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MODELLING AND COMPARISON OF DIFFERENT DESIGN SOLUTIONS AND EXPERIMENTAL RESULTS FOR DC TRANSFERRED ARC PLASMA CUTTING TORCHES

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ABSTRACT

The aim of this work is mainly to investigate by means of a 2-D FLUENT© based numerical model the behaviour of different types of transferred arc dual gas plasma torches used for cutting of metallic materials, giving the physical reasons for the industrial success of various design and process solutions appeared over the last years. Flow and heat transfer equations are solved with coupled electromagnetic ones, for an optically thin LTE plasma, while turbulence phenomena are taken into account by means of a k-ε RNG model, including the prediction of thermal behaviour of the solid components of the torch head and the efficiency of nozzle and electrode cooling systems in various operating conditions including gas mixtures (O_2/air, H35/N_2, N_2/N_2). Radiation is included in the calculation of heat transfer to the surfaces of the components using a customized Discrete Ordinate (DO) model. Additional experimental results have been obtained using a high speed camera (HSC), during pilot arcing and piercing of mild and stainless steel plates of various thickness and in different operating conditions. The technique has provided new insight of the PAC process and some interesting phenomena have been highlighted: such as, the trajectory and velocity of hafnium particles emitted from the electrode during pilot arcing and the effect of non perfectly aligned consumables (shield-nozzle) on inducing destructive piercing.

KEY WORDS

Plasma arc cutting; DC transferred arc thermal plasma; modelling of thermal plasmas; high speed imaging.

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INTRODUCTION

Transferred arc plasma torches are widely used in industrial cutting process of metallic materials because of their ability to cut a wide range of metals and because of the very high productivity that can be achieved with this technology. The plasma arc cutting process is characterized by a transferred electric arc that is established between an electrode that is part of the cutting torch (the cathode) and another electrode that is the metallic workpiece to be cut (the anode). In order to obtain a high quality cut and a high productivity, the plasma jet must be, among the other things, as collimated as possible and must have the higher achievable power density. With this regard, modelling and numerical simulation may be very useful tools for the investigation of the characteristics of the plasma discharge generated in these kinds of devices, as well as for the optimization of industrial cutting torches. In recent years, numerical simulation has gained popularity as a tool for torch design and a lot of papers have been published on this topic (see, for example, [1- 6], just to name but a few).

The particular approach of this paper is in line with the research work done by the Authors in recent years to fulfil the need for understanding the physical reasons behind industrially successfully ideas taking as a starting point either patented solutions or commercial solutions based on those patents in the field of plasma arc cutting. In this frame, it must be said that the Authors have decided to investigate by means of numerical simulation the behaviour of a number of plasma torches for metal cutting available on the market; such torches have being measured in detail and the resulting geometries used within FLUENT© in typical operating conditions fit for cutting at a certain current level. Results have been analyzed with respect to plasma behaviour and conclusions have been drawn concerning the powerfulness of numerical simulation as a tool for cutting torch design.

PHYSICAL-MATHEMATICAL MODEL

Two-dimensional computational model for the simulation of a transferred arc plasma torch require the simultaneous solution of the coupled set of non linear fluid dynamic, electromagnetic and energy transfer equations as done in [4-6] by some of the authors for a free-burning arc configuration.

In the present model, turbulence phenomena are taken into account by means of a k-ε Realizable model in order to better describe the flow field inside the device. Since flow inside the plasma torch presents a transitional regime from laminar to turbulent regime (i.e. the flow is turbulent in the region close to the inlet, nearly laminar inside the nozzle and turbulent again at the nozzle exit), a detailed treatment of the boundary layer is performed using a very fine grid near the walls, in order to capture the details of flow field and the mechanisms of turbulence generation. The main simplifying assumptions on which the developed models are based are: stationary discharge, optically thin plasma and local thermodynamic equilibrium (LTE).

The electromagnetic equations are solved, by the FLUENT® solver, by means of a *user-defined scalar* (UDS). Calculation of the radiation field inside the plasma discharge has been performed paper using the net emission coefficient (*nec*) approach with a plasma radius of 0.5 mm, while plasma is considered globally as an optically thin medium. Then radiation intensity distribution inside the nozzle can be calculated by means of a Discrete Ordinate (DO) approach in which the radiation intensity *I(**r**,**s**)* is function of position ***r*** and a discretized set of directions ***s***, while the *nec* is used as radiation source. Within this approach is possible to take into account absorption and reflection of radiation on the walls of the plasma chamber in order to gain information on the heat fluxes from plasma to nozzle and cathode materials. The thermodynamic and transport coefficients of the different plasma mixtures used for the numerical simulations are those given in [7,8].

