Comparison of empirical and predicted substrate temperature during surface melting of microalloyed steel using TIG technique and considering three shielding gases

Munoz-Escalona, P.; Walker, A.; Ogwu, A.; Mridha, S.; Baker, T. N.

Accepted Manuscript

Title: Comparison of empirical and predicted substrate temperature during surface melting of microalloyed steel using TIG technique and considering three shielding gases

Authors: P. Muñoz-Escalona, A. Walker, A. Ogwu, S. Mridha, T.N. Baker

Please cite this article as: Muñoz-Escalona P, Walker A, Ogwu A, Mridha S, Baker TN, Comparison of empirical and predicted substrate temperature during surface melting of microalloyed steel using TIG technique and considering three shielding gases, *Applied Surface Science* (2010), https://doi.org/10.1016/j.apsusc.2017.11.014

Comparison of empirical and predicted substrate temperature during surface melting of microalloyed steel using TIG technique and considering three shielding gases

P. Muñoz-Escalona[1], A. Walker[2], A. Ogwu[1], S. Mridha[3] and T.N. Baker[3] [‡]

[1]School of Engineering and Computing, University of the West of Scotland, Paisley, PA1 2BE, UK,
[2]School of Science and Sport, University of the West of Scotland, Paisley, PA1 2BE, UK,
[3] Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, G1 1XQ, UK.

Corresponding author: p.munoz@uws.ac.uk

PLEASE NOTE I AM UPLOADING THIS FILE BECAUSE THE SYSTEM IS NOT RECOGNISING THE REVISED MANUSCRIPT AS THE MANUSCRIPT FILE!

Highlights

- Surface engineering
- Mathematical model to predict temperature
- Tungsten Inert Gas technique
- Effect of shielding gas on material's properties

Abstract

Erosion and wear resistance of steel can be enhanced by incorporating a ceramic powder in the surface. This aspect of surface engineering has applications in areas such as mining, agriculture and transport . An economic alternative to laser for melting the surface is by using a tungsten inert gas torch. The process requires shielding gas to protect the melted and re-solidified track from oxygen and hydrogen in the environment, which often have a deleterious effect on the mechanical properties of the modified surface. During the melting process, the heat produced is conducted to the substrate ahead of the torch; this has been described as 'preheat' giving a temperature several hundred degrees higher than the area under the torchTo reduce the number of trial and error experiments for determining the optimal conditions to modify the surface, a mathematical model, based on the Rosenthal approach, was developed. Experiments using TIG technique were conducted on microalloyed steel using argon, helium and nitrogen shielding gases to obtain heating and cooling curves from positions along the melted track. The data for argon was compared with the model. This first attempt to validate the model was satisfactory, showing a deviation of 6% (35°C) between experimental and numerical values.

Keywords: surface engineering, TIG, temperature prediction, mathematical model

1. Introduction

Surface engineering techniques are used to improve the surface properties of many alloys including microalloyed steels. Techniques such as high powered lasers for transformation hardening [1] surface melting [2-4] and development of surface metal matrix composites [4-8] are well established. More recently the tungsten inert gas (TIG) technique has been explored as a heat source for the surface modification of steels as a much cheaper option than lasers [9-12]. Both techniques require a gaseous shielding atmosphere, usually $_2$, Ar, He, CO_2 or mixture of these gases. The shielding gas protects the metal transfer stream and the molten weld pool from contamination

resulting from dissolution from the atmosphere of nitrogen, oxygen and water vapour , which often have a deleterious effect on the mechanical properties of the modified surface] [13-17].

Shielding gases also provide a medium for the electrical current to flow in the plasma jet between workpiece and electrode.

In all laser and welding melting techniques, the heat generated by the source is normally also conducted to the substrate ahead of the torch, and has been described as 'preheat' [18,19]. This leads to a gradually higher substrate temperature, from the start to the finish of a melted surface track [17], which is increased when multipass tracks are produced to modify the area of a surface [19].

Therefore iIt is essential that chosen surface treatment produces a modified layer of such a thickness that it still provides the improved properties, such as wear or erosion resistance, over the life-time of the component. A treatment which provides a small preheat means that the maximum temperatures reached during the processing are similar in different parts of the substrate, leading to similar cooling rates on solidification.

