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Review of Arc Efficiency Values for Gas Tungsten Arc Welding

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Abstract

The aim of this study was to review the literature that specifies arc efficiency values for gas tungsten arc welding (GTAW) and, if possible, propose a plausible value range. The literature review covered the years between 1955 and 2011, and showed that the arc efficiency values published lie in a wide range. Values between 0.36 and 0.90 were found for GTAW DCEN. Only a few studies covered DCEP and AC current welding. Specific information about the reproducibility of calorimetric studies was scarce (considering both random and systematic errors). A plausible arc efficiency range (95% confidence) for GTAW DCEN was estimated to be 0.73 – 0.82 with an average value of 0.78. The arc efficiency is lowered by longer arcs (increased arc gap). Reports describing the influence of arc current and travel speed, however, conflict. The GTAW process with DCEN is an efficient welding method.

Keywords

Gas tungsten arc welding; GTA welding; GTAW; TIG welding; TIG; Arc welding; Energy input; Energy losses; Heat flow; Arc efficiency; Process parameters; Power factor.

List of symbols

η_a	arc efficiency
q_w	net power input to a substrate
q_n	gross power input
η_m	melting efficiency
q_m	power used for melting
2D	2 dimensional (heat flow)
3D	3 dimensional (heat flow)
DCEN	direct current electrode negative
DCEP	direct current electrode positive
EN	electrode negative
FEM	Finite Element Method
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
MMA	Manual Metal Arc welding
P_{av}	average power (defined by Eq. (2) or (3))
PAW	Plasma Arc Welding
SAW	Submerged Arc Welding
SEC	Seebeck Envelope Calorimeter
TIG	Tungsten Inert Gas welding

1. Introduction

Why is it important to know the arc efficiency of TIG welding more precisely? GTAW is one of the most widely used arc welding method for welding stainless steels, far more used than, for example, gas metal arc welding (GMAW). It is important to know how much of the energy is actually transferred to the material being welded. A wide range of arc efficiency values for GTAW has been reported over the years. Values between 0.22 and 0.80 can be found in different monographs [1-4], but reported range is actually larger. This report examines the background references and the relevance of values for GTAW that have been determined, and attempts to define a narrower band for the arc efficiency, η_a .

Arc efficiency (also known as *process efficiency*, *thermal efficiency* and *heat transfer efficiency*) plays an important role in many aspects of welding technology. The concept is used, for example, when estimating process performance, in calculating cooling rates or cooling times, and when modelling fusion characteristics. It has become more important to know η_a more precisely, and to know how different process parameters (such as current, welding speed, electrode tip angle and type of shielding gas) influence the arc efficiency, for instance in order to use today's numerical heat-transfer-models accurately. Arc efficiency, η_a , is normally defined as:

$$\eta_a = q_w/q_n \quad (1)$$

Where q_w is the net power input transferred to the plate (substrate) and q_n is the gross (or nominal) power input to the arc from a certain power source. The part not transferred to the work piece, $[1-\eta_a]$, is lost through radiation, convection, electrode heating and heat conduction in the TIG torch. Figure 1 shows schematically the flows of energy during welding. Calorimetric methods are often used to measure q_w , and several methods have been developed.

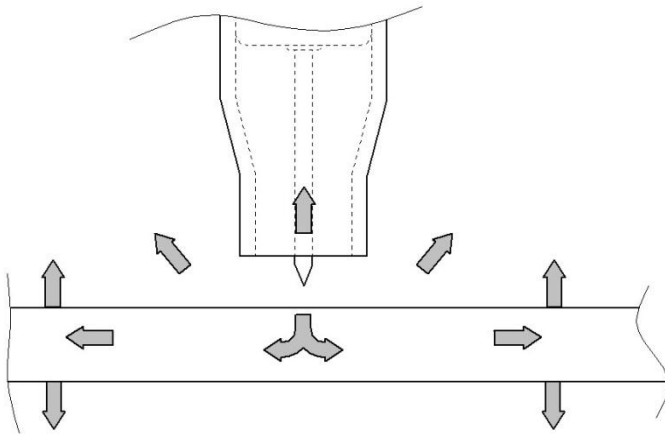


Fig 1. A schematic TIG torch and the heat transfer around it.

The gross energy input during welding can be measured in several ways. In the case of DC arc welding, q_n is simply the product of current I , voltage U at the arc, and welding time t . In the case of welding with a sinusoidal AC current, effective values of voltage u and current i can be used, together with the *power factor* φ , when estimating arc power, P : $P = u i \cos(\varphi)$. A better estimate of the gross arc power is obtained using the arithmetic mean of the instantaneous power value. This is necessary when the current and voltage are highly fluctuating, for example in short arc or pulsed arc GMAW. The arithmetic mean, P_{av} , can be calculated from the measured instantaneous current i_i and voltage u_i values at the arc:

$$P_{av} = \sum(u_i i_i)/n \quad (2)$$

where the summation is made from $i = 1$ to $i = n$. When the sampling frequency n tends to high values, Eq. (2) is replaced by:

$$P_{av} = (1/T) \int u(t) i(t) dt \quad (3)$$

This defines the average power. Integration is made over the time interval of interest, T [19].

Melting efficiency, η_m , (also known as *fusion efficiency* and *thermal efficiency of fusion*) is another important process property. Process performance can, for example, be described by the two parameters η_a and η_m . The arc efficiency must be known in order to determine experimentally the melting efficiency of a given process or a given set of welding parameters. Only a fraction of the energy supplied to the substrate is actually used for melting. The remaining part is lost through heat diffusion in the base material. The ratio of the power used for melting (fusion), q_m , to the power actually supplied to the substrate, q_w , defines the melting efficiency according to:

$$\eta_m = q_m/q_w \quad (4)$$

Analytical models for calculating η_m are given in, for example, References [3] and [4]. For a rapidly moving high-power heat source, theoretically about 48% of the effective (net) heat input is available for fusion (in the 2D case). This value has been calculated by assuming that heat diffusion is exclusively perpendicular to the moving heat source and that no filler material is added [4]. Experimental results agree with the calculated value [14, 16, 22]. It is interesting to note that the analytical 2D model and the experimental support for it were presented by Wells [22] as early as 1952.

