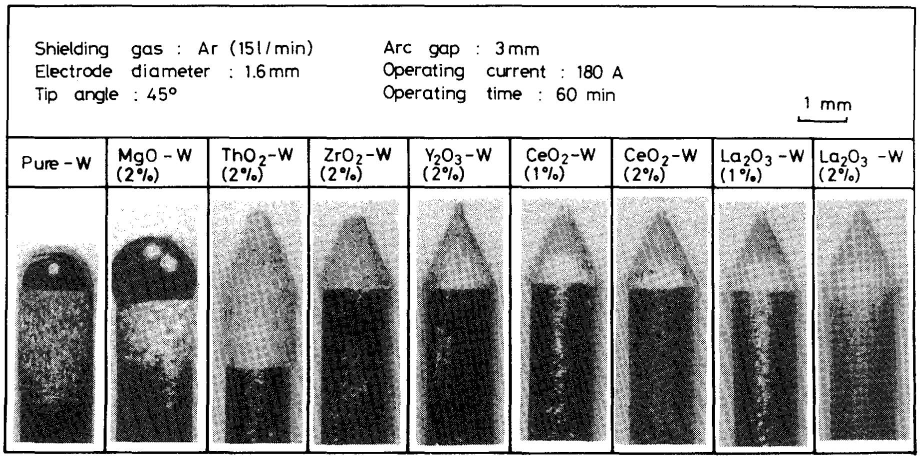

Fig. 3 Change in shape of electrode tip due to heavy loading[14].

cations. Also, A. Matsunawa[12] recognized independently in 1966 the existence of the region, which they termed Cathode Plasma Ball (CPB) in the course of an abrasion study of graphite electrodes in low pressure hydrogen arcs. They also clarified the close relationships between the CPB behaviour and the modes of the graphite cathode as well as the overall arc characteristics. It was confirmed that the CPB could be observed in other gases with any typical hot cathode electrode material, and also that both the normal and cathode spot mode arcs under atmospheric pressure showed the same CPB at lower pressures, although the size was different according to the initial mode.

The CPB increases its size with reduction in pressure and increase in the arc current, and the dark space becomes indistinct at higher pressures and currents. The CPB is concluded to be the cathode thermal ionisation region where the high energy emitted electrons collided with particles and finally thermalised. Some physical properties of cathode materials at low pressure argon arcs showing the length of CPB for each material (**Table 1**).

(5) Electrode Material:

Two materials used as welding electrodes form thermionic cathode, namely, carbon and tungsten. Other elements such as molybdenum and tantalum are also sufficiently refractory to operate in the same manner, but their use in welding is exceptional. Pure tungsten, tungsten alloyed with La, Re, Th, Y, Mg and Ce are used as electrode in GTA welding.

Pure tungsten has the disadvantage that in the cathode spot mode the tip of the electrode melts and becomes spherical, and this permits the cathode spot, and therefore the arc column, to wander.[4]

Figure 3 shows the appearance of electrode tip after one hour burning at 180A. La_2O_3-W electrode showed the least change in shape. Y_2O_3-W electrode has also little melting at the tip. Pure W and MgO-W electrodes displayed serious melting. This fact is associated with the lower work function of oxides materials, which permits equal current density of electron emission at lower temperatures.[4]

Generally the oxides have strong effect on the microstructure of the electrode. However, the oxides are insolable in tungsten and remain distributed throughout the metal, presenting a mechanical obstruction proportional to their surface. The thoria particles decrease the grain size as thoria content is increased from 1 to 5%[15]. Thoria is sometimes added to tungsten for incandescent lamp filaments in order to control the grain size on recrystallization[10,11]. The additive also determins the size of the grains when the metal is annealed after working. The character of the grain boundaries is also affected by the thoria content. In pure metal they are smooth and nearly straight, whilst the obstraction of the thoria has impared to them a ragged out line.

Although thoria restrains the growth of small grains, it has less effect upon grains, which, owing to favourable conditions, such as local absence of thoria or temperature gradients, have become comparatively large. By restraining the growth of smaller grains it may increase the grain size contrast and produce exaggerated growth and their is an optimum value in neighbourhood of 4% of thoria for this effect to occur[16].

(6) The Operational Characteristics:

6-1. Arc Starting Perofrmance

Starting is accomplished by one of two means, namely, by superimposed high-frequency spark or by contact of the electrode with the work. Reliability of spark starting is dependent upon the previous history of tungsten electrode. The transition from the high-frequency spark to an arc is often erratic, resulting in spoilage of work, especially with mechanized setups. The resulting arc is unstable and the arc cathode spot is highly mobile and frequently travels up the electrode, resulting in damage to the collet. The phenomenon is shown in **Fig. 4**, quoted from Ref. (17). The problem of erratic starting and instability has been solved by the use of an electrode containing the necessary oxide.

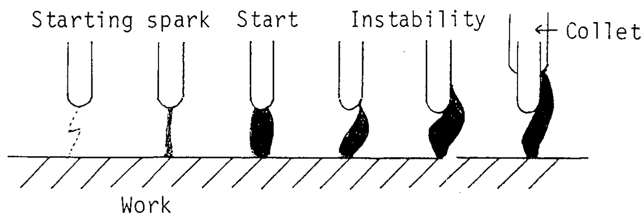

Fig. 4 Diagram showing bad effect of erratic motion of arc roots[17].

The criterion for evaluating starting characteristics was the minimum Open-Circuit Voltage (OCV) required for reliable starting with superimposed HF Spark (HF off after ignition) from a standard unit. Obviously, the best electrode is that requiring the least starting voltage.

Starting performance was classified to three groups, that is, successful arc starting, incomplete arc starting showing apparent crimbing up and erratic motion of arc root, and failure in arc following. Obtained results are illustrated in **Fig. 5**. La_2O_3-W, CeO_2-W and ThO_2-W electrodes have superior arc starting characteristics.

Some of the more important test results are summarized in Table 2[17]. These data indicate the marked improvement resulting from the use of thoria content. The full benefit of thoria does not become evident until the thoria content is approximately 5%. Lower proportions exhibit random starting voltages which are relatively high compared to those obtained with the optimum thoria content. Table 2 also gives the operating current range for pure tungsten and for the thoriated electrodes. These changes have been observed to be either excessive melting of the tip, especially in the case of pure tungsten or necking down of the electrode in the region above the tip. The latter condition is usually found in thoriated electrodes.

The last column of Table 2 shows the current at which

Table 2 Electrode characteristics (Quoted from Ref. (17)).

Work material	Min. dependable OCV for starting			Operating current range, A.	Failure current, A.
Anode	Copper	stainless steel	silicon steel		
Tungsten pointed	95	95	95	50-370	400
Thoriated tungsten pointed (1% ThO_2)	40-65	55-70	70-75	10-350	385
High-thoria, pointed (15% ThO_2)	35	40	40	6-310	350

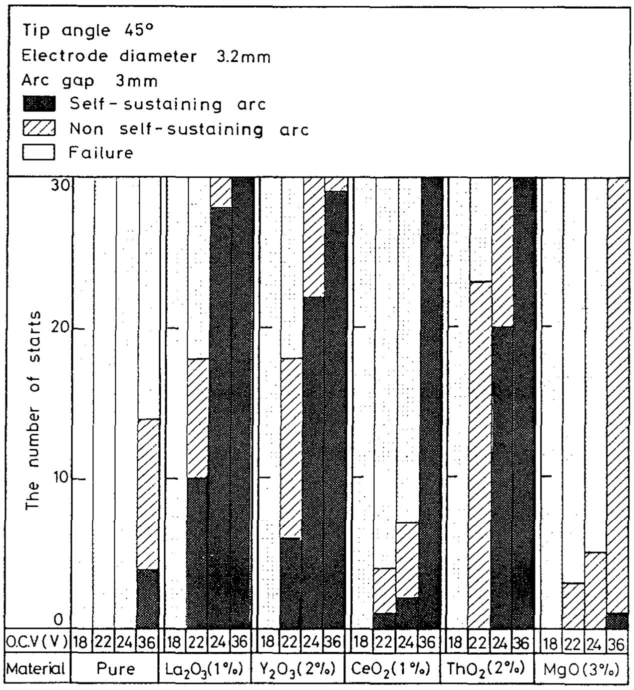

Fig. 5 Arc starting characteristics by O.C.V. test for various W-electrode[14].

failure occured for the three electrode materials. In all cases, the failure appeared as a melting off of a short section of the electrode at the tip.

