JTTEE5 16:684–689
DOI: 10.1007/s11666-007-9100-1

Peer Reviewed

Improvement of Plasma Gun Performance Using Comprehensive Fluid Element Modeling II

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(*Submitted March 9, 2007; in revised form July 12, 2007*)

Use of a comprehensive validated computer model of a thermal spray process enables an ability to improve, optimize, and fine-tune the performance of that thermal spray process. A validated model of the Sulzer Metco Triplex*Pro*™ 200 plasma gun has been used to improve the performance of the actual gun in terms of enhancing gas flow dynamics, thermal management, and overall performance in terms of a robust design. Internal changes to the gun geometry using the model have extended the life of the hardware. In addition the model has permitted the investigation of the fundamental operation of the gun, specific to the behavior and path of the arcs, as well as the ability to operate the plasma gun, under simulation, in operating regimes that currently cannot be supported by the physical hardware. The model has been run at gas pressures above 1.4 Mpa and/or voltages above 300 V that currently cannot be obtained with the physical hardware due to equipment limitations to evaluate the potential to extend the operating window of the Sulzer Metco Triplex*Pro*™ 200 gun beyond current levels in terms of particle velocity and temperature. The end result is an improved process tool for applying thermal spray coatings ranging from ceramics applied at high particle temperature and low particle velocities to carbides and alloys applied at lower temperatures and higher velocities.

Keywords CFD modeling, fluid dynamics, high velocity plasma, plasma gun

1. Introduction

The application of modern computational modeling to thermal spray has produced a detailed and accurate model of the inner workings of the Sulzer Metco Triplex*Pro*™ 200 Plasma Gun (Ref 1, 2) manufactured in Westbury, NY, USA. Development and validation of the model took several man-years to complete along with considerable resources covering the fields of plasma physics, electrical arc physics, computational modeling, as well as considerable practical knowledge in the operation of a plasma thermal spray gun. The development of such a model is not the end in itself but a means to achieve the desired goal of improving the performance of plasma guns.

This article is an invited paper selected from presentations at the 2007 International Thermal Spray Conference and has been expanded from the original presentation. It is simultaneously published in *Global Coating Solutions, Proceedings of the 2007 International Thermal Spray Conference*, Beijing, China, May 14-16, 2007, Basil R. Marple, Margaret M. Hyland, Yuk-Chiu Lau, Chang-Jiu Li, Rogerio S. Lima, and Ghislain Montavon, Ed., ASM International, Materials Park, OH, 2007.

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Prior to development of computational models the development of plasma guns was done mostly empirically, often by trial and error, or through accidental discovery and realization of cause and affect relationships. Granted there was a considerable amount of knowledge regarding the physics involved with generating and sustaining a plasma arc, there was no method to actually verify exactly what was happening inside the gun. Often designs were implemented wherein the reasons why something was the way it was were not even known. This is called ‘‘practical art’’ and statements like ‘‘that is how it has to be in order for it to work’’ were common. Computational models offer far more understanding as to the why and permit higher levels of intelligent design.

The first model developed for thermal spray simulated one aspect of the operation of a process gun. In most cases this was the fluid dynamics aspect, being the easiest to model and in some cases validate (Ref 3, 4). Other models were developed that could simulate a plasma fluid and injection of powder into a fluid flow, etc. (Ref 5). Still others were able to combine fluid flow with chemical reactions (Ref 6, 7). Yet further models provided some insight into the behavior of plasma arcs (Ref 8, 2). As computational power increased and equations for modeling further developed and enhanced, the ability to produce a comprehensive model became feasible.

A comprehensive model of a plasma gun permits the maximum level of understanding as one can now see the interactions between fluid dynamics, arc dynamics, particle dynamics, and even thermal dynamics. Having such a model provides a plethora of opportunity for improvement.

2. Initial Evaluation

During the development and immediately following a number of opportunities arose to evaluate the performance of the gun. No sooner than a model step was completed then it was put to good use to evaluate and enhance the operation of the gun. A number of experiments were conducted operating the gun in the model under various sets of conditions, some of which are currently not possible in the real world.

2.1 Examination of High Velocity Plasma Operation

One of the first opportunities for improving the performance of the Triplex*Pro*™ 200 plasma gun was discovered during the first simulations of the supersonic gas flow produced with the 5.0 mm internal diameter high velocity (HV) nozzle. During the development of the model it was decided to be creative and explore operating regimes that cannot be explored in the real world due to physical and equipment limitations. Once the gas flows were validated a set of model runs were performed with the HV nozzle (5 mm internal diameter) by increasing the back pressure in the gun to observe the resulting gas flows. The intent was to evaluate the operation of the gun in terms of gas flow at extreme gas velocities to see what happens—pure curiosity. Heat input was simulated at this point by assuming a uniform gas temperature of about 2760 K as a starting point knowing that an actual plasma gun will produce at least this average gas temperature, even at low power conditions. The gas modeled was Argon only. Table 1 lists the model run conditions and the results.