Heat conduction in the direction of motion of the power source is more important at lower travel speeds, and η_m will consequently be reduced. For slow-moving power sources, such as manual GTAW, the thermal efficiency is, indeed, much lower. A value of about 0.16 has been reported [17] in GTAW experiments (travel speed of 0.5 m/min).

2. Methods to determine arc efficiency

Two different approaches to determine arc efficiency are available. One is based on the use of calorimetric experiments, while the other uses different heat flow models calibrated with measured parameters (such as depth of penetration, fused area and maximum temperature at a certain distance from the weld centreline). Both methods, of course, are subject to various sources of error. The use of calorimetric experiments is a *direct* approach, whereas a calculation through modelling and simulation (relying on several fundamental assumptions in the model) is an *indirect* approach when estimating η_a . Calorimetric experiments have been extensively used in the past, while modelling studies have increased in popularity

recently, partly because of increased accuracy and speed of today's numerical calculations (achieved, for example, by the use of FEM).

Calorimetric experiments measure the net energy, q_w , transferred to the substrate. The following methods are commonly used [15]:

1. Cooling water is used to remove the heat from the substrate during welding, and the efficiency is estimated from the temperature rise and rate of flow of the cooling water.
2. The workpiece is dropped into liquid nitrogen directly after welding, and the weight loss of liquid nitrogen due to vaporization is measured.
3. Welding is performed on a plate placed at the bottom of a calorimeter. The electrode is withdrawn and the lid of the calorimeter is quickly closed. The total heat transferred to the workpiece is estimated by integrating a calorimetric signal over the cooling time.

There are, of course, variants of these methods [18]. The first method can be varied by mounting a fixed TIG torch with its arc burning against a water-cooled copper anode [6, 12] (although other anode materials have also been used [5]). This variant is often used for GTAW welding. Some authors have argued that the heat intensity on a water-cooled anode (DCEN) is greater than that on a molten weld pool, for a given arc current and voltage, because the convective heat transported by the plasma to the anode is greater [12]. However, other authors have argued that about 89% of the energy transfer from an arc is by electrons [6]. Convection and radiation account for the remaining 11%, and these processes may be affected by the surface temperature being lower. This, however, should not have a major effect on arc efficiency – a difference of the order of 4 to 6% has been estimated [13].

Accurate calorimetric measurements of η_a are difficult and accurate values can be obtained only if random and systematic errors are carefully considered [20]. The error in calorimetric studies $\Delta\eta_a/\eta_a$ consists of two parts:

$$\Delta\eta_a/\eta_a = \Delta q_w/q_w + \Delta q_n/q_n \quad (5)$$

The measuring error in the gross arc power input, $\Delta q_n/q_n$, depends on how the arc current and voltage are measured and how the gross arc power is calculated. Electrical measuring systems have accuracies that are better than 1%, and the error in $\Delta q_n/q_n$ should, therefore, be less than that. Some authors have claimed that the lowest $\Delta q_n/q_n$ error values can be obtained are in the order of 3% [6], while others suggest that 5% is more realistic [18].

The error in the net power input transferred to the plate $\Delta q_w/q_w$ can be much larger, and the result is affected by both systematic and random errors. The calorimeter (design and ease of use) may have a large influence. Calibrations of a Seebeck Envelope Calorimeter (SEC), for example, have been carried out at an accuracy better than 1% [13, 14, 16], whereas the random error for an insulated box was 1.5% and that for a nitrogen calorimeter was 8% [20]. The SEC system will be discussed in more detail below. The uncertainty when estimating the enthalpy increase in a workpiece, on the other hand, was about 3% in one case [18]. Thus,

the total error, $\Delta\eta_a/\eta_a$, could be of the order of 10%, as is also discussed later. The reproducibility of repeated measurements in one case was reported to be 10% [6].

Larger errors can, however, be introduced due to uncontrolled heat losses prior to the start of the calorimetric measurements [20, 26]. Heat losses occur, for example, during welding (from plate surfaces to surroundings and/or to a clamping jig used during the welding operation), when unclamping the sample, during the transfer of the sample to the calorimeter, etc.

The influence of welding time and delay time on the η_a values determined for GMAW has been recently investigated [20]. Heat losses during welding and handling operations can cause significant underestimation in arc efficiency (up to 30%). This must be measured and compensated for when determining η_a . One way to do this is to extrapolate down to zero welding and delay time (although this requires the execution of a large number of experiments) [20].

As mentioned above, analytical and numerical methods (modelling and simulation) have been used to estimate arc efficiency. This can be done in various ways: by synchronizing measured maximum temperatures in the HAZ, for example, or by correlating the depth of penetration or the size of the fused area with values predicted from moving heat source solutions in the search for the optimum η_a value. This method is semi-empirical. Different approaches have been used – such as the use of a point heat source, line heat source (Rosenthal solution) or distributed heat source (Rykalin, Pavelic or Goldak). Other numerical methods have used finite difference or finite element methods [8, 13, 15, 17, 25, 27, 28].

The accuracy of the η_a values determined depends on, among other things, the heat source model used, the material data (density, thermal conductivity, heat capacity, phase change, melting temperature, emissivity, etc.) used in the computations and their temperature dependence, and the accuracy of measurement of the matching parameter (depth, width or the size of the fused area). Few reports explicitly evaluate the accuracy of η_a in modelling-simulation experiments, and few state the sensitivity of the analytical/numerical model to variations in different input parameters.

3. Early studies of GTAW arc efficiency

Rykalin [3] reported in an early work, based on Russian calorimetric experiments, arc efficiency values between 0.50 and 0.70 for a carbon arc (physically similar to a TIG arc). Rykalin showed that the arc efficiency decreases with increasing arc length (increasing arc voltage) due to an increase in heat losses [3]. Further results reporting similar η_a values were published during the 1950s and 1960s [5, 6]. These will be discussed in more detail below.