A mathematical model for predicting the temperature ahead of the heat source has been developed for laser transformation hardening by Ion et al[20], based on the Rosenthal approach [21], which was also used initially by Gray et al. [22] who applied this to welding processes. This is known to show satisfactory results for predicting temperatures in the heat affected zone. The present work is the first part in applying these earlier analytical approaches to surface engineering using the TIG technique, with the aim of linking the temperature distribution at any stage of melting and fusion of a track, to microstructure and properties. Based on temperature data recorded for three shielding gases, argon, helium and nitrogen, argon was chosen for a comparative study. Here the effect of the shielding gas in developing the level of preheat along the track, which is recorded as an increase in temperature, is compared with the results given by the analytical model. When fully developed, the model should lead to the optimal conditions for surface engineering incorporating ceramics powders into the molten surfaces as a means of developing improved properties.

2. Experimental Method

Three plates of a microalloyed steel with composition of 0.1C-0.7Mn-0.20Si -0.05Cu-0.05Nb (all in wt. %) with dimensions, 300 x 30 x 10 mm where used as a substrate. Each plate was drilled from the underside of the 10 mm thick substrate to place thermocouples type K at 75, 150 and 225 mm from the sample's edge, dividing the melted track into four sections. Each hole had 1 mm diameter and 5 mm depth. Fig.1 shows details of thermocouples positions, the tip of the thermocouple being located 5mm below the surface.

A TIG technique was used to melt the surface of the substrate by using a Miller Dynastry 300DX torch to generate an arc with a 2.4 mm diameter thoriated tungsten electrode. The electrode was direct current negative and the tip of the electrode was placed 1 mm above the specimen surface. Each sample was melted on the surface as shown in Fig. 1b. The current (I), the voltage (V), the speed (s), were changed as shown in Table 1 in order to guarantee a constant energy input (E) of ~ 840 J/mm along the melt track when using three different shielding gases, argon (Ar), nitrogen (N) and helium (He) at a constant flow rate of 10 L/min. The energy input was chosen from previous results [10, 15]. Table 2 gives the thermal properties of the microalloyed steel and the shielding gases used in this research.

The energy input was calculated using Eq. 1.

$$E = \eta\, VI/s \hspace{10em} \text{(Eq. 1)}$$

where η is the efficiency of energy absorption, which was taken as 48% for a TIG process [20].

During the melting process, the temperatures were recorded by the thermocouples, and once the melting process was completed, the samples were allowed to cool at room temperature.

3. Results
3.1. Experimental Results

Figure 2 shows the temperatures registered by the thermocouples when using the different shielding gases with an energy input of ~ 840J/mm.

 Analysing Figure 2, it is observed that all the samples recorded a higher temperature at the end of the melted track, which was registered by thermocouple 3; this is due to the preheating process the samples were subjected to during the melting of the track. The maximum temperatures recorded in each of the three positions is given in Table 3, emphasizing the effect when using helium.

Also, it is observed that argon registered the smallest increment between the recorded temperatures of thermocouple 1 (75 mm) and that of thermocouple 3 (225 mm), when compared to nitrogen and helium. , The temperature difference between these two thermocouples for argon is 45 °C , while those for nitrogen and helium is 210 °C and 150 °C respectively. This result is associated with the smaller values of specific heat and thermal conductivity of argon compared with nitrogen and helium. For this reason, the temperature data recorded using an argon shielding gas for TIG surface engineering was chosen for comparison with that predicted by the model.

3.2 Modelling

The heat flow in the plate is modelled using the heat equation in two-dimensions (in space)

$$k\nabla^2 T(x, y, t) = rc\partial T/\partial t(x, y, t)$$

(Eq. 2)

where k is the thermal conductivity (*W/mmK*), $\mathbf{\nabla} = \mathbf{i}(\partial/\partial \mathbf{x}) + \mathbf{j}(\partial/\partial \mathbf{y}) + \mathbf{k}(\partial/\partial \mathbf{z})$ is the usual differential operator, T is the temperature of the plate (°C), r is the density of the steel (*kg/mm³*), c is the heat capacity of the steel (*J/kgK*) and x, y and t are the spatial (*mm*) and time (*s*) variables, respectively. The dependence on the spatial component z is neglected due to the assumed symmetry with the spatial component y. It is assumed that the plate has constant room temperature T_0 (°C) on each boundary which is not affected by the TIG process. That is,

$$T(0, y, t) = T_0, \qquad T(300, y, t) = T_0, \qquad T(x, 0, t) = T_0.$$

(Eq. 3)

Following [11-17], the boundary condition on the TIG affected boundary is proposed to be

$$T(x, 10, t) = T_0 + (\text{P}/kd)e^{-(\alpha(x-vt)^2)} + (P\beta/kd)(1/(x\text{-}vt))^2$$

(Eq.4)

where $P=hEI$ is the power of the heat applied, d is the arc length (*mm*), α is a point source factor (*1/mm²*), v is the welding speed (*mm/s*) and β is a spread factor (*Kmm²*). Of course, a full derivation of the boundary condition from first principles must be addressed for a more accurate solution. Figure 3 shows the cross-sectional area of the plate towards the longitudinal side with the boundaries conditions that were considered.