SELECTED RESULTS

Hypertherm HPR-130 Plasma Torch With Vented Nozzle Technology

This patent concerns the existence of a "bypass channel formed between the inner and outer nozzle pieces" that "directs the bypass flow to atmosphere"; moreover, "the pre-orifice and nozzle orifice are positioned and dimensioned to optimize the mass flow velocity and the strength of a vortex type flow at the pre-orifice; thereby creating a virtual nozzle immediately below the electrode". The final result obtained by means of this patented solution is that "the gas flow in the plasma chamber is highly uniform and very steady" [9].

Starting on the fact that "in known high definition torches the plasma flow is typically swirled" the inventors propose the patented solution to overcome the problems related to low levels of mass flow rates that were usual in the prior solutions for high definition torches where "the level of stabilization provided by vortex flow are or cold wall stabilization are not sufficient to overcome the arc stability problems …", also due to the "severe chocking effect of the heated gas in the nozzle" that prevents from using the expedient of increasing the gas flow to the torch.

So, the patented solution proposes "an improved nozzle and method of operation" to enhance arc stability, cut quality and consumables life by venting to the atmosphere a portion of the injected plasma gas before it reaches the nozzle orifice.

Based on torch geometry and operating conditions at 130A on cutting mild steel, numerical simulation can give some insight in the effects induced on the arc when the vented nozzle solution is considered with respect to a non-vented one.
First of all it is possible to evaluate the flow rate of which is vented from the plasma chamber as a function of pressure and temperature in the vent chamber; this result can then be used as a boundary condition in the main simulation of plasma behavior during arc discharge with the vented nozzle technology.

The near axis region in the plasma chamber for the vented case shows higher plasma temperature than for the non-vented case while only slight differences in the nozzle orifice region are deducible for the two different torch configurations (see Figure 1).

Once again in line with the claims of the mentioned patent, big differences in the radial behavior of axial mass flow rate can be seen from comparative simulation of the vented and non-vented case in the chamber region, while only slight differences can be experienced in the nozzle orifice region.

Most interesting results concern the effect of the vented technology on plasma swirl velocity in the plasma chamber and in the nozzle orifice region. Figure 2 shows that swirl velocity for the vented case is 4-5 times higher than for the non-vented case at the beginning of the nozzle orifice, as claimed in the mentioned patent.

Some more conclusions can be drawn considering results summarized in Figure 3 and more simulation results which are not presented here [6]: the introduction of an anticlockwise component of secondary gas swirl leaves unaffected plasma behaviour in the plasma chamber in comparison with the vented case with ordinary clock-wise swirl. In the nozzle exit region the radial distribution of swirl velocity has the same maximum absolute values, opposite in sign.

Anticlockwise swirl of secondary gas is also claimed in the Tanaka Engineering Works Ltd patent JP2001 225170 [10] as a solution to diminish both right and left bevel angles. The abovementioned patent describes the problem to be solved in terms of providing a plasma torch “that can realize common linear cutting easily at a cost with a simple and inexpensive structure”; the patented solution is aimed at providing the dual gas torch with a “plasma gas nozzle […] for forming a swirling flow […] of plasma gas that swirls toward a desired cutting point […] of a material […] to be cut and an assist gas nozzle […] for forming a swirling flow […] of assist gas that swirls toward the cutting point […], in the opposite direction from the plasma gas swirling flow”. This solution claims to provide a reduction of both left and right bevel angles during cutting, together with a slight “bottom *kerf*” widening. Patent drawings highlight the effect of the interaction between primary and secondary gas ad an increase in importance of the axial component of the jet with respect to the swirl component in the *kerf* region.