Schellhaase's [2] monograph from 1985 describes several processes and quotes several references (mainly German). The values reported for GTAW and mild steel welding range between 0.45 and 0.75. There is no information whether this is DC-welding or AC-welding,

but Schellhaase states that increasing the arc power decreases the arc efficiency. Several heat loss mechanisms are mentioned. Energy losses through radiation, heat conduction and convection will increase as the length of arc increases, and the arc efficiency will decrease.

Apps & Milner [5] studied heat flow in TIG welding without filler material for aluminium, lead, nickel, copper and Armco iron. According to the authors the heat produced at the anode comes from the electron current in the arc, which enters the small area of the anode spot. A smaller contribution to the heat produced stems from the heat received from the positive arc column by either radiation or gaseous conduction. Apps and Milner measured heat input using calorimetric methods. A commercial welding torch was used, and the metal specimen was placed above a copper calorimeter. The arc was extinguished after 10-30 s welding and the specimen was dropped into the calorimeter. Corrections for heat losses from the calorimeter were made. Changing the arc time had no effect on the results, which contrasts with more recent results [20]. DCEN was used for all metals except aluminium.

Measurement of current and voltage presented no difficulties with the DC arcs, but the question of current and voltage waveforms arose for AC arcs [5]. The current was almost sinusoidal and the RMS value was recorded with "normal" AC instruments. Furthermore, the arc voltage was in phase with the current, and exhibited an almost square waveform (measured with an oscilloscope). The maximum value was recorded by an AC instrument. The power consumed was calculated by taking 90% of the product of the instrument readings. As will be seen later, substantial errors may be introduced when using RMS values if the current and voltage fluctuate, as is the case in, for example, pulsed GMAW [19]. Arc efficiency values based on RMS values can be substantially lower than the "true" values calculated from average instantaneous power. The values determined by Apps & Milner [5], given these limitations, were:

- Armco iron (DCEN) 0.60-0.78
- Nickel (DCEN) 0.44-0.56
- Aluminium (AC) 0.31-0.44

Wilkinson and Milner [6] studied the energy distribution in arcs between a non-consumable (fixed) tungsten electrode and a water-cooled copper anode in different shielding gases (argon, nitrogen, helium and hydrogen). The investigation focused on examining the heat flow to the anode, and determined that this flow comprised electron heating, together with heat transfer from the plasma jet. The authors found that most of the energy expended in the arc passed to the anode, while the remainder was divided between cathode (electrode) heating and heat carried away by the gas, which left the arc region at high temperatures.

The experimental set up and the measuring procedure are described in detail [6]. The authors found that precautions were indeed necessary to obtain reproducible results. Careful measurements using optimal techniques enabled the measured heat and power consumed to agree to within 3%. However, measurements from one occasion to another agreed to within 10%. The arc efficiency values stated are the mean values from several experiments (usually three, but occasionally more).

The heat entering the anode accounted for 80-90% of the total energy dissipated in the arc, and was about the same for the different shielding gases [6]. The heat dissipated in this way, however, decreased with increasing arc length (from 90% down to 80%). The arc efficiency was 5-10% higher (depending on arc length) when nitrogen was used as shielding gas than it was with argon. The heat given to the cathode was about the same for both gases, and amounted to only a few percent of the total energy.

In a work by Christensen *et al.* [7], often referred to, η_a was determined for several processes including SAW, MMA, GMAW and GTAW. These authors used a calorimetric procedure consisting of depositing a weld bead onto a plate cooled by a rapid stream of running water, the temperature rise of which was measured by means of a thermocouple. Details of their measuring technique were reported elsewhere and the test conditions are not known. The following values were, however, reported for GTAW:

- Mild steel (DCEN) 0.36-0.46
- Aluminium (AC) 0.21-0.43

These values are much lower than the efficiencies reported for TIG arcs by contemporary and later studies. It is interesting, however, to note that Christensen *et al.* observed that the η_a values reported for mild steel by Apps & Milner [5] were considerably higher than their own values. The reason for the difference, however, was not explored further.

Niles & Jackson [8] made early attempts with modelling and simulation. They welded a steel base plate of thickness 25 mm (mild steel, HY80 steel and HY130 steel) and measured the temperature response at a certain distance from the GTAW bead-on-plate weld fusion line. Effective (net) power input P_e was calculated by the Rosenthal equation for the 3D case (assuming a point source, semi-infinite body, constant thermal material properties, no heat losses to the surroundings, etc.), and maximum temperatures, T_{max} , at certain distances from the weld line were recorded, together with other process parameters (travel speed, v , and total arc energy, P_t). Arc efficiency was then given by $\eta_a = P_e/P_t$. They calculated arc efficiency values in the range 0.35-0.65. They discovered that η_a fell from 0.65 to 0.35 when the arc current was increased from 125 A to 225 A, contrary to other results [16, 18, 28]. Changes in the electrode tip vertex angle (from 30° to 120°) did not influence calculated arc efficiency values.

Collings *et al.* [23] carried out interesting calorimetric experiments with high-speed GTAW DCEN (travel speeds between 0.1 and 1 m/s, with arc currents between 100 and 650 A). Their apparatus included a fixed TIG torch and a rotating anode. The magnitude of the total heat transferred to the workpiece could be determined and the arc efficiency calculated. Melting efficiency under various conditions was also determined (the maximum value reported was about 0.5). These authors studied a wide range of welding conditions (current, travel speed, tip angle, electrode distance and the addition of hydrogen to the argon shielding gas). Workpieces were either mild steel or stainless steel. The arc efficiency for these high-speed TIG arcs lay in the range 0.77-0.90, similar to the η_a values for TIG arcs moving at speeds an order of magnitude lower. Increasing the electrode distance (arc gap) lowered η_a . Moreover, the heat input to the workpiece per unit time was very nearly

proportional to arc current, and insensitive to large changes in electrode tip angle and travel speed, within the observed experimental scatter of 10% [23]. Addition of 10-20% hydrogen to the shielding gas increased the arc efficiency.