6-2. Arc Voltage-Current Characteristics:

In order to be able to analyze the complete electrical arc circuit, static volt-ampere characteristics are needed. The volt-ampere characteristics for GTA welding with tungsten electrode negative has been investigated by a number of authors, and the results are summarised by Jackson[2].

At low currents the arc voltage falls sharply with increasing current and reaches a minimum at current of between 100 A and 300 A. The minimum voltage and the general form of the voltage-current characteristics depends upon the cathodic electrode size and material, on the anode size, material and temperature, on the nature of shielding gas and on the arc length.

The sensitivity of volt-ampere characteristics to these factors is demonstrated by the family of volt-ampere curves covering a broad range of experimental conditions shown in Fig. 6[6].

At a fixed current, differences in operating voltage observed with different cathodes are believed to be caused by changes in potential drop in the immediate vicinity of the electrodes.

Since the anode was the same in all cases, the anode drop is expected to be independent of cathode changes for a given current. The observed total arc-voltage changes are, therefore, believed to be caused by changes in the cathode potential drop.

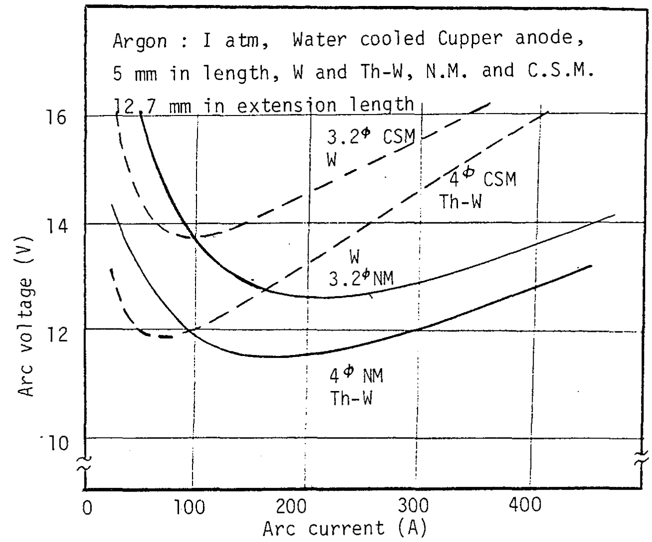

Fig. 6 Comparison between V-I characteristics in cathode-spot-mode and that in normal-mode[6].

Jackson, however, refered to the change in voltage caused by the change in cathode shape. In measuring normal-mode volt-ampere curves with pure tungsten cathode, voltage data taken with increasing current are different from those taken with deacreasing current[6]. Actually the data taken in cyclic manner and two curves show, in effect, a hysteresis.

This hysteresis is a result of a relatively slow change in molten tip shape with current. If the current is suddenly increased, the new opperating point will fall initially on the upper curve and gradually drop to the lower voltage as the tip geometry changes with continued operation at the new current.

Examples of volt-ampere curve for the cathode-spot mode are shown in Fig. 6. At currents below 100 A, these curves rises sharply. A hysteresis effect similar to that observed in the normal mode was also observed with the cathode-spot mode.

The typical shape of the voltage-current characteristics indicates that this curve is the result of at least two factors.

(1) The explanations which has been suggested is that the voltage current curve is the result of the sum of
   a- an arc potential increasing more or less linearly with current,
   b- a potential associated with the power required to maintain the arc action at the cathode which decrease as the temperature increases with current.

(2) The measurement of volt-ampere characteristics requires painstaking laboratory techniques. Since the data may be dependent upon the experimental conditions, such as electrode material, shape, extension length, power supply system and so on, absolute

values may be almost impossible to establish. The data selected from a number of investigators are scattered as shown in Ref. (2).

A few data have been reported by Morten and Gage[18] comparing the volt-ampere characteristics with another gas than argon such as neon krypton, xenon and helium shielding for a tungsten cathode, molten titanium anode with a 0.5-in. arc length **Fig. 7**. The low current arc in a helium atmosphere with a molten titanium anode appears to contain iones of the metal only as evidenced by the presence of titanium spectral lines excluding the helium spectral lines. A sharp transition in the helium arc is found to take place at about 150 amp. The voltage drops and the radiation are altered by the sudden appearance of helium lines in the central arc region. It is difficult in practice to measure the voltage between the cathode spot and the anode. The arc voltage reported by most observers includes the voltage drop across all or part of the electrodes and this contributes to the rising part of the characteristics.

Where correction are made for potential drop in the leads and the electrode, the voltage of an argon shielded tungsten arc decreases sharply up to 50 amp., then levels out and either remains level or rises gently. The equation for the volt-ampere characteristics at constant arc length is

$$V = A + BI + C/I$$

and the values of the constants found by Goldman[19] are given in Table 3.

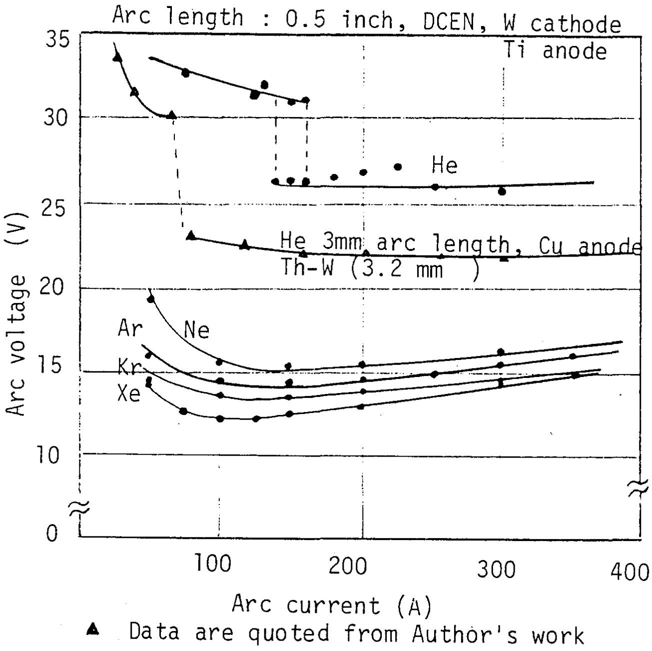

Fig. 7 V-I characteristics for arcs in various gases[13].

Table 3 Constants for arc characteristics[19].