The subject of bevel angle formation during cutting has been recently addressed by Nemchinsky and Severance [11]; in their recent topical review paper on plasma arc cutting, they propose a qualitative reason for the formation of different bevel angles for left and right region of the cutting *kerf* in dual gas PAC systems: that on the basis of the interaction of the whole swirled plasma jet (the Authors don’t say if reference is made to dual gas torches with coherent primary and secondary swirl or to single gas torches with swirled gas) with the workpiece; the “hottest” part of the jet being in contact with the metal on the left side of the *kerf*, while the “coldest” part of the jet is in contact with the metal on the right side. But this approach would be unsuccessful in explaining the positive effects of anticlockwise secondary swirl on cut quality: in fact, taking into account the whole radial extension of the plasma jet as a means for cutting the workpiece, with anticlockwise secondary swirl one should experience a left bevel angle smaller that the right one; but that is not the case in real life, in many operating conditions and materials. On the contrary, one can conclude from the analysis of simulation results performed on Hypertherm HPR130^{TM} (which uses the solution of anticlockwise secondary swirl in a wide range of operating conditions, both on mild and stainless steel, with excellent results for cut quality) that the main effect of anticlockwise secondary swirl is a relevant reduction of plasma swirl velocity in the post nozzle region of the jet which is radially limited to the *kerf* width (“core”).

A qualitative conclusion can so be drawn (see Figure 4): on one side the qualitative analysis proposed in [11] doesn’t seem to describe the bilateral reduction of bevel angle that can be experienced with anticlockwise secondary swirl; on the other side that reduction could be in fact related to the reduction of plasma swirl velocity in the central region of jet effectively interacting with the *kerf* region.

In that sense Figure 5 and Figure 6 describe the radial distribution of such a velocity when the secondary gas swirls coherently with the primary gas or anticlockwise: curves obtained from numerical simulation of the Hypertherm HPR-130 torch (plasma gas: O_2; secondary gas: air; nozzle diameter: 1.41mm; current: 130A; plasma gas pressure: 6 bar; secondary gas pressure: 1 bar) are parameterized for various distances downstream the torch exit (z=0) within the range of usual stand-off distances between torch head and workpiece in such operating conditions.

Komatsu 120A Plasma Torch

Again on the side of patents and related technology that aim to arc stabilization during metal cutting, is useful to keep into account the accomplishments done in early '90s by Kabushiki Kaisha Komatsu with two patents strongly related to one another: "Method of machining plate materials with a plasma cutter and plasma torch", US 5,202,544, (13 April 1993) [12] and "Transferred plasma arc torch", US 5,214,263 (25 May 1993) [13]. The first patent is aimed at the reduction of double-arc phenomena and to the enhancement of arc stability by using a "magnetization apparatus" that produces an additional swirl velocity component to plasma velocity in the vicinity of the electrode, for torches where the nozzle diameter is less than 1.6 mm. The second one is aimed at obtaining "an excellent cut face having a small angle of inclination" by means of a particular "double chamber" nozzle that is able to reduce cut quality sensibility to even small deviations from axial symmetry in consumables, as coming both from bad alignment and from nozzle and electrode wear somehow induced by cutting operation.
Measurement of the magnetic filed generated by means of the permanent magnet embedded in the Komatsu 120A torch have been performed in the Cebora laboratories and results (see Figure 7 and Figure 8) fit the claims of patent US 5,202,544. Based on torch geometry and operating conditions at 120A on cutting mild steel (primary plasma gas: air; secondary gas: air; nozzle diameter: 1.37 mm; current: 120A; primary gas pressure: 3 bar; secondary gas pressure: 1 bar), from numerical simulation of the device it is possible to conclude that the main effect of the superimposed magnetic field of the Komatsu torch is that of raising the value of plasma swirl velocity in the plasma chamber near cathode region (maximum values about 7 m/s with respect to 0.05 m/s of the non-magnetic configuration) as in Figure 9; plasma temperature (see Figure 10) and velocity distribution do not seem to be much affected by the presence of the magnetic field, as well as plasma swirl velocity at the nozzle exit. For what concerns the industrial importance of the "double chamber" solution patented by Komatsu, it must be said that Hypertherm, Thermadyne, Kjellberg and Cebora all use similar chamber geometries (not infringing the Komatsu patent) in a wide range of operating conditions for mild steel cutting.