Ghent *et al.* [9] conducted calorimetric experiments with a fixed and a moving DCEN TIG torch. They showed that the arc efficiency decreases with increasing arc power, and they report values for stationary and moving weld pools between 0.83 and 0.58 (for values of arc power between 1.2 and 3.0 kW). They showed that the efficiency can be lowered either by increasing the arc gap or by increasing the current. Net power input depends on the heat losses from the anode [9]. They give no information about measurement errors except for the information that the total power collected varied between 0.97 and 1.06 of power generated. Smartt *et al.* [11] have shown that GTAW arc efficiency decreases with increasing arc voltage. They report an arc efficiency value of 0.75 for a 304 stainless steel.

Tsai & Eagar [12] studied experimentally heat and current fluxes, and their distributions, in GTAW with a split water-cooled copper anode (fixed torch). The heat and current distributions followed each other closely, since a major part of the heat is carried by electrons according to the authors. They measured also arc efficiency and recorded values were greater than 0.80. Indeed, they also showed that η_a dropped slightly from 0.90 at 100 A to 0.82 at 280 A.

Geidt *et al.* [13] provide an example of the use of the Seebeck Envelope Calorimeter (SEC). A GTA bead-on-plate weld (DCEN) of length 75 mm was made on a 12.7 mm thick 304L stainless steel plate with the calorimeter lid open. The travel speed was constant at 0.847 mm/s in all trials. Welding heat input ranged between 0.57 and 2.41 MJ/m. The calorimeter lid was closed over the sample immediately after welding was completed and the time required to reach equilibrium was determined. This was approximately 6 hours. The arc efficiency values ranged between 0.80 and 0.84, with an average of 0.81 ± 0.013 . The 95% confidence range, therefore, is 0.79–0.84. These values are higher than the values determined by Christensen *et al.* [7] and by Niles & Jackson [8], but they are supported by several calorimetric measurements and later modelling and simulation calculations. In addition, they agree well with the early results obtained by Apps & Milner [5] and Wilkinson *et al.* [6].

An interesting part of the study of Geidt *et al.* [13] is the comparison of arc efficiencies determined from temperature fields in the base metal and fusion zone measurements with the calorimetric values. As mentioned earlier, values determined in this way are adjusted to obtain agreement between analytical and/or numerical solutions and the experimental measurements (Geidt *et al.* measured penetration depth). The average value from calculations using a moving-point source solution (the 3D Rosenthal equation) was 0.57 ± 0.06 , which is about 30% lower than the reported calorimetric average value. They concluded that better models must be used for the overall prediction of weld characteristics such as η_a . Improved models should include, for example, distributed heating, heat of fusion, thermal property variation and convection. When more advanced heat transfer models were used estimated arc efficiencies (0.75-0.80) approached those obtained from calorimetric measurements [13].

4. GTAW arc efficiency values reported after 1990

Fuerschbach & Knorovsky [14] carried out extensive calorimetric studies of GTAW and PAW (DCEN) with similar calorimetric equipment (SEC) as that used by Geidt *et al.* [13]. Edge welds were chosen (the industrial application was micro-welded components). They used an extensive experimental set up for GTAW (DCEN, continuous and pulsed current). Two different base materials were included (304L SS and Nickel 200), and two test plates (1.3 x 25 x 127 mm each) were joined with an edge weld. Arc output energy was determined by multiplying the voltage and current waveforms together, and then integrating the resulting power waveform for the weld period using the internal software of the measuring oscilloscope. Travel speed ranged between 4.2 and 25.4 mm/s, the current between 29 and 205 A, the pulse duty cycle between 0.2 and 1.0 and the pulse rate between 8.3 and 27.8 Hz, with different values used for continuous and pulsed-current experiments.

Their results showed that arc efficiency was relatively insensitive to travel speed. Measured values ranged between 0.8-0.85 for travel speeds between 10 and 25 mm/s, and decreased slightly, from 0.8 to 0.7, when the travel speed was reduced from 10 to 5 mm/s. The major part (approximately 90%) of the energy was transferred by electrons according to the authors, and they assumed that current was the dominant parameter in the energy balance, and that convective and radiative losses were of secondary importance. The arc efficiency was also relatively insensitive to the duty cycle in the pulsed-current experiments, with η_a values between 0.80 and 0.85. It fell to approximately down to 0.75 for the lowest duty cycle (approximately 0.28). Another interesting result was that arc efficiency did not depend on the anode material (304L or Ni200). This may indicate that the electron work functions in a GTAW arc for the two materials are similar, since the anode work function is believed to affect GTAW arc efficiency strongly. The similarity of η_a values for 304L and Ni 200 led Fuerschbach & Knorovsky [14] to suggest that little (if any) difference in arc efficiency is expected between other iron-based and nickel-based alloys. It is however a complicated matter which can be discussed at some length.

Dutta *et al.* [15] determined gas tungsten arc efficiencies using experimental and analytical (computational) techniques. Measurements of the width and depth of the weld pool were obtained from sections using optical microscopy. These measurements allowed a 3D FEM model to be constructed, which was used to calculate the arc efficiency, using an algorithm that accounted for weld pool convection and variations in specific heat. Some welding was done in a groove (depth x width: 1.6 x 1.6 mm) in order to simulate butt welding, while other welds were bead-on-plate welds, to be used as a comparison. A naval HY-80 steel (0.16% C) was used in all tests. Welding speed ranged between 1.27 and 2.12 mm/s, the current between 237 and 322 A, and the arc voltage between 10.7 and 13.8 V. Their calculations gave a mean value of about 72% for the arc efficiency. The authors believed that the variation in the efficiency value obtained (between 0.62 and 0.85) was due to variations in arc current, voltage, welding speed and inherent unsteadiness of the welding process itself. Dutta *et al.* [15] also found that a higher power input results in lower arc efficiencies, and that slower welding speed results in higher efficiency. They also found no significant difference in arc efficiency between grooved and ungrooved plates, at the same welding speed and power input.