Arc gap mm	A	B	C	V min V	I at V min. A
1.0	7.2	0.007	170	9.3	156
2.0	6.7	0.010	175	9.4	132
8.0	10.0	0.015	160	12.75	110
16.0	14.0	0.007	160	16.1	151

6-3. Voltage-Arc Length Characteristics:

When working with low pressure, low current arcs, it is customary to determine the plasma potential gradient from the slope of the voltage arc length curves. The sum of the electrode drops is usually determined from a zero length extrapolation of the voltage-arc length curve. In such measurements, the electrode drops are assumed to be independent of arc length. In high current welding arcs at atmospheric pressure and relatively short length, this procedure may not be satisfactory since the electrode drops depend on the electrode separation. Voltage-arc length characteristics for 200, and 400 amp. arcs operating in both modes are plotted in **Fig. 8**.

Voltage-arc length characteristics for various electrodes and arc currents are shown in **Fig. 9**. The lower three curves show the effect of different thermal regimes at the electrode; where the heat sink is greatest (anode and cathode both non-molten) the arc voltage is highest. The

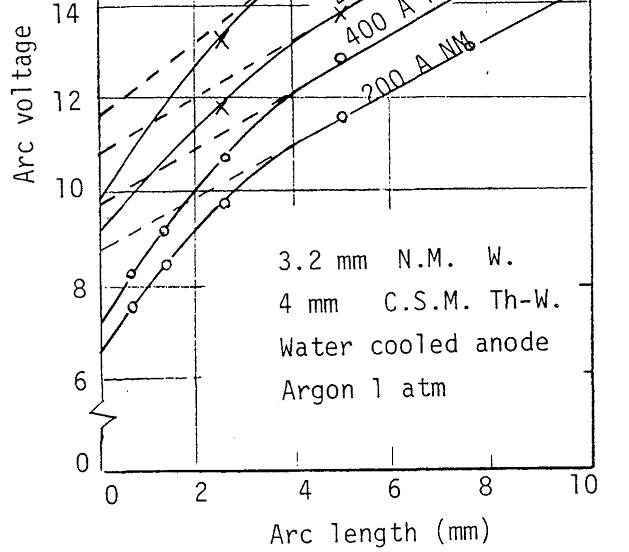

Fig. 8 Effect of changing current and mode of operation on voltage-length characteristics of arc[6].

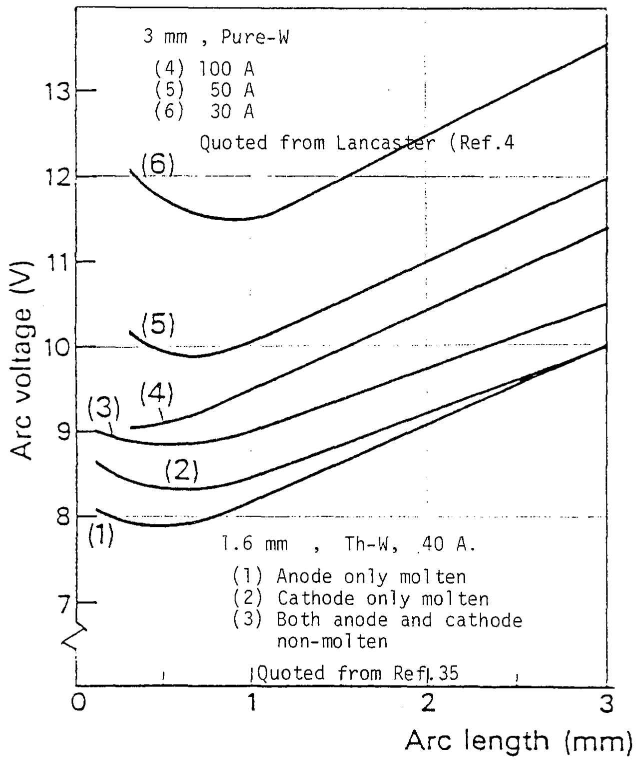

Fig. 9 Voltage- arc length curves for argon-shielded tungsten arcs[4].

upper three curves show the effect of current at 100 amp. and below. Five of the six curves show an increase in voltage at arc length below about 1 mm. This effect is not always observed. A similar voltage rise is at times caused by a deflection of the arc away from the electrode axis with extremely short gaps. As the current is increased to 200 amp. and above, this deflection is not observed. Additional voltage-length data for currents up to 1000 amp. are shown in **Fig. 10.**

Extrapolation of the voltage-arc length characteristics to zero arc length gives only a zero length limit of the sum of the electrode potentials. But this extrapolation with constant slope from points at lengths greater than 0.2 in. does give a significant value for the long arc electrode

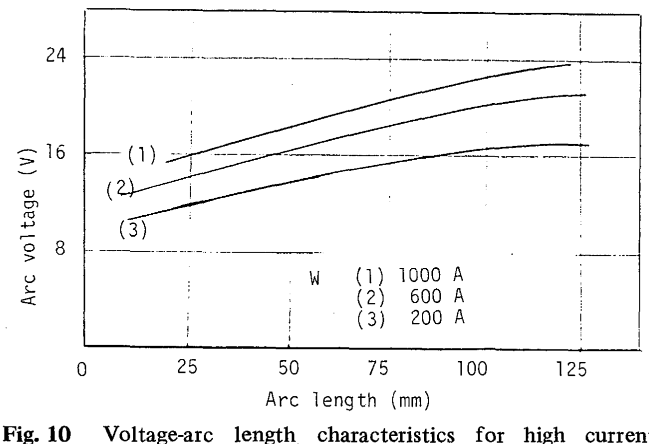

Fig. 10 Voltage-arc length characteristics for high current tungsten/argon arc[2].

potential drops.

6-4. Electric-Field Intensity:

If one assumes the electric-field intensity at a given point on the arc axis to be constant across the plasma its magnitude at any point along the axis can be calculated.

Measurements of the electric-field intensity show that it is a maximum close to the tungsten cathode falls to minimum close to the anode (in this case water-cooled) and rises slightly very near the anode. Olsen distinguished between a "normal mode" of operation and the "cathode spot mode". It is suggested that the decrease in the electric-field intensity for the normal mode operation is associated with an increase in the diameter of the conduction column.

However, as we mentioned in the preceeding subsection, that several authors have observed an increase in arc voltage at arc length below 0.5–0.8 mm. Also, it may be seen from Fig. 8 that the electric field intensity varies across the arc volumn, being usually highest in the vicinity of the cathode. The apparent straight line characteristics may be due to the extension of that part of the column where the potential gradient is indeed constant, and the value of cathode drop obtained by extrapolation may be too high.

6-5. Current Density:

When a cathode is heated to a sufficiently high temperature electrons are emitted with a current density J given by the Richardson-Dushman equation.

$$J = AT^2 e^{-b/T}$$

Where:

A Constant has a value about $6 \times 10^5 A/m^2K^2$ for most metals

b $= \phi e/k$ where ϕ is the work function of the cathode surface

e Is the charge on an electron

k Boltzman's constant

T The surface temperature in Kelvin

The current density of thermionic emission thus depends ciritacally upon the cathode surface temperature, and, unless this can be increased to a sufficiently high value, it is not possible to reach the current densities which are encountered in arcs. The thermionic emission can explain current densities at the cathode of the order estimated from measurement **Fig. 11**. These current densities on tungsten are in the range 10^6 to 10^8 A/m^2 when it is emitting thermionically, and the cathode spot normally occupies a fixed position.