Besides simulation, also diagnostics based on high speed (HS) imaging can play an important role for investigating dross generation, anode attachment location, arc transients during cutting and pilot arcing and piercing [2,14, 17-21]. The cutting process is started with ignition of a low current (25 A) arc discharge between cathode and nozzle (pilot arc) by means of a short HF pulse. Once the pilot arc is established, the particular set of gas operating conditions induces the arc to be blown out of the nozzle and attach to the workpiece. While piercing, the torch is usually immobile, even though, for thick plates, a progressive increase of the stand-off can be implemented to avoid bridging phenomena and attaching to the shield of the molten metal which is ejected from the *kerf*. Also plasma gas changes from pilot arc (typically air or nitrogen) to piercing (typically air or oxygen, for MS), to minimize electrode erosion. Images have been obtained using a NAC Memrecam K3R HS camera with a 180 mm focal-length lens, protected by a sacrificial neutral filter at a stand-off distance of 1 m from a Cebora (HQC164 for the range 25-120 A and HQC 254 for the range 120-250 A) plasma torch, joined with a digital oscilloscope (LeCroy LT374M), synchronizing the start acquisition time of both instruments, during pilot arcing and piercing of MS and SS plates in different operating conditions, using Cebora plasma sources. Fig. 11 shows a picture during piercing of a mild steel slab 40 mm thick when using non perfectly aligned torch head components; this leads to an off-axis discharge with ejection of molten metal sideways and on the shield surface. Fig. 12 shows images taken during pilot arcing: the typical arc loop attachment point moves along the nozzle edge faster than the maximum fps of the camera, leading to those ‘frozen’ sequence of images, each with a “double discharge” appearance. In Fig. 13 the piercing phase of stainless a stainless steel slab 15 mm thick is shown, starting with the pilot arc phase at t = 0 and reaching maximum current (100 A) at around 100 ms; piercing is completed at t = 400 ms, while at 2,200 ms the torch is shut down using a slope down current profile.

In conclusion, the use of high speed camera as a diagnostic tool for characterizing pre-cut phases in plasma arc cutting analysis has been shown. Also, among results not presented here, the images captured by the HSC have been time-correlated to the oscilloscope waveforms of voltage, current and pressure inside the nozzle while pilot arcing images have been obtained in the absence of the torch shield cup (without secondary gas), in order to observe the arc loop attachment on the nozzle tip. Pilot arcing duration has been extended with respect to real cutting conditions in order to fully observe arc loop attachment phenomena. In some cases, it has been possible to evaluate time necessary for the pilot arc to exit from the nozzle, arc transfer time and to investigate double arcing phenomena, together with a hypothesis of correlation between arc instabilities with arc voltage oscillations and arc shapes with pressure and current transients.

CONCLUSIONS AND FUTURE DEVELOPMENTS

A whole lot of simulation results have not been presented here due to the limited space available, even though they have been presented during the oral talk at the conference (simulation results for Cebora Plasma Prof 164 HQC, Thermadyne XT-300, ESAB PT-600, Kjellberg PerCut 160) [22]. Fluid dynamics seems to be one of the most important factors to be considered in the design of a plasma cutting torch. Swirl component is responsible for the stability of the discharge and affects nozzle life and cut quality. Results show that actually the Hypertherm and Komatsu patents here described are both somehow related to the increasing of swirl component in different regions the plasma chamber. Yet a strong swirl component might have the important drawback of reducing electrode life and of increasing the wall angle difference between the two cutting sides. In some operating conditions the latter effect can be reduced using a secondary gas with anticlockwise swirl component.

The selected group of results here presented show how numerical simulation and high speed imaging of plasma torches for metal cutting can give a deep insight in the physics of arc discharge and be a useful tool for torch design.

Still, we need to undertake big efforts, especially for fulfilling the following research aims: to take into account non-equilibrium effects within our modelling codes; to evaluate the effect of secondary gas swirl injections with different directions and the effect of various different approaches for the geometry of the plasma chamber; to simulate also cutting torches of Hypertherm Inc. with "coaxial nozzle technology" as from patent US 6,207,923 (27 March 2001, by J. Lindsay); to simulate Koike Sanso Kogyo cutting plasma torches, especially for their most interesting way of treating swirled injection of plasma gas; to study via high speed camera diagnostics plasma and secondary gas mixing to support results coming from simulation; to fully simulate the electrode region and the thermal behaviour of the solid components of the torch head, including the thermal histories and trajectories of hafnium oxide particles emitted from the insert under non-idealized conditions; to study 3D effects of secondary gas swirl injections with different flow rates and geometry of the diffuser; to study the effect of various different approaches for the geometry of the plasma chamber in addition to what has been presented here; to find a useful link between a full simulation of the *kerf* region and experiments to predict cut quality; to simulate shut-down transients (less than 100ms) to understand electrode erosion behaviour and hope to support experiments; to use more parallel CPU power to efficiently use simulation for torch design.