4. Discussion

The choice of shielding gas has a major influence on the arc temperature and therefore on the maximum surface and HAZ temperatures of the specimen. Shielding gases also affect the shape of the molten pool in welding and the track dimensions produced using TIG for surface engineering.[16,17] These parameters will in turn determine the microstructure and mechanical/toughness properties of the surface engineered specimen, through variations in the cooling rate under different gases.. Compared with argon, all the other shielding gases and gas mixtures are expected to give a greater weld depth, since the higher heat flux density is likely to dominate, as shown by the data collected in Table 2. Fig.2 shows a substantial increase in temperature under the same energy input conditions for the three positions and confirmed experimentally in the case of TIG shielded by nitrogen and helium. [12, 16, 17] It is noted that as well as the generally desirable effect of increasing the weld depth (16,17), addition of molecular gases to argon may have deleterious effects on the weld pool. These could include the promotion of porosity and introduction of contaminants, and these factors should be considered in choosing the optimum shielding gas composition of a given objective [24, 25].It is for these reasons that unmixed argon was chosen as the shielding gas to be used in current projects concerning the development of surface metal matrix composites using TIG [26,27]. The implication of the graphs in Fig.2, is that using helium as a shielding gas, could have major affects in producing different microstructures with a range of properties such as hardness, depending on test position in the surface treated alloy [16, 18, 23].On the other hand, the advantage of using helium is that it may allow lower heat inputs to be used.

Due to the many similarities between using TIG as a heat source for welding and also for surface engineering, a model based on that devised by Rosenthal [21] was used to predict temperature variations with time at three positions, 5mm below the surface, along the melted track, Fig.1. Rosenthal's model assumes no liquid phase is present, and therefore is applicable only to deal with solids, such as HAZ and parent plate.

The comparison in the present work between the experimental temperature readings with the mathematical heat transfer model is shown in the graphs in Fig.4.

Here in Fig.4 it can be seen that the temperature variation associated with the preheat can be predicted satisfactorily using the constants given in Equation 1 and Table2. With argon as the shielding gas, the difference between experimental readings and those predicted by the model is 6% (max 35°C). It is also seen that the curves determined experimentally from the three positions merge after 2500s cooling, when the temperature is <100°C.

°Future work is centered on constructing a fully nonlinear mathematical model of the TIG process and consequent heat flow from first principles. In particular, the prediction of the peak temperature reached in the melt zone will be sought, as this will enable a better understanding of the development of microstructures and related properties when incorporating ceramic powders during a surface engineering process.

5. Conclusions

Experimental data on the temperature changes at three positions along the track melted on a microalloyed steel surface by a TIG torch were recorded using three shielding gases, argon, helium and nitrogen. The data collected using argon showed the smallest effect of preheat ahead of TIG torch.

A mathematical model, based on the Rosenthal approach normally used in welding situations, was developed to predict temperature of melted track at any point in space/time. Based on the lower preheat recorded using argon as the shielding gas , a comparison has been made of the experimental data and the temperature changes predicted by the model. This initial modelling attempt with a ~6% difference, shows a satisfactory quantitative agreement with experimental data.

6. Funding

7. Acknowledgment

References

[1]   R. Bach, E Damascheck, Geissler and H.W Bergmann: Laser Transformation Hardening of Different Steels, in Proc.3rd European conf. on Laser treatment of materials (ECLAT'90), (H.W.Bergmann and R.Kupfer, eds.), Coberg,Sprwechsaal   Publishing Group (1990) p. 265-282.

[2] J.D. Ayers and R.J Schaefer. Consolidation of thermal spray coatings by laser remelting'. Proc.conf. Laser applications in material processes',(J. F. Ready   ed.), Bellingham, SPIE (1979) p. 57- 64,

[3]   N.B. Dahotre and. K Mukherjee. Development of microstructure in laser surface alloying of steel with chromium. Journal of Materials Science, 25, (1990), p.445-454.