Above argumentative explanation was done by Guile[3]. Also the effect on the arc plasma of changing current and

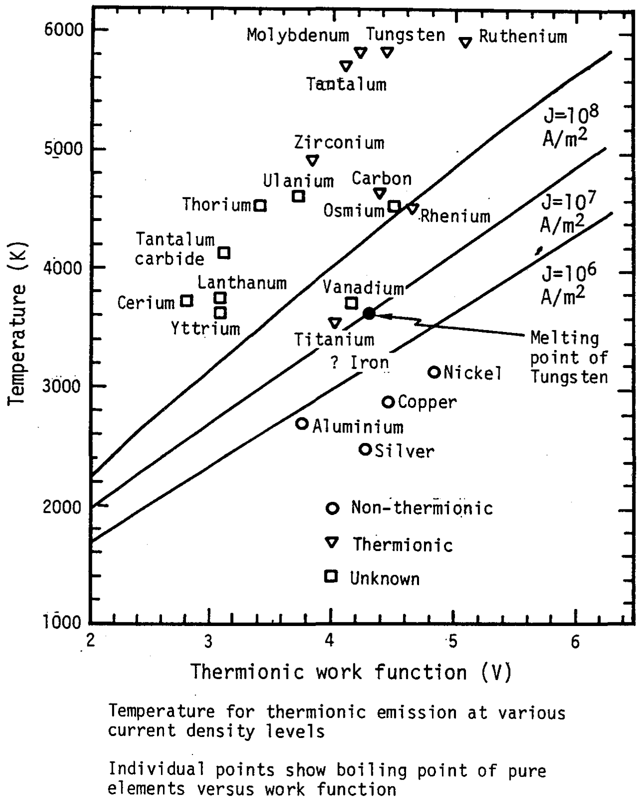

Fig. 11 Temperature for thermionic emission at various current density levels[3].

modes of operation are best shown by radial current density distribution at the anode and cathode area. The distributions of plasma are calculated by Olsen from the temperature distributions of plasma and electrical conductivity. An increase in total arc current only distributes the current over a larger area of the anode with no change in peak current density on arc axis.

The current density of the surface of electrode has not yet been measured.

6-6. Arc Pressure:

The arc pressure stability is one of the conditions to have a uniform welded joint. In other words the pressure exerted by the welding arc on the molten pool is one of the parameters which determines the depth of penetration of the weld. The flow of heat from the arc to the work piece melts the metal to a certain depth, while the applied pressure digs a depression in the molten pool giving access for the heat flux to the metal deeper inside the work piece. To obtain good penetration, a high pressure would be desirable with the risk of blow through when welding in a joint with a finite root gap. Experiments show that the arc pressure influenced by several factors as follows

(1) *Tip Angle and The Trunction of Electrode*

The changes in these parameters affecting the fluctuation of the flow pressure and disturb the dynamic equilibrium of the weld pool[20,21,22]. The electrode with initial trunction gives completely different results with an increasing truncation radius, the maximum pressure decreases and the curves become flatter **Fig. 12.**

(2) *Welding Speed*

The results of several investigators[23] show that welding at higher speeds is characterised by lowering the arc pressure, and also by the displacement of the arc pressure maximum, caused by the asymmetric distribution of current density, to the front part of the active spot. This is a consequence of the more intensive cooling of the arc column and the active spot, and especially of the front part of the latter, and of a reduction in the size of the column and the spot, as shown in **Fig. 13.**

The pressure distribution under a TIG arc has been measured and published in a number of papers. Erohkin et al.[20] found that for sharp electrode tips the distribution was a steep Gaussian, but for plunt electrodes and significant end flats it was more rectangular with a lower maximum. Selyanenkov et al.[25] found an exponential radial distribution for fairly sharp tips. Furthermore, during practical welding, the flow patter, and hence the pressure distribution, will be influenced by the shape of the groove and the pool surface[26]. Also the pressure distribution along the work piece depends on the flow pattern and is not directly related to the current distribution at the work piece.

As a conclusion we can say that the arc pressure is originated mainly by the induced flow of plasma gas due to the expansion of current path near the cathode. The truncation or deformation due to melting changes the thermal state of electrode and the impedance for induced flow of plasma gas, consequently leads to a change in the arc pressure[14] **Fig. 14** shows the arc pressure distribution

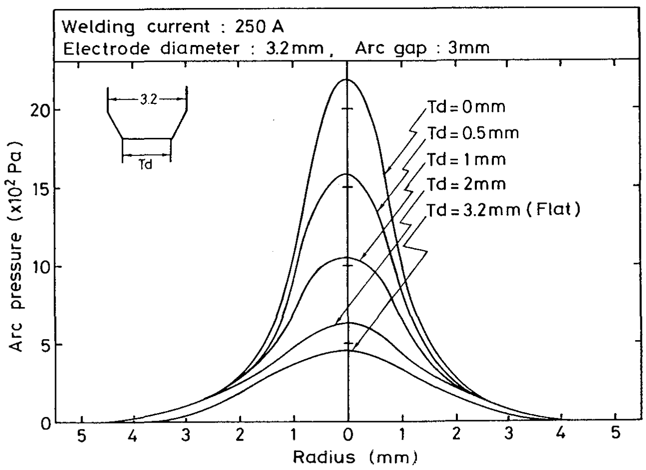

Fig. 12 Arc pressure distribution at various radii of electrode truncation[14].

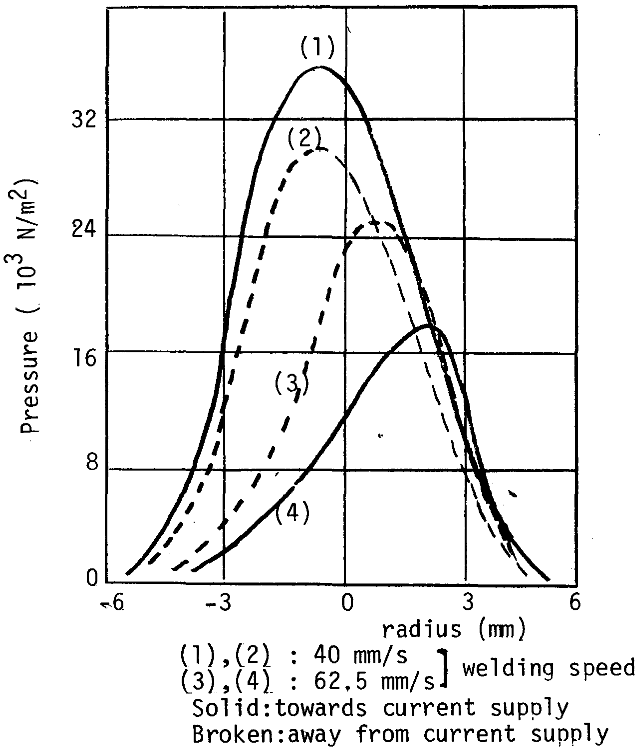

Fig. 13 Dependence of distributions of arc pressure on welding speed[23].

at the water cooled copper anode for several electrode materials measured by a semiconductor transducer and the arc pressure as a function of arc current is illustrated in **Fig. 15**. Also **Fig. 16** shows the maximum arc pressure at various radii of electrode truncation related with arc current, in which the curve of pure tungsten appeared in Fig. is also plotted with adotted line. The results represent the CeO_2-W, Y_2O_3-W and La_2O_3-W electrodes have little deformation of electrode tip[14].

6-7. Electrode Temperature and Temperature Distribution:

It is important to measure the temperature of the arc in analysing a metallurgical reaction e.g. the reaction between gas and metal in the arc or in grasping the melting phenomena of welding materials. Especially is it a prerequisite for the investigation of the generating phenomena of welding fume. Also the arc temperature determines the degree of dissociation and of ionisation at the arc column.

The relation between temperature and degree of ionization is given by the Saha equation. In **Figs. 17**, the degree of ionisation is plotted as a function of temperature for some gases and metal vapours.