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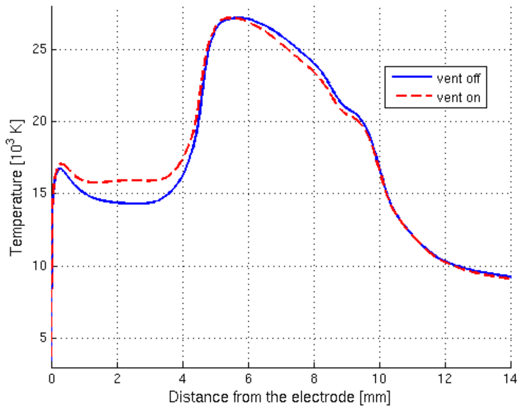


Fig. 1. Plasma temperature [K] on the torch axis from simulation for the vented and non-vented case. Picture taken from [22].

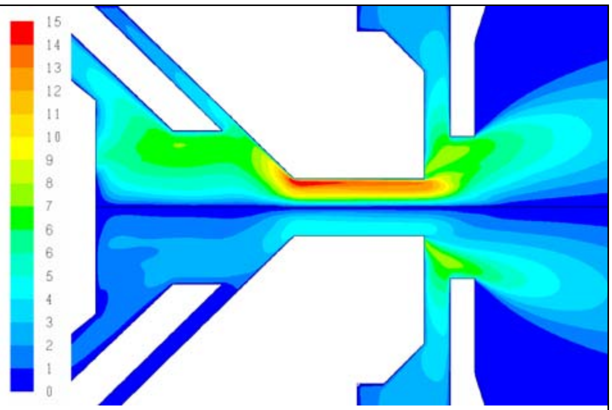


Fig. 2. Plasma swirl velocity [m/s] from simulation for the vented (upper-half) and non-vented case (lower-half). Picture taken from [22].

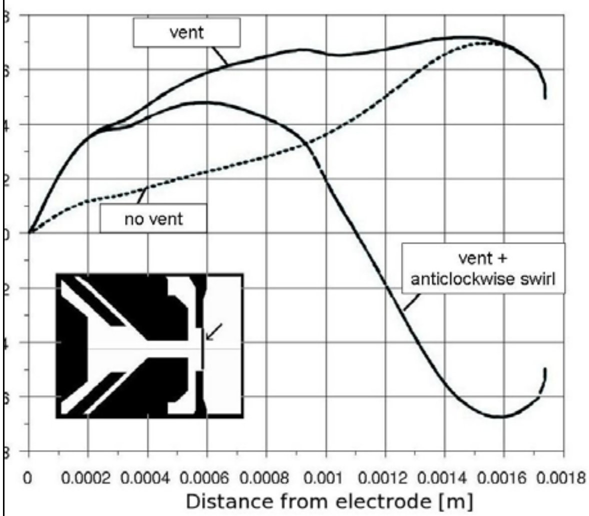


Fig. 3. Radial behavior of plasma swirl velocity [m/s] at the nozzle exit from simulation for the vented case with two types of secondary gas swirl and for the non-vented case. Picture taken from [22].

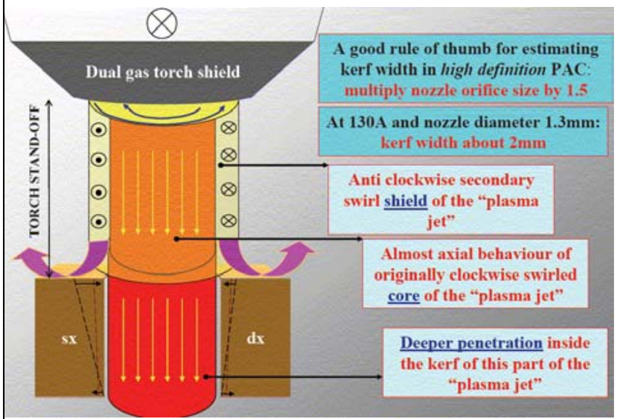


Fig. 4. Qualitative explanation of formation of bevel angle based on evidence of the effects of anticlockwise secondary swirl. Picture taken from [22].

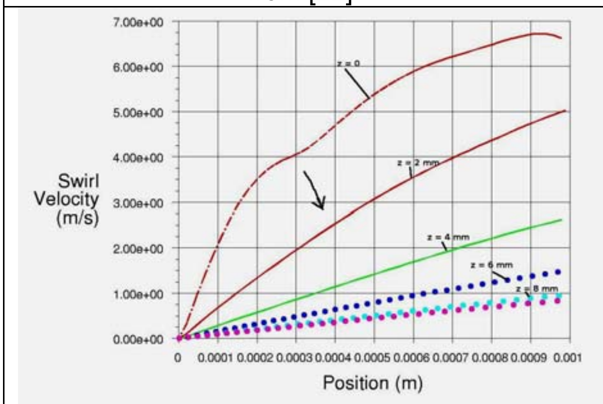


Fig. 5. Plasma swirl velocity at a distance z [mm] downstream torch shield along the radius of the jet with secondary gas swirl coherent with the primary gas swirl. Picture taken from [22].