Also DuPont & Marder [16] used the SEC equipment. They made an extensive experimental study of arc efficiency for several processes, including PAW, GTAW, GMAW and SAW. GTA welding was carried out on a 100 x 100 mm square steel plate, 25 mm thick (A 36 carbon steel). The current ranged between 250 and 350 A, the voltage between 15 and 16 V, and the travel speed was kept constant at 7 mm/s. Welding time was shorter than 10 s and the transfer time to the calorimeter was shorter than 3 s, in order to minimize the heat losses that occurred before the substrate was in the calorimeter. The authors also calculated heat loss prior to measurements (welding + transfer), and found that they were less than 1% of the total arc power. The arc efficiency did not vary significantly over the current range investigated and a value of $\eta_a = 0.67 \pm 0.05$ (8% variance) was determined for GTAW DCEN.

Orlowicz & Trytek [24] studied the thermal response of spheroidal graphite cast iron (substrate) in calorimetric GTAW DCEN experiments. Travel speeds ranged from 0.2 to 0.8 m/min and arc currents from 100 to 300 A. The influence of electrode distance (arc gap from 3 to 6 mm) on η_a was also studied. They determined arc efficiency values between 0.39 and 0.77, and concluded that η_a depends on travel speed (it decreased as travel speed increased), contrary to what had been reported earlier. At low travel speeds (< 0.4 m/min) and currents between 100 and 300 A, they report η_a values in the range 0.66 – 0.77, which are similar to those reported by other authors. It is more plausible that arc efficiency lies in the range 0.66 – 0.77. Increasing the arc gap reduced the arc efficiency [24].

Mishra & DebRoy [25] used a heat-transfer and fluid-flow-based model to analyse a specific weld geometry using various combinations of welding variables. They point out that the models for GTAW have five uncertain parameters, i.e. arc efficiency, arc radius, power distribution factor, the effective thermal conductivity of the liquid metal, and its viscosity. The numerical model was applied to GTAW DCEN of a Ti-6Al-4V alloy, and used to calculate various sets of welding variables when analysing specified weld geometries. The highest value of arc efficiency calculated was 0.72, in line with previous reports.

Malin & Sciammarella [26] made some interesting statements about measurement errors of the SEC equipment, and they pointed out some specific drawbacks when using such equipment in welding. The SEC is not a turnkey device intended for welding. It was designed for biomedical research and needs additional equipment (including a chiller, a data-acquisition unit and processing hardware) to function properly in welding experiments, and it needs to be modified for such experiments. One measurement takes about 6 hours. Malin & Sciammarella estimated in the following manner the errors introduced when using a SEC equipment: The SEC does not account for heat losses during welding and during transfer of the specimen into the calorimeter. These losses depend on a number of factors (size of specimen and its physical properties, welding time, transfer time, etc.). The heat loss thus neglected could cause measurement error of the order of 2% [26]. Moreover, the SEC does not differentiate between transient and quasi-stationary energies. Due to the rather short length (max 90 mm) of the specimen, the transient zones (start and stop areas) will therefore influence the measurements. An additional source of error of up to 7% is thus introduced since transient and stationary (nominal) energies will be averaged [26]. Malin & Sciammarella did conclude that the total error in measuring η_a is of the order of 9%, which is in the same order as mentioned previously.

Gonzalez *et al.* [27] have recently studied experimentally the heat flux transferred to a fixed anode (a stationary water-cooled copper anode). Their main object was to determine the heat flux transferred (by determining, for example, temperatures and temperature profiles). The paper also contains interesting data relating to the power transmitted to the cooling water and total (input) power. The scatter in these measurements can also be analysed from Gonzales *et al.*'s paper. The average arc efficiency for four different input powers (from 1.1 to 1.6 kW) was 0.70, with a range between 0.63 and 0.77. The estimated scatter in their power input measurements was 2%, whereas the estimated scatter in the power transmitted to the cooling water was 10%.

Goncalves *et al.* [17] compared two modelling techniques when studying thermal phenomena (heat flux) during GTAW. The first thermal model (A) considers quasi-stationary heat conduction (using what is essentially the Rosenthal equation) in the interior of a plate, whereas the second model (B) uses a general transient heat equation for heat diffusion with phase change. The heat flux generated from the welding process can be estimated in both cases, and temperature curves/profiles calculated considering the phase change, various thermal properties, and heat losses to the surroundings due to convection and radiation from the base metal. The temperature profiles calculated by the two models were compared with experimental profiles obtained from TIG welding an AISI 304 steel plate with dimensions 200 x 50 x 4 mm, current 78 A, voltage 15 V, and a constant travel speed of 8.33 mm/s (arc power = 1,18 kW). Heat flow estimations allowed an arc efficiency of 0.67 ± 0.09 to be calculated with model A. (It ranged between 0.56 and 0.77 at four different thermocouple locations.) The accuracy of model B was estimated by calculating the weld pool radius, and comparing the estimated values with the measured values (golden sections).

Model B was used to estimate the heat of fusion, heat transfer in the plate and heat losses due to convection/radiation. Goncalves *et al.* [17] were then able to estimate arc efficiency and thermal efficiency dynamically during the complete welding sequence through synchronization with the thermocouples. The thermal (fusion) efficiency was constant during the welding operation, and had a value of about 0.16 in the specific set up used. The "instantaneous" arc efficiency was about 0.8 (during an arc start-up process lasting 2 seconds), then fell slightly in an asymptotic manner from about 0.74 (after completion of the arc start-up process) to about 0.70 at the end of the welding operation, when more heat is consumed by heat transfer in the plate and heat losses due to convection and radiation.

Cantin & Francis [18] studied several different process situations, and investigated the influence of polarity, alternating current balance, shielding gas composition (Ar, Ar+75%He, He), arc length and welding current on arc power and arc efficiency. They used a calorimetric approach that involved experiments in which GTAW weld runs were made on a cubical (110 x 120 x 120 mm) insulated block of electrical conductor-grade aluminium. The temperature rise in the block was measured with several thermocouples attached to it, and the energy absorbed in the sample was calculated. Arc power was estimated by numerical integration of arc voltage and current during the welding. Cantin & Francis [18] are among the few who have discussed the significance of different errors in their measurements, and they concluded that the uncertainty in the estimated arc power is about 5%, whereas the

uncertainty in the estimated internal energy in the workpiece is about 3%. The total error in arc efficiency measurements is thus about 8%.