The majority of temperature measurement of arc column have been made spectroscopically, and the majority of such measurement have been made of the argon shielded tungsten/copper arc. By Olsen, it is shown that the temperature of arc does not appear to vary oreatly with arc current up to 400 amp. without increase in radius of arc temperature isitherms. And, the electrical conductivity of argon reaches a plateau at about 2×10^4 K, so that this is probably an optimum temperature for a plasma just close to thermionic cathode.

Kobayashi and Suga[27] also found that the temperature of the TIG arc is approximately 1.5×10^4 K, which almost coincides with several investigators[6,28,29]. Moreover, they found that there is an apparent decrease in the arc temperature from the arc center towards the surrounding atmosphere, and that this tendency is more marked in the vicinity of tungsten cathode and when the supplied electric power is reduced, as shown in **Fig. 18**. The axial distribution of the average arc temperature is shown in

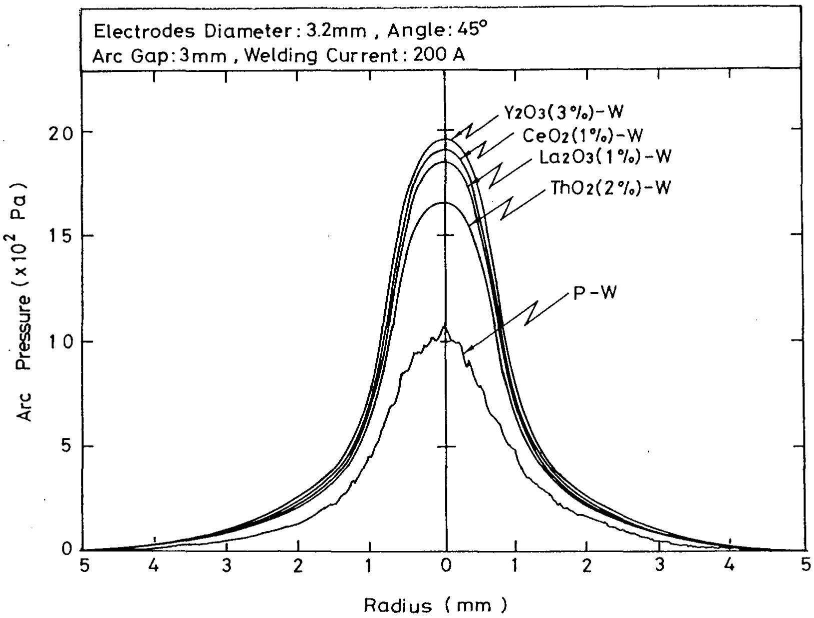

Fig. 14 Arc pressure distributions for various tungsten cathode[14].

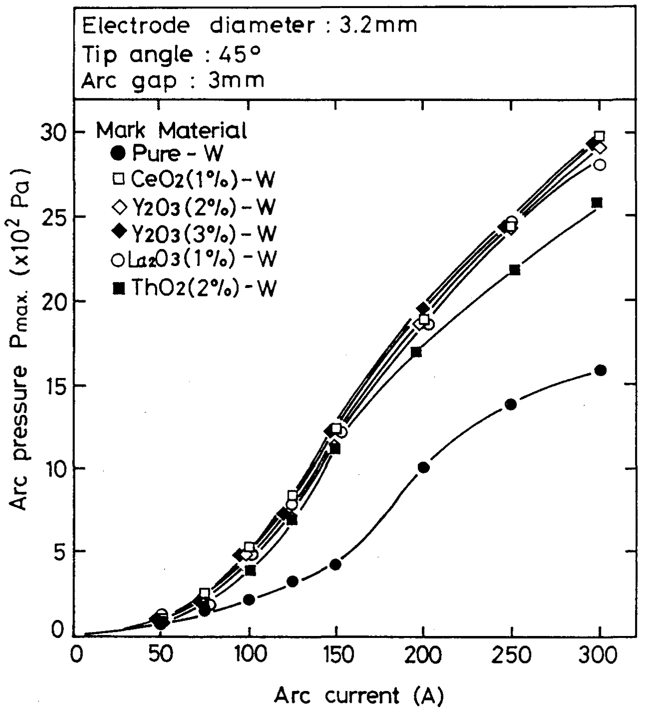

Fig. 15 Effect of current on maximum arc pressure for various tungsten cathode[14].

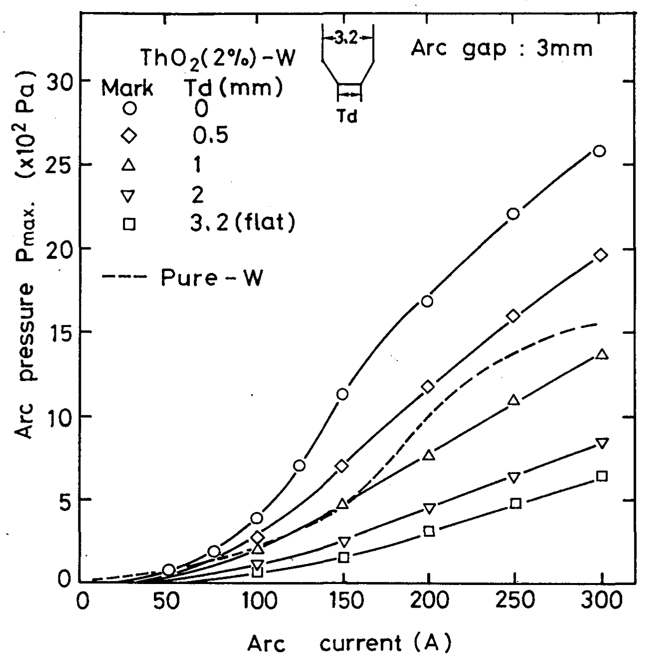

Fig. 16 Effect of truncated diameter of electrode tip on arc pressure[14].

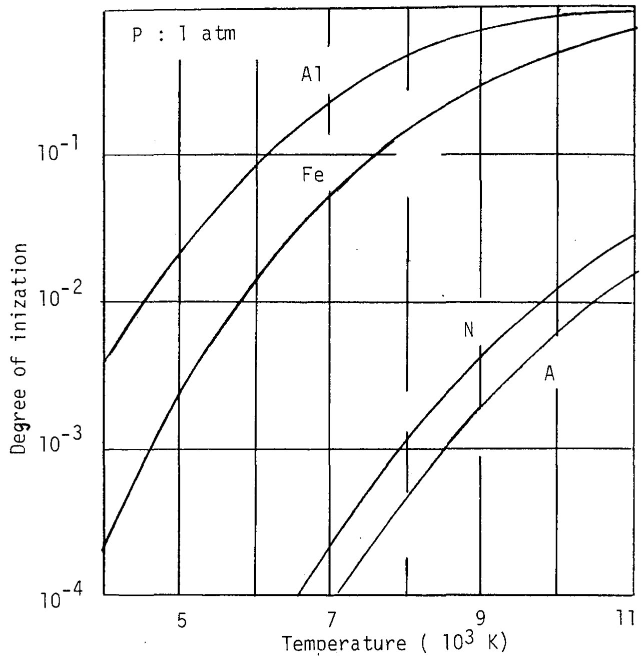

Fig. 17 Degree of ionization as a function of temperature for some metal vapor (Aluminum and Iron) and gases (Nitrogen and Argon)[3].