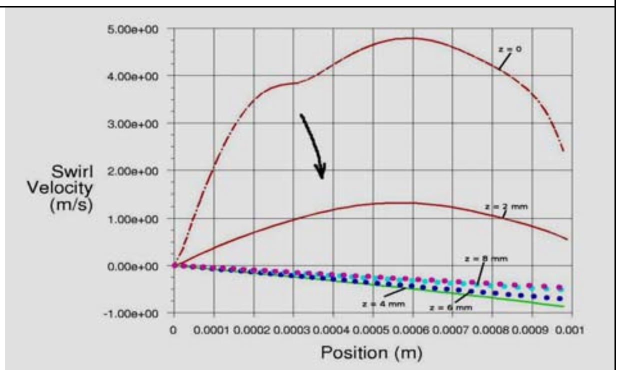


Fig. 6. Plasma swirl velocity at a distance z [mm] downstream torch shield along the radius of the jet with anticlockwise swirl of the secondary gas. Picture taken from [22].

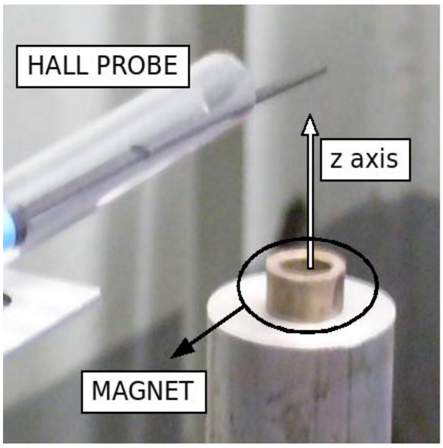


Fig. 7. Experimental setup for 2-D reconstruction with Hall effect probe of magnetic flux generated by the permanent magnet embedded in the Komatsu torch (internal diameter: 10mm; external diameter: 14.8mm; height: 8mm) as from patent [12]. Picture taken from [22].

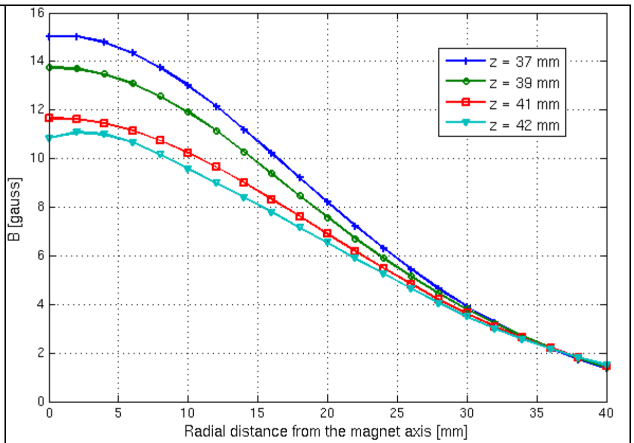


Fig. 8. Magnetic field magnitude [gauss] of the Komatsu magnet as function of radial distance from the axis [mm] and for different distances from the magnet [mm] (cathode tip at z = 37 mm and nozzle exit at z = 42 mm). Picture taken from [22].

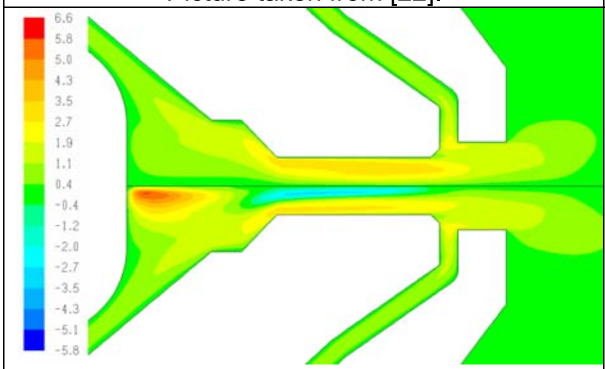


Fig. 9. Comparison of plasma swirl velocity [m/s] from simulation for the Komatsu plasma torch with (below) and without (above) magnetization apparatus under the following operating conditions: 120A, plasma gas pressure (air)=3 bar; secondary gas pressure (air)=1 bar; nozzle diameter=1.37mm. Picture taken from [22].