[4]   J. D .Ayers and T. R. Tucker: Particulate-TiC-hardened steel surfaces by laser melt injection. Thin Solid Films, 73, (1980), p. 201-207.

[5]   J.H.Abboud and D.R.F. West: Microstructure of titanium injected with SiC particles by laser processing. Journal of Material Science Letters,Vol.10, (1991), p.1149-1152

[6]   A.Y. Fasasi, M. Pons, C. Tassin, A. Galerie, G. Sainfort and C. Polak. Laser-surface melting of mild-steel with submicronic titanium carbide powders: Journal of Materials Science, 29, (1994), p. 5121-5126.

[7]   S. Mridha and T. N. Baker: Metal matrix composite layers formed by laser processing of commercial purity Ti-SiCp in nitrogen environment. Material Science and Technology, Vol.12, (1996), p. 595-602.

[8]   S. Mridha and T. N. Baker. Metal matrix composite layer formation with 3 mu m SiC powder on IMI318 titanium alloy surfaces through laser treatment. Journal of Material Processing Technology., Vol.63, (1997), p.432-437.

[9]   S. Mridha, S.Y. Ho and S.T. Kum. Surface layer addition of hard particles using TIG arc melting. Conf.proc, 'Processing and Fabrication of Advanced MaterialsVI'(K.A. Khor, T.S. Srivatsan and J.J. Moore, eds.), Singapore, (1998) , p. 1331-1338,.

[10] X. H Wang, S.L Song, Z.D Zou and S.Y Qu. Fabricating TiC particles reinforced Fe-based composite coatings produced by GTAW multi-layers melting process. Material Science Engineering. A, 441, (2006), p. 60-67

[11] X.H Wang, S.L Song, S.Y Qu and Z.D Zou. Characterization of in situ synthesized TiC particle reinforced Fe-based composite coatings produced by multi-pass overlapping GTAW melting process "Surface Coating Technology. 201, (2007), p. 5899-5905

[12] S. Mridha and S. Dyuti. Formation of TiN Dispersed Composite Layer on Steel Surfaces by Titanium Powder Preplacement and TIG Surface Melting Processes", Advanced Materials Research, (2011), p. 264-265, 1415-1420.

[13] K.A Lyttle. Shielding Gases". ASM Handbook Welding , Brazing and Soldering. Vol 6, (1993) p. 64-69

[14] M. Tanaka, S. Tashiro, T. Satoh, A. B. Murphy & J. J. Lowke. Influence of shielding gas composition on arc properties in TIG welding. Science of Technol.Weld. Join.,Vol.13 (2008),p.225-231.

[15] I. Bitharas , S.W. Campbell , A.M. Galloway , N.A. McPherson , A.J.Moore. Visualisation of alternating shielding gas flow in GTAW, Mater. design , Vol.91, (2016) p.424-431.

[16] P.Muñoz-Escalona, S Mridha and T.N Baker. Effect of Shielding Gas on the Properties and microstructure of melted steel surface TIG Torch Adv. Mater. Proc. Technol., Vol. 1, (2015) p.435-443.

[17] P. Muñoz-Escalona, S.Mridha and T.N.Baker. Effect of Shielding Gas and Energy Input on the Surface Geometry and Microstructure of a Microalloyed Steel Surface Melted with a TIG Torch. Adv.Mater. Proc. Technol., DOI:10.1080/2374068X.2017.1350021 on-line 10 July 2017

[18] P. Patel, S. Mridha and T.N. Baker. Influence of Shielding Gases on Preheat Produced in Surface Coatings Incorporating SiC Particulates into Microalloy Steel using TIG Technique. In press, Materials Science and Technology, Vol.30,(2014),p.1506-1514.

[19] C. Hu and T.N.Baker. The importance of preheat before laser nitriding a Ti-6Al-4V alloy. Mater. Sci.Eng. A. Vol.265, (1999), p.268-275

[20] C. Ion, K.E. Easterling and M.F. Ashby. A 2nd report on diagrams of microstructure and hardness for heat-affected zones in welds. Acta Metallurgica.Vol.32, (1984) p.1949- 1962.

[21] D. Rosenthal. Mathematical Theory of Heat Distribution in Welding and Cutting. Welding J. Vol. 20, (1941) p. 220-234.

[22] T.G. Gray, J. Spence and T.H. North. Rational Welding Design. Newnes- Butterworth, London, 1975.