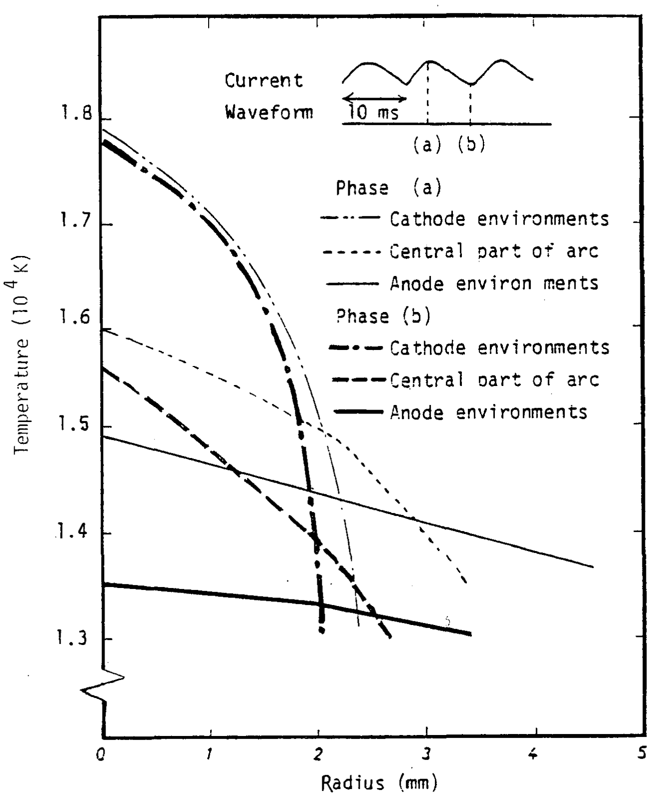

Fig. 18 Radial distributions of arc temperature[27].

Fig. 19[27]. From the figure, the arc temperature increase towards the tungsten cathode. The reason is assumed to be that the thermal movement at the cathode enviroments becomes active owing to the higher current density caused by arc contraction. But Key et al.[30] they found relatively low temperatures close to the cathode. They pointed it is very difficult to determine the thermal state of the plasma in the vicinity of cathode.

Effect of welding parameters on arc temperature

(1) *Shielding Gas*

The effect of shielding gas composition on the arc column temperature was investigated by Key et al.[30], who found that pure argon, 90% He-10% Ar, and 95% Ar-5% H_2 all produced about the same peak temperature, although the spread of the arc was greater in helium/argon and argon/hydrogen mixtures.

(2) *Welding Current*

Kobayashi et al.[27] found that the arc temperature elevates as the welding current increases as shown in Fig. 20. This tendency can be explained in terms of thermal movement, which becomes active by the

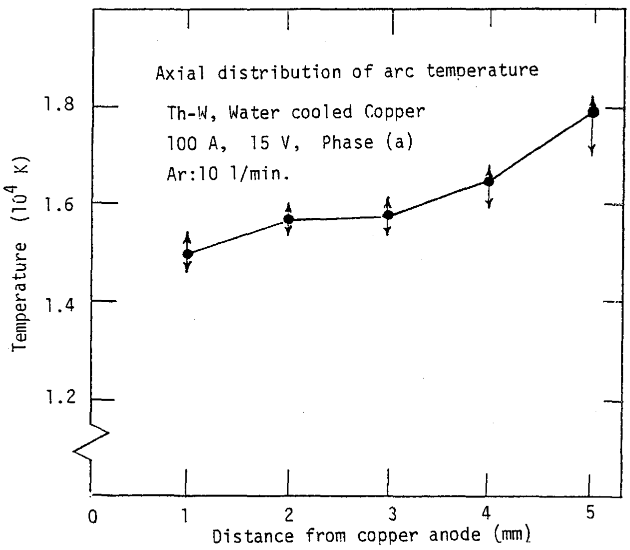

Fig. 19 Axial distribution of arc temperature[27].

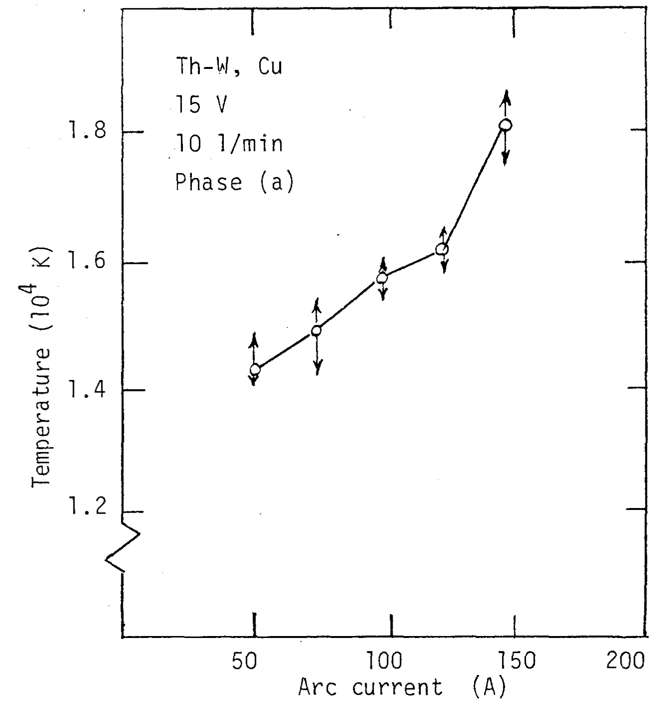

Fig. 20 Relationship between arc current and arc temperature[27].

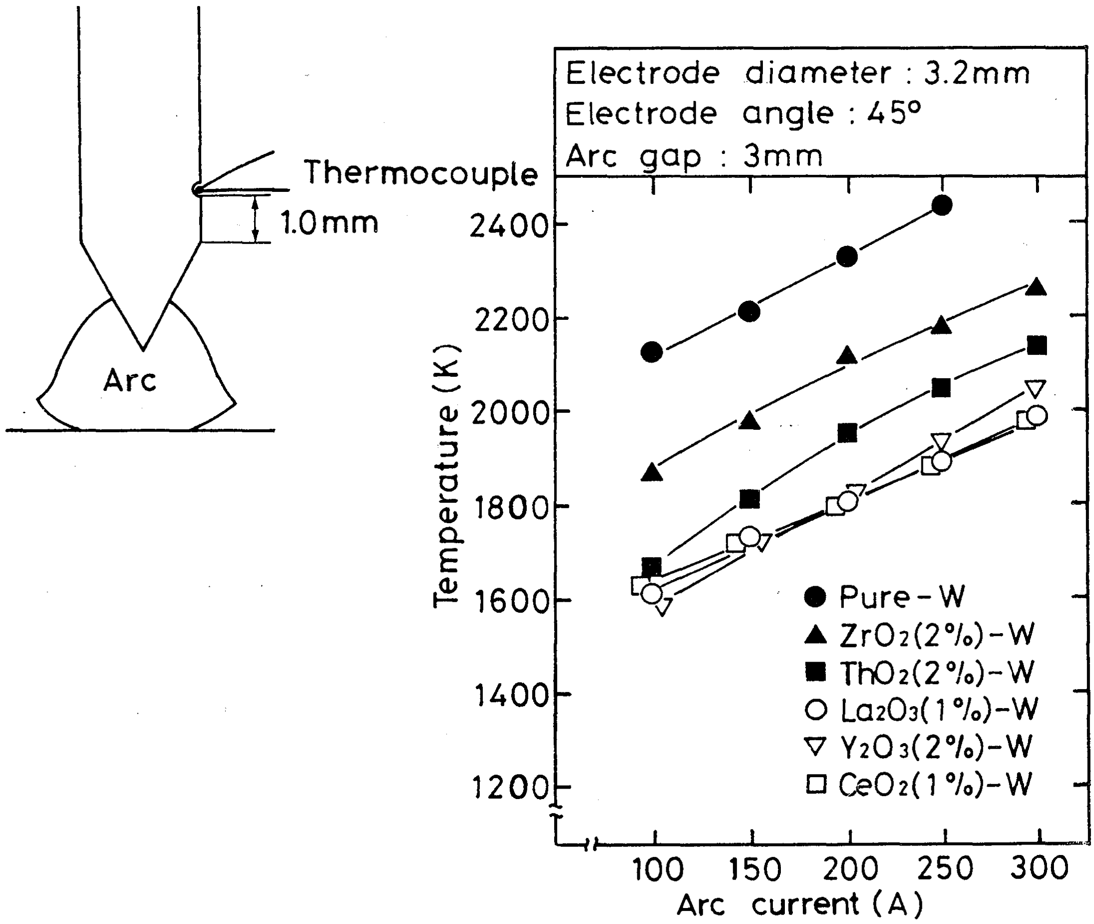

Fig. 21 Electrode temperature measurement by thermocouple[14].