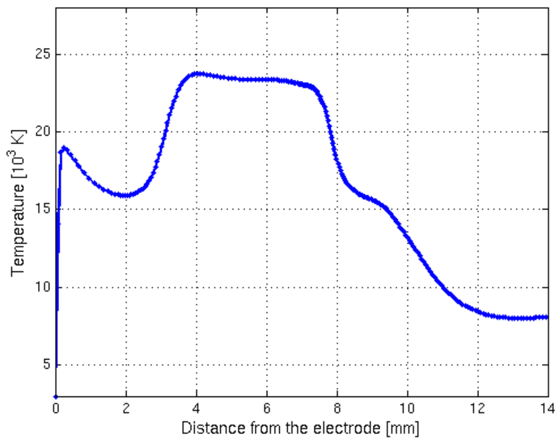


Fig. 10. Plasma temperature [K] on the axis of the torch from simulation for the Komatsu plasma torch with magnetization apparatus under operating conditions as in Fig. 9. Picture taken from [22].

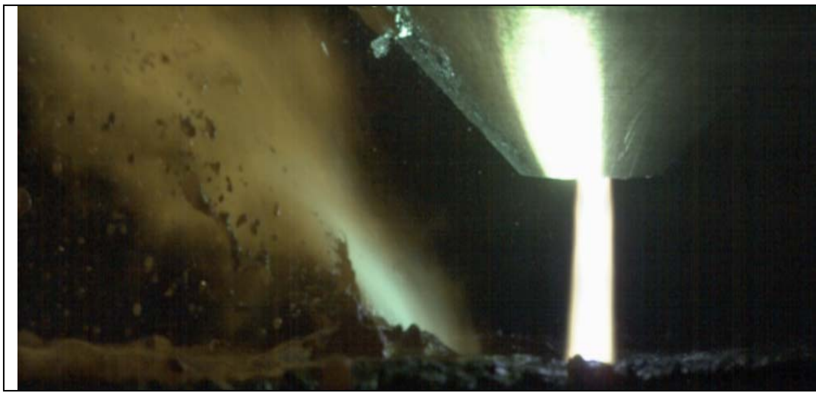
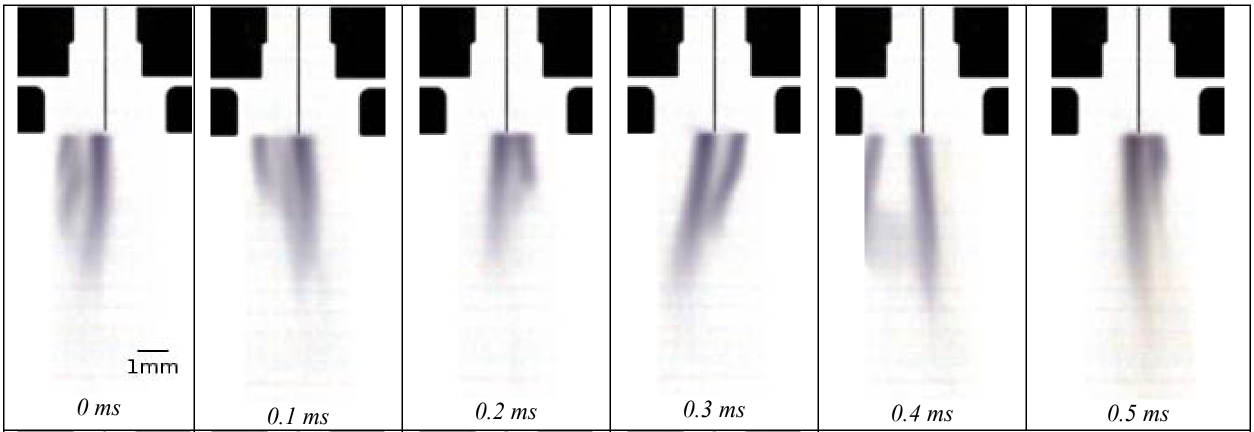


Figure 11. Piercing of a 40 mm MS slab using non perfectly aligned torch head components (1.9 mm nozzle, 250 A, cut plasma/shield gas: O_2/air, 1,000 fps, 1/20,000 shutter time). Pictures taken from [20].