[23] T. N. Baker and M. S. Selamat. Surface engineering of Ti-6Al-4V by nitriding and powder alloying using $CWCO_2$ laser. Materials.Science and Technology.,Vol.24 (2008),p.189-200.

[24] M. Ebrahimnia , M.Goodarzi , M Nouri and M,. Sheikhi. Study of the effect of shielding gas composition on the mechanical weld properties of steel ST 37–2 in gas metal arc welding. Materials.Design, Vol.30, (2009). p.3891–3895.

[25] P. Kah and J. Martikainen. Influence of shielding gases in the welding of metals, Internal. J.Adv. Manufact. Technol., Vol.64, (2012) ,9-12.

[26] P. Muñoz de Escalona, S. Mridha and T. N. Baker. Effect of silicon carbide particle size on the microstructure and properties of a coating layer on steel produced by TIG technique. Advances in Materials and Processing Technologies, Vol.4 (2016), 2, 451-460.

[27] P. Muñoz de Escalona, C. Lees, F.Sillars, S. Mridha and T. N. Baker. Development of a metal matrix composite layer on a microalloyed steel surface by incorporating Ti_2AlC particles using a TIG torch technique. Advances in Materials and Processing Technologies, DOI: 10.1080/2374068X.2017.1350542 on-line 10 July 2017.
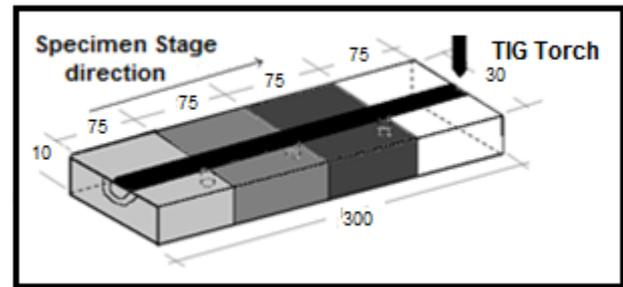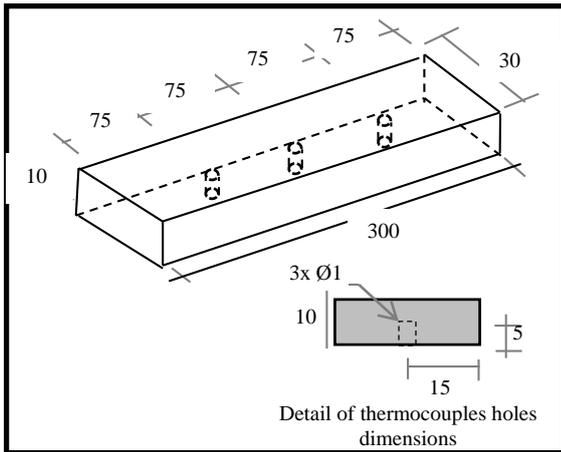
a)

Figure 1. Schematic TIG melted surface. a) Sample's dimensions and location of thermocouple b) location of melted track and welding direction
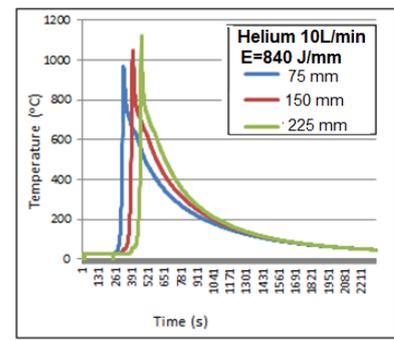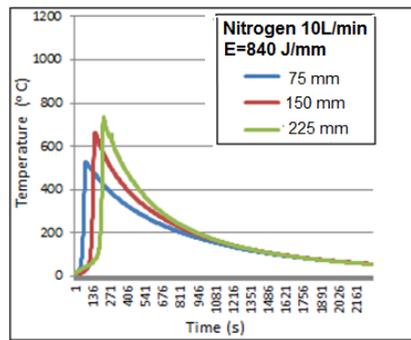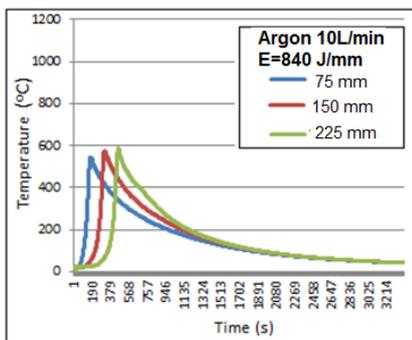
a)   b)   c)