increase in the supplied power. F. Matsuda and M. Ushio[14] measured the electrode temperature just above the conical zone of cathode by the use of a thermo-couple for various electrode materials with changing the current as shown in **Fig. 21**. Measured value is not the temperature of the working area (spot area) as the cathode, but, it should reflect the thermal state of cathode. Also, they found the same trend, besides that the La_2O_3-W, Y_2O_3-W and CeO_2-W electrodes showed the lowest temperatures.

(3) *Welding Voltage*

The relationship between welding voltage and the average arc temperature is shown in **Fig. 22**[27]. The arc temperature decreases with increase of welding voltage. This because the current density at the measured part (central part of the arc) decreases with voltage increase judging from the shape of the arc. However, it is reported that the arc temperature is not influenced by the voltage[31].

(4) *Gas Flow Rate*

The argon gas flow rate has no influence on the arc temperature within the usually applied range[27].

(7) Electrode Erosion and Formation of Rim:

Electrode erosion due to arcing has been experimentally observed in the form of small (0.1 μm diameter) spheres which have been transported to the opposite electrode, by Eoin W. Gray and Julian R. Pharney[32].

There are three mechanisms for the formation of the

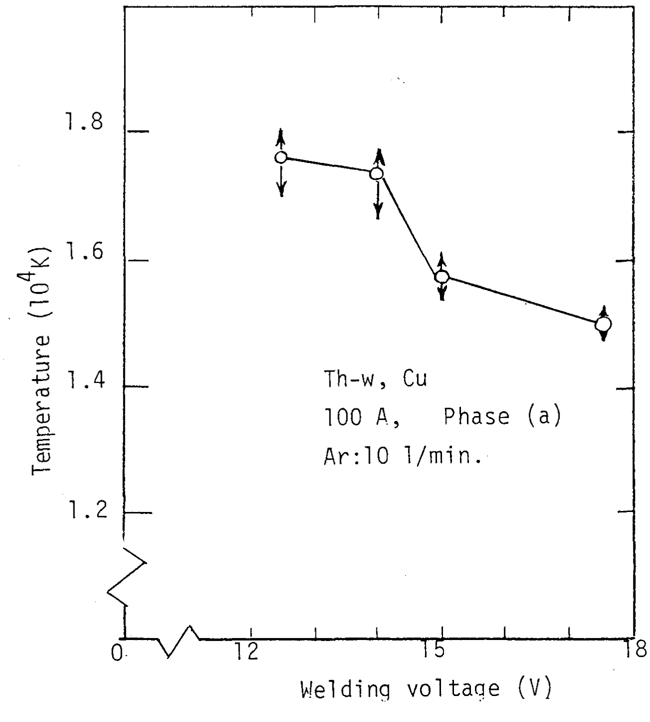

Fig. 22 Relationship between welding voltage and arc temperature[27].

observed sphere. The first, when we consider separating contacts, is that of the rupture of the molten bridge which is formed by the separation of current carrying contacts. When the bridge ruptures, molten metal and vapor are explosively expelled into the interelectrode gap and may form droplets. However, this method of droplet production would supply only a small number of particles per operation and thousands observed must obviously be formed by other means.

A second mechanism of material transfer is postulated when large electric fields exist following the abrupt cassation of arc current. The resultant electrostatic force can pull the molten electrode matrial into the gap, and depending on whether this force is stronger than that of the surface tension of the molten metal, particles or protuberances may or may not be formed. Subsequent metal cooling, which can occur rapidly, then enables observation of the resulting particles and protuberances.

The third mechanism of material transfer is occured by electrostatic pulling of molten anode material as a result of high electrostatic fields existing in the interelectrode gap either the prearc ignition stages or immediately following arc extinction.

7-1. Effect of Shielding Gases:

According to the welding condition, some times it is recommended to use shielding mixture of argon with another gases such as CO_2, O_2, N, H_2 ... etc. **Figure 23** and **24** shows the effect of oxygen or nitrogen, or CO_2 contents in the argon shielding gas on the consumption of electrode. It is clearly observed that the addition of oxidising component to argon leads to failure of the cathode and formation of "rim" as shown in **Fig. 25**.

There are several mechanisms of rim formation one of them is reported in reference[34] and basied on the mechanism of explosive escape of thoria from the electrode as mentioned before.

The second one is showed in reference[33]. Here the authors believe that the explanation of electrode wear on the basis of the explosive escape of thoria from the body of the electrode is inconclusive, because the rim does not form, at the zone of maximum temperature and they examined the microstructure which did not reveal the formation of cavities in the body of electrode at rim zone. In addition, the micro X-ray analysis showed the presence of thorium in the rim. According to that they suggested the following explanation:

In welding with activated tungsten electrodes, due to the lower operating temperature, the volume of molten electrode metal is considerably smaller. Consequently, the droplet does not separate from the electrode. Under the effect of arc pressure, the molten electrode metal is pushed upwards from the zone of highest temperature,

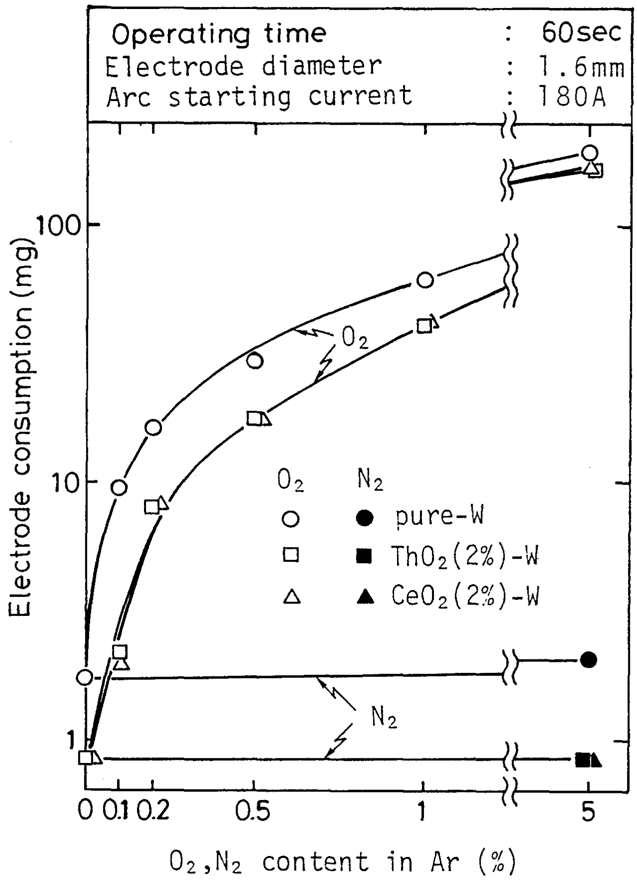

Fig. 23 Effect of oxygen and nitrogen introduced in argon shielding gas on electrode consumption[14].