The arc efficiencies determined in **DCEN** experiments fell within the range 0.76-0.89, which agrees well with the calorimetric experiments in various materials described earlier. It is, however, much higher than the values reported by Christensen *et al.* [7]. Most of the arc power is transferred to the workpiece, and relative high arc efficiencies are obtained. Cantin & Francis' results also showed that the type of shielding gas has a significant influence on the arc efficiency in DCEN tests. The η_a values are higher with Ar+75%He and with helium (average 0.87), than with pure argon (average 0.79). They concluded that the difference depends on differences in heat losses. Heat loss through radiation will be dominant when argon is used as shielding gas, whereas conduction and convection losses will dominate with helium. The lowest total radiative, conductive and convective losses occur with a shielding gas of composition Ar+75%He [18]. The values of η_a determined suggested also that changes in welding current (in the range 100 A-200 A) do not have a significant influence.

The arc efficiencies during **DCEP** were lower, as expected, since the direction of the current is reversed. Approximately 25% less energy is transferred to the workpiece during DCEP than is transferred during DCEN. The arc efficiencies measured were in the range 0.52-0.63, and the cathode (the substrate in this case) was the major recipient of the arc energy, since η_a was greater than 0.50. Also in this case, higher η_a values were recorded (average 0.62) with Ar+75%He than with pure argon (average 0.55), although the difference was not as large as that for DCEN. An increase in arc length (from 2 to 4 mm) gave a slight decrease in arc efficiency.

Arc efficiencies with **AC** power were intermediate between those of DCEN and DCEP and ranged between 0.65 and 0.83. The efficiency depended on the EN fraction (which ranged from 0.50 – 0.75). The arc efficiency was 0.71 ± 0.03 when using argon with an EN of 0.50. An interesting approach in their study is the calculation of arc efficiencies with AC power using a weighted average of the arc efficiencies obtained with DCEN and DCEP polarities, under otherwise identical welding conditions. The estimated arc efficiencies agreed reasonably well with the measured values.

Bag & De [28] provide a further recent example of a modelling and simulation approach. They point out, as Mishra & DebRoy [25] also did, that the data that are necessary for adequate modelling of heat transfer and fluid calculations in GTAW are uncertain. Bag & De [28], however, "synchronized" their calculations with calculations for another substrate (Stainless 304), which was DCEN TIG-welded (using an arc power between 1.0 and 2.0 kW and a travel speed between 5.0 and 8.8 mm/s). The size of the test plates is not mentioned. Calculations of the input parameters to the model that were uncertain gave a the optimum arc efficiency value of 0.65, which is somewhat below the values reported by previous authors.

Arul & Sellamuthu [29] developed recently a creative modelling approach, with the goal of overcoming the difficulties of solving complex heat and fluid flow models when predicting temperature distributions, cooling rates and weld pool geometry. The arc parameter used as

a measure of the arc heat distribution, were experimentally determined from arc images. They used a 1005 carbon steel with dimensions 150 x 50 x 25 mm as substrate, and current values between 100 and 200 A with travel speeds between 0 and 10 mm/s. The arc images were recorded by a CCD camera. They selected the weld pool width as synchronizing parameter. The average arc efficiency determined was 0.74, with an estimated scatter in the data of the order of ± 0.05 (7%), when the current and travel speed varied. Arul & Sellamuthu conclude that the arc efficiency was independent of both current and travel speed.

5. Discussion

The references that have been reviewed present a wide range of arc efficiency values, and this is true both for those determined through calorimetric experiments and for those determined through modelling and simulation studies. Table 1 presents a summary of the η_a values and their ranges.

Few authors have estimated experimental errors in their calorimetric experiments and/or in their modelling and simulation studies in a thorough manner. Measurement system errors, for example, can be classified into two main categories: accuracy and precision. *Accuracy* is the difference between the measured value and the “actual value”. This is, of course, difficult to estimate in the present case since a very large number of experiments have to be made in order to determine the “actual value”. *Precision*, on the other hand, is the variation when measurements are repeated with the same equipment. Precision consist of two parts, *repeatability* – which is the variation due to the measuring equipment (the device) and *reproducibility* – which is the variation due to the measuring system. This variation occurs when different “operators” measure the same object using the same equipment (device) or when measurements are made in different laboratories with the same equipment. High repeatability means that random errors have a small influence on the result, and high reproducibility indicates that both random and systematic errors are small.

As mentioned experimental errors were estimated and/or discussed only in a few cases, and no clear distinction was generally made between accuracy and precision. Precision was mentioned in some cases, and the subsequent discussion dealt with repeatability and reproducibility, often without distinguishing between them. The calorimetric studies mentioned above discuss errors in some cases. These reports suggest that the error in power input measurements is less than 2%. Several reports, in contrast, indicate that the error in estimating the transmitted power (or heat) to a given substrate is of the order of 10%. The total error, therefore, can be estimated to be 12%, which is the linearized error estimate according to Eq. (5). The magnitude of experimental errors in $\Delta\eta_a/\eta_a$ can to a certain degree explain the variations between arc efficiency values given in Table 1.

A difference between two average η_a values less than 12% is not significant at a confidence level of 90%. In order for a 10% difference between two measured η_a values to be significant (at the 95% confidence level), the total error in calorimetric experiments must be less than

5%. It is an open question whether this reproducibility can be achieved with the systems used today.

Modelling and simulation experiments are also influenced by different types of errors. These errors are either errors inherent to the model used or experimental errors. Creating a model requires several assumptions about material parameters (such as specific heat, density, conductivity and viscosity) and their temperature dependence. These may not be fully known. Furthermore, modelling is subject also to measurement errors, for instance when determining the “synchronizing parameter” (such as the depth of penetration, width of weld bead, weld metal area and peak temperature) which is used to calculate the arc efficiency. The modelling and simulation studies discussed here present no information about experimental errors.

Table 1 allows us to estimate an average value and standard deviation for GTAW DCEN. Furthermore Table 2 shows the ranges in the individual cases, median values and individual spans. Assuming that the values can be described by a normal distribution allows us to calculate the mean value and standard deviation. A further assumption that must be made is that the substrate has no influence on the arc efficiency. This is supported by the literature mentioned earlier. Other factors, such as arc gap and arc power, may also influence the η_a value, but it is difficult to consider these parameters presently since literature data conflicts.