Figure 2. Temperature versus time registered by thermocouples located at different locations in the plate a) argon, b) nitrogen and c) helium
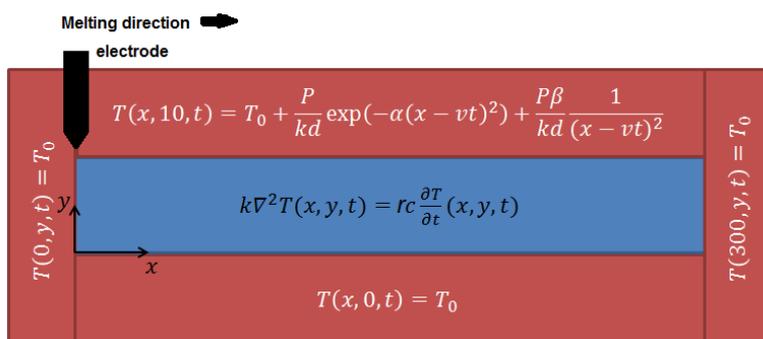

Figure 3. Schematic drawing of plate indicating the mathematical model and boundaries conditions in each part of the plate
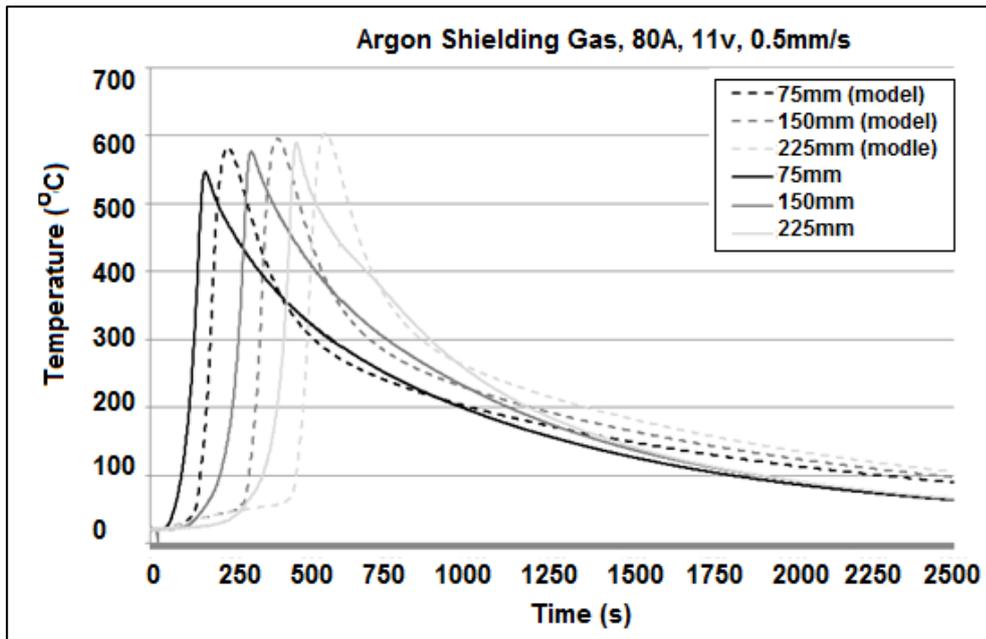
Figure 4. Comparison between experimental and numerical values obtained using developed mathematical model (Equation2) when using argon as shielding gas

Table 1. Conditions used in the experiment

Sample (Gas)	I [A]	V [v]	s [mm/s]	E [J/mm]
Argon	80	11	0.5	840
Nitrogen	80	22	1	840
Helium	97	18	1	840

Table 2. Thermal properties of the parent material and shielding gases used in this research

Property	Parent material	Argon	Nitrogen	Helium
Density [Kg/m^3]	7850	1.661	1.165	0.169
Specific heat [kJ /Kg K]	0.49	0.520	1.040	5.190
Thermal conductivity [W/m K]	54.00	0.016	0.024	0.143
First ionization potential [eV]		15.80	14.50	24.58

Table 3. Maximum values of temperature registered by each thermocouple located at different positions in the melted track

Gas	Temperature (ºC) Thermocouple 1 (75mm)	Thermocouple 2 (150mm)	Thermocouple 3 (225mm)
Argon	545	575	590
Nitrogen	530	660	740
Helium	970	1050	1120