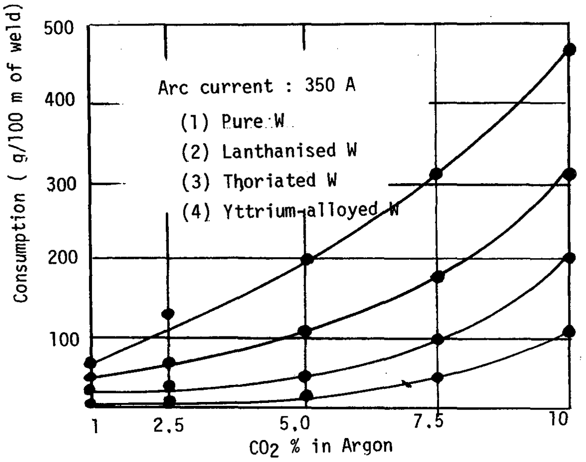

Fig. 24 Effect of CO_2 content in argon on consumption of various tungsten electrode[33].

and it solidifies in the zone of lower temperature at the periphery of the electrode. It is evident that this displacement is facilitated by a reduction in surface tension with increase in the oxygen content in the shielding gas.

The second mechanism is showed in reference[22] in which the tests was carried out on Y_2O_3 activated electrode.

This mechanism can be explain as follows:

(1) In the initial period (during 1.5–2 min.) Yttrium

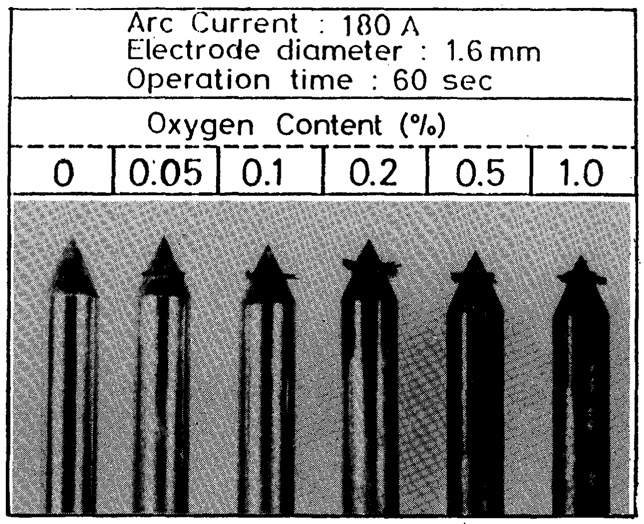

Fig. 25 Chan-e in electrode shape due to oxygen mixing into argon shielding gas[14].

oxide is transferred rapidly from the surface of the electrode to near cathode zone of the arc. This transfer leads to:

a- A reduction in electric field strength at this zone.

b- A reduction in the kinetic energy of electron travelling to the arc column.

c- A consequent reduction in the kinetic energyof the neutral particles (argon atoms) that take part in the formation of the plasma flow; i.e. the dynamic pressure of the flow decrease.

(2) In the second period:
The removal of Yttrium oxide from the surface of the electrode leading to:

a- An increase in the electric field strength near the cathode zone of the arc.

b- The kinetic energy of the electrons increases.

c- But the pressure of plasma flow continuous to decrease because the increase in kinetic energy of the negative ions that form in the near cathode zone, and they bombared the electrode.

d- The latter begins to disintegrate rapidly and this results in the formation of rim on the electrode, which disrupts the laminar nature of the flow of argon into the near cathode zone.

Another mechanism was suggested in reference (9) by F. Matsuda and M. Ushio. They said that the material of the rim is considered to originate from the electrode surface through oxidation of tungsten. Electrode diameter of the rod part just behind the conical part, is greatly reduced. Tungsten is very easy to oxydize and its products can evaporate and decompose with comparatively low temperature as shown in **Fig. 26**. The vapor of oxydized tungsten may travel along the gas flow which follows to the induced plasma flow, and through decomposition pure

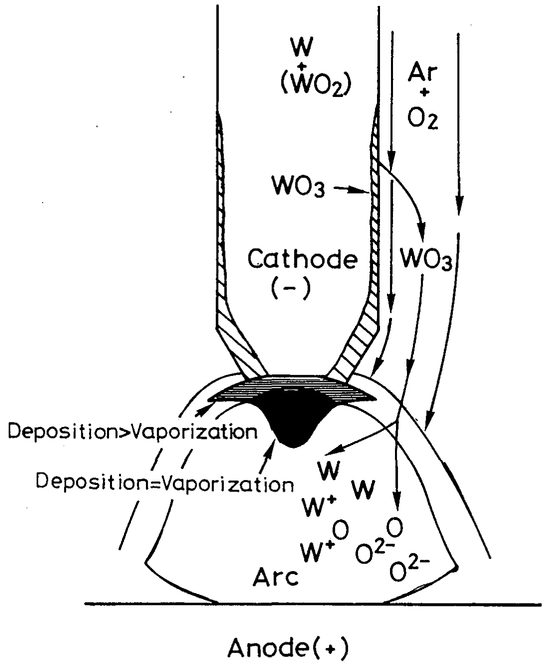

Fig. 26 Mechanism of electrode consumption and formation of rim[14].

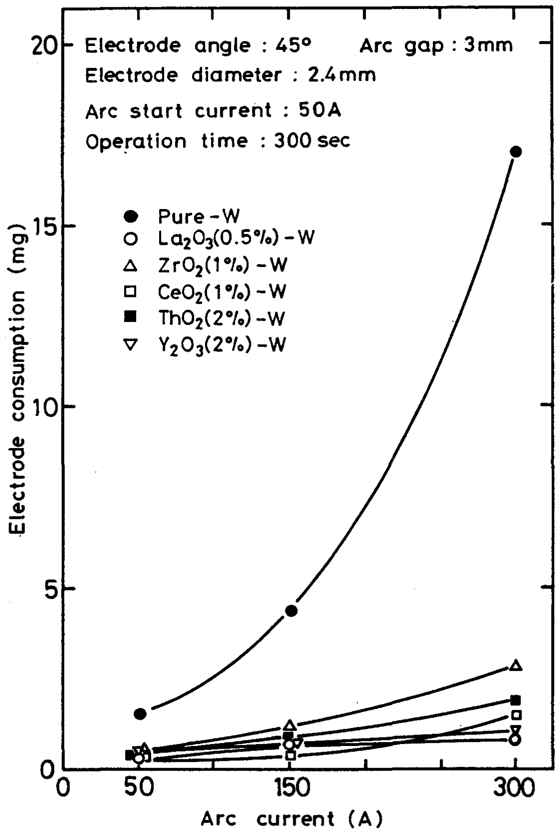

Fig. 27 Effect of arc current on electrode consumption.

tungsten may deposit on the surface where the situation is suitable for crystal growth.

7-2. Effect of Arc Current:

A measurement of the effect of arc current on several electrode materials was carried out in steady state with DCEN polarity[14]. Decrease in weight of electrode after 5 minutes arc burning were plotted as a function of arc current, which is illustrated in **Fig. 27**. The consumption of the electrode generally increases with increasing welding current. But tungsten oxide electrodes displayed very little consumption compared with pure tungsten electrode.

As a conclusion of these articles the mechanism of rim formation and electrode consumption need farther more studies in near future, and also to produce a new types of unconsumable elecrodes.

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