Table 1. Summary of arc efficiency values published between 1955 and 2011, and their ranges. The range has been estimated from published values in some cases. The more plausible data range in [24] was selected.

Reference	Year	η_a range	Substrate	Comments
Apps & Milner [5]	1955	0.60 – 0.78	Armco iron	DCEN
Apps & Milner [5]	1955	0.31 – 0.44	Aluminium	AC current
Wilkinson & Milner [6]	1960	0.80 – 0.90	Water-cooled copper anode	Water-cooled copper anode
Christensen <i>et al.</i> [7]	1965	0.36 – 0.46	Mild steel	DCEN
Christensen <i>et al.</i> [7]	1965	0.21 – 0.43	Aluminium	AC current
Niles & Jackson [8]	1975	0.35 – 0.65	Steel	Modelling
Ghent <i>et al.</i> [9]	1979	0.58 – 0.83	Steel	DCEN
Collings <i>et al.</i> [23]	1979	0.77 – 0.90	Mild steel & Stainless	DCEN
Smartt <i>et al.</i> [11]	1985	0.75	Stainless 304L	DCEN
Tsai & Eagar [12]	1985	0.80 – 0.90	Water-cooled copper anode	DCEN
Geidt <i>et al.</i> [13]	1989	0.79 – 0.84	Stainless 304L	DCEN
Geidt <i>et al.</i> [13]	1989	0.57	“	Modelling
Fuerschbach & Knorovsky [14]	1991	0.80 – 0.85	Stainless 304L & Ni 200	DCEN
Dutta <i>et al.</i> [15]	1994	0.62 – 0.85	HY-80 steel	Modelling
DuPont & Marder [16]	1995	0.62 – 0.72	A 36 steel	DCEN
Orlowicz & Trytek [24]	2003	0.66– 0.77 (0.39 – 0.77)	Spheroidal cast iron	DCEN
Mishra & DebRoy [25]	2005	0.72	Ti-6Al-4V	Modelling
Goncalves <i>et al.</i> [17]	2006	0.56 – 0.77	Stainless 304L	Modelling
Cantin & Francis [18]	2005	0.76 – 0.89	Aluminium	DCEN
Cantin & Francis [18]	2005	0.52 – 0.63	Aluminium	DCEP
Cantin & Francis [18]	2005	0.65 – 0.83	Aluminium	AC current
Gonzalez <i>et al.</i> [27]	2007	0.63 – 0.77	Water-cooled copper anode	DCEN
Bag & De [28]	2010	0.65	Stainless 304	Modelling
Arul & Sellamuthu [29]	2011	0.74	1005 steel	Modelling

Table 2. Arc efficiency range, median values and span for GTAW DCEN according to Table1.

References	Range	Substrate	Median	Span
[5]	0.60 – 0.78	Armco iron	0.69	0.18
[6]	0.80 – 0.90	Copper anode	0.85	0.10
[7]	0.36 – 0.46 (omitted)	Mild steel	0.41	0.10
[9]	0.58 – 0.83	Steel	0.71	0.25
[23]	0.77 – 0.90	Mild steel & Stainless	0.84	0.13
[12]	0.80 – 0.90	Copper anode	0.85	0.10
[13]	0.79 – 0.84	Stainless 304L	0.82	0.05
[14]	0.80 – 0.85	Stainless & Ni 200	0.83	0.05
[16]	0.62 – 0.72	A 36 steel	0.67	0.10
[24]	0.66 – 0.77 (0.39 – 0.77)	Spheroidal cast iron	0.72	0.11
[18]	0.76 – 0.89	Aluminium	0.83	0.13
[27]	0.63 – 0.77	Copper anode	0.70	0.14

The median value 0.41 given by [7] may be an outlier. Even though the proof for it is lacking presently, the min-max data given by [7] were omitted from the calculations. The average η_a value of all min-max data was then 0.78 ± 0.10 (13 % variance). They follow almost a normal distribution (Andersson-Darling), and with the calculated standard deviation, the 95% confidence interval for the arc efficiency at GTAW DCEN was estimated to be $0.73 - 0.82$, indicating that the process is indeed an efficient welding method. The estimated η_a interval covers many different substrates and process parameters (arc length, travel speed, current, electrode tip angle and shielding gases).

Figures 2 and 3 show the median values as functions of the year of publication for calorimetric measurements and for modelling, respectively. The η_a values calculated from modelling and simulation increase through the years (Fig. 3), as the model accuracy was increased. It is interesting to note that the gap between the two approaches becomes lower during the years and that they approach each other.

Most studies of arc efficiency have been concerned with DCEN, although DCEP and AC current (pulsed current welding with EN polarity, for example) are also of industrial importance. η_a is lower in these cases, but the limited number of published studies makes it difficult to estimate an accurate range. Table 1 does, however, provide some information.

In the reviewed literature there are no Factorial experiments or Design Of Experiments (DOE). The main process parameters of interest are, for example, travel speed, arc current and arc gap. A simple 2^3 factorial test would suffice to show both the influence and the relationships between these variables. Several articles indicate that the arc efficiency becomes lower as the arc length is increased [3, 9, 23]. Results with respect to the influence of arc current and travel speed, however, are conflicting. Some authors report that arc current and travel speed have no influence [14, 16, 18, 23, 28], while others report that they do [2, 8, 9, 11, 12, 15, 24].