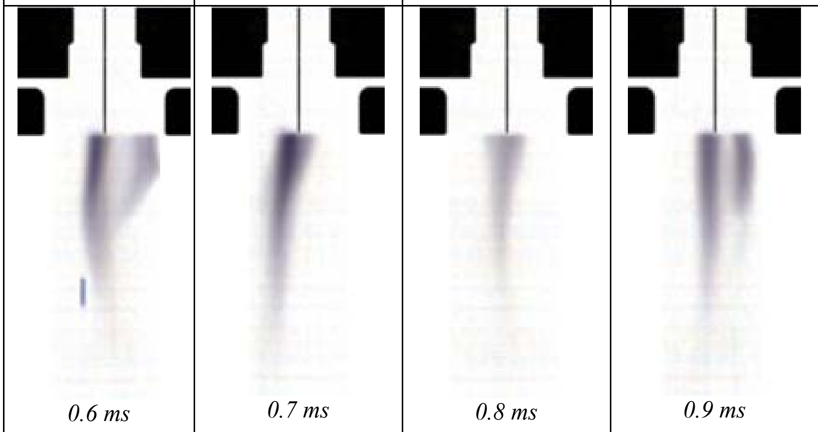


Figure 12. Pilot arc images at different time steps for a torch with 1.9 mm nozzle and 3.5 mm shield diameter, at 25 A (plasma/shield gas: Air/Air). The t = 0 ms frame is the first noticeable after ignition. Nozzle and shield are partly sketched in black with torch axis. Images are acquired at 10,000 fps and 1/200,000 s shutter time without any filtering. For t = 0.6 ms a particle exits the orifice at ~1,350 m/s, probably coming from cracking of the solid layer of HfO_2 on the emitter during pilot arcing [1] and on a shorter time-scale than the one typical for liquid metal droplets ejection during transients [14]. Pictures taken from [20]

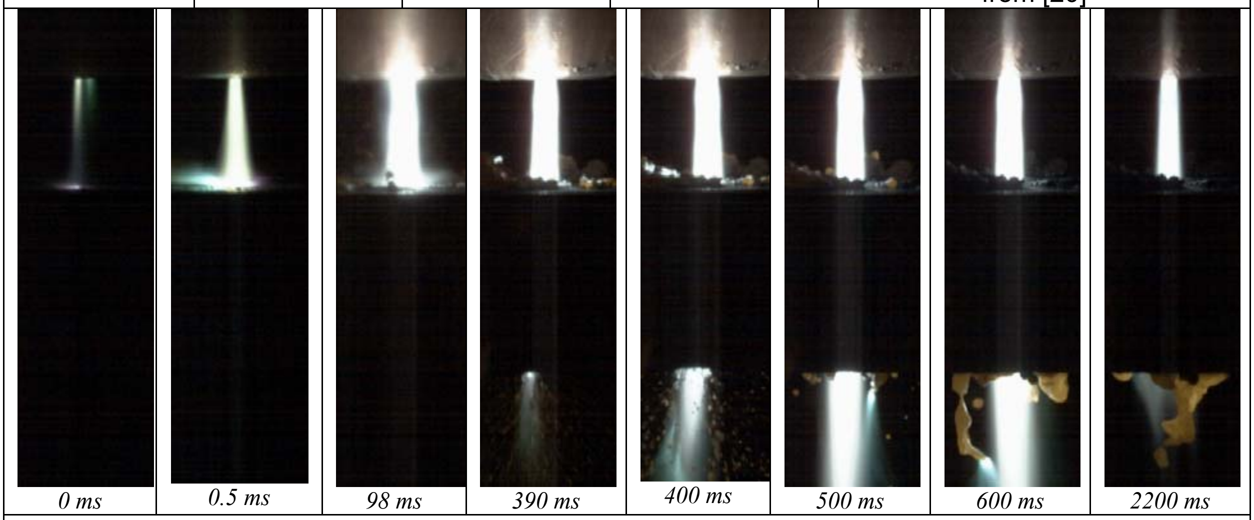


Figure 13. Piercing of a 15 mm SS slab (1.6 mm nozzle, 100 A, pilot arc plasma/shield gas: N_2/N_2, cut plasma/shield gas: H35/N_2, 1,000 fps, 1/20,000 shutter time). Multiple arc root attachments from plasma jet through conductive metal vapour projecting from dross nodules accumulated around the pierce bottom edge can also be seen in frames from 400 to 600 ms. Pictures taken from [20]