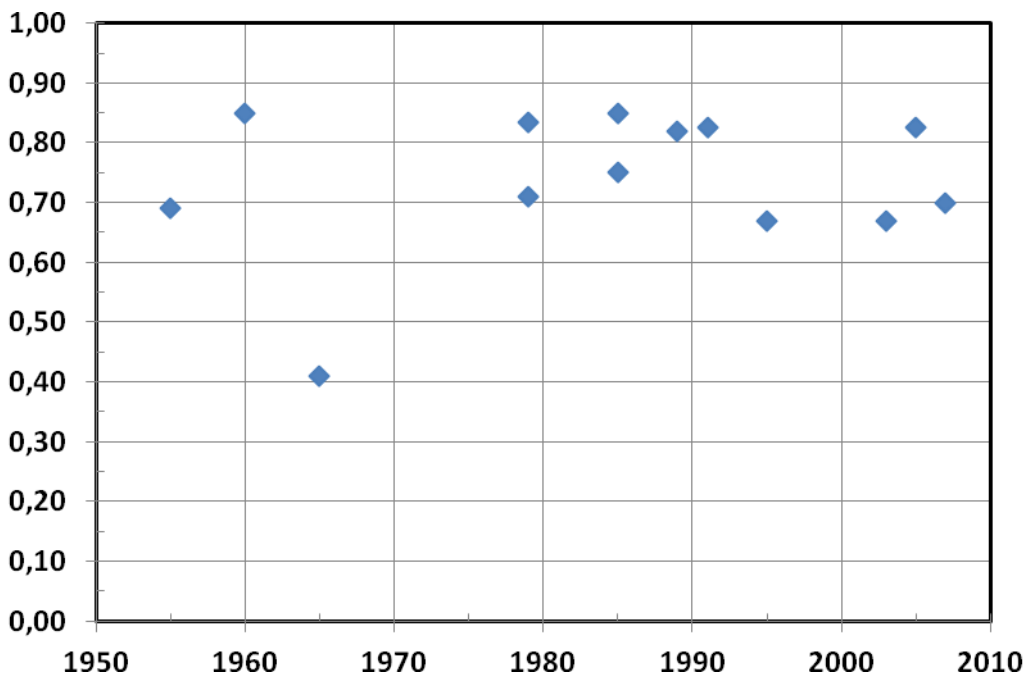


Fig 2. Published median values of arc efficiency for GTAW DCEN obtained from calorimetric experiments as a function of year of publication. See also Tables 1 and 2.

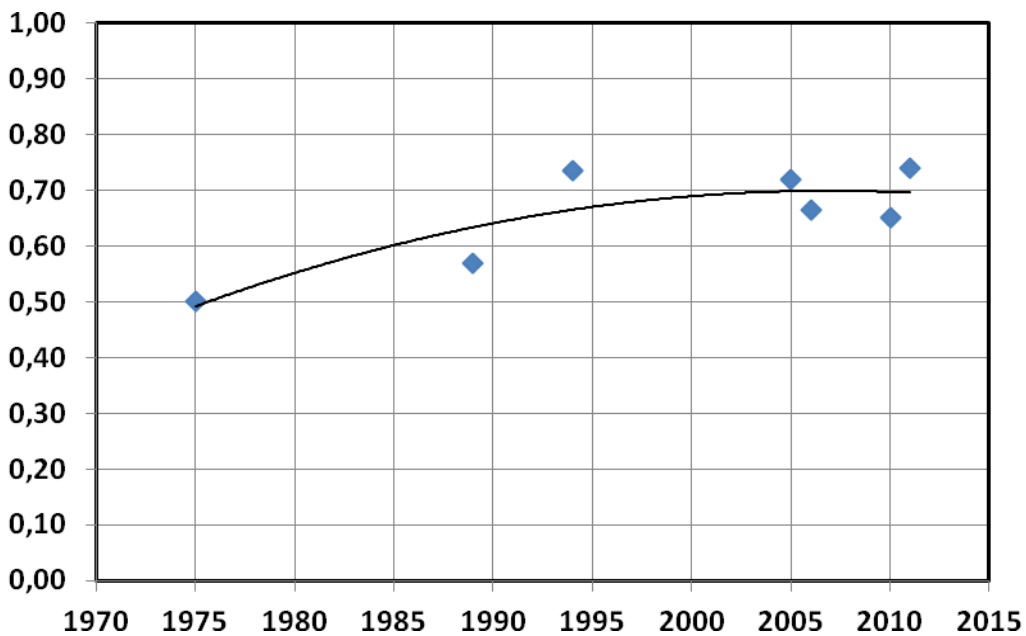


Fig 3. Published median values of arc efficiency for GTAW DCEN obtained from modelling and simulation studies as a function of year of publication. See also Tables 1 and 2.

Some of the earlier investigations [5, 12, 14] claims that the major part of the heat transferred in the GTAW DCEN arc to the anode is due to the electron flux. In the light of more recent mathematical arc models this can be questioned. In one modelling and simulation study performed for instance by Goodarzi, *et al* [30] it was shown that about 53 % of the total heat flux was due to electrons, about 42 % was due to convection and the remaining part about 5 % was due to radiation. In future studies of arc efficiencies it would be of interest to apply recent mathematical arc models in a more direct way.

6. Conclusions

Values for arc efficiency in GTAW DCEN that have been published lie in a wide range, from 0.36 to 0.90. Most studies have examined DCEN and only a few have covered DCEP and AC current welding.

In many cases measurement errors are not reported for the applied methods, both in calorimetric experiments and in modelling and simulation studies. Specific information about the reproducibility of calorimetric studies (considering both random and systematic errors) is scarce. The information presented in the reports that do discuss errors, allows the total error when determining arc efficiency with calorimetric methods to be estimated to be 12% for a “good practice” procedure.

In order for a 10% difference between two measured η_a values to be significant (at a 95% confidence level), the total error in calorimetric experiments must be less than 5%. It is an open question whether this reproducibility can be achieved with the systems used today.

A plausible arc efficiency range for GTAW DCEN in the (calorimetric) studies considered here is 0.73 – 0.82 with an average of 0.78 for different substrates (mild steel, stainless steel, Ni alloys, cast iron). The arc efficiency is lowered by longer arcs (increased arc gap). Reports describing the influence of arc current and travel speed, however, conflict. An average value of 0.78 indicates that the GTAW DCEN process is an efficient welding method.

Arc efficiency GTAW DCEN values, calculated from modelling and simulation studies have increased over the years, and approaches values determined in calorimetric studies.

Studies of DCEP and AC current welding (such as pulsed current welding with EN polarity) indicate that the arc efficiency is lower in these cases. Only a few studies have been published, however, and it is difficult to determine the range accurately.

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