Under normal or expected operating conditions for HV plasma it was known that the back pressure inside the gun would be about 0.2-0.3 MPa as measured in the actual gun during several trial runs with the HV nozzle. Examination of the actual flow patterns in the nozzle as shown in Fig. 1 show that the initial nozzle design was not ideal for the actual operating conditions.

The flow conditions clearly show overexpansion with the gas flow breaking away from the nozzle walls prior to exiting the gun. This overexpansion could be observed in the running of the actual gun as a fuzzy definition of the plasma plume near the nozzle exit.

Table 1 Model runs with gas flow only using simulated heating and increasing back pressure

Run number	Back pressure, MPa	Gas flow, slpm	Heat input to gas, kJ/s*
1	0.025	90	0.6
2	0.05	105	1.2
3	0.2	190	4.7
4	0.5	380	11.7
5	0.92	650	21.6
6	1.1	760	25.8
7	1.5	1020	35.2

*Based on no losses to the environment

The ideal operating condition for this nozzle was determined to be when the back pressure was increased to about 1.1 MPa as shown in Fig. 2.

Note that the velocity magnitude shown as coloration in each figure is relative and not directly comparable between the two figures. At 1.1 MPa the flow undergoes nearly ideal expansion and is almost parallel to the nozzle. The problem is the gun cannot be operated, nor is it intended to be, operated at this high a back pressure and flow.

As a result of this discovery the nozzle design was changed to optimize performance at roughly 0.25 MPa backpressure, increasing the operating efficiency in the expected operating regime of the HV plasma applications and within the expected range of back pressure. The result also produced a more defined arc plume when tested in the physical gun itself.

2.2 Examination of Internal Gas Flow Patterns

Once the arc model was complete and coupled to the fluid flow model a complete picture of the workings of the internal plasma flow resulted. Several relationships between the arc and gas geometry were observed.

The first relationship identified is the gas swirl and the orientation of the arcs. In the rear gas chamber where the

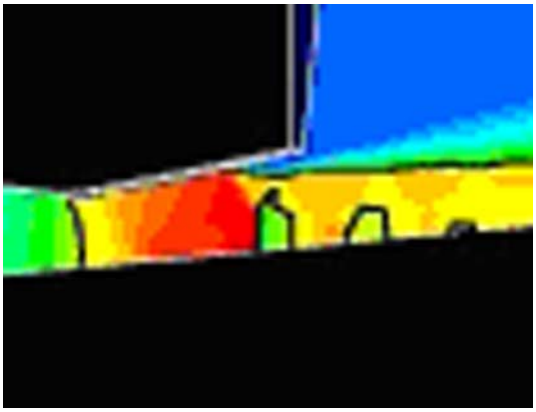

Fig. 1 Nozzle exit flow conditions for 0.2 MPa back pressure

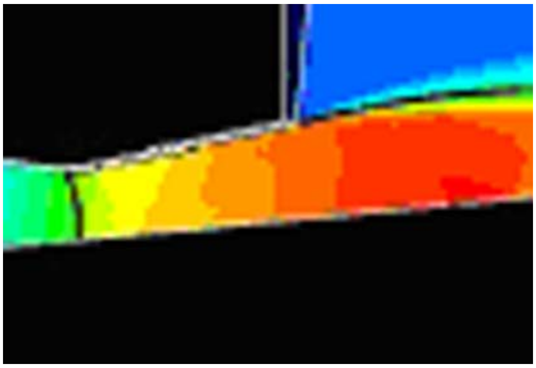

Fig. 2 Nozzle exit flow conditions for 1.1 MPa back pressure

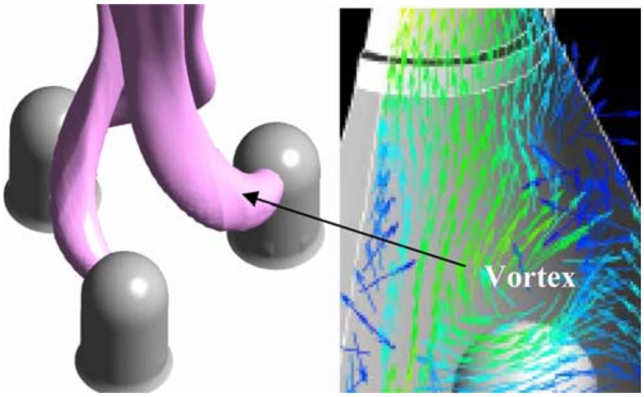

Fig. 3 Comparison of arc path to cutaway slice of gas flow pattern at trailing edge of electrode showing vortex corresponding to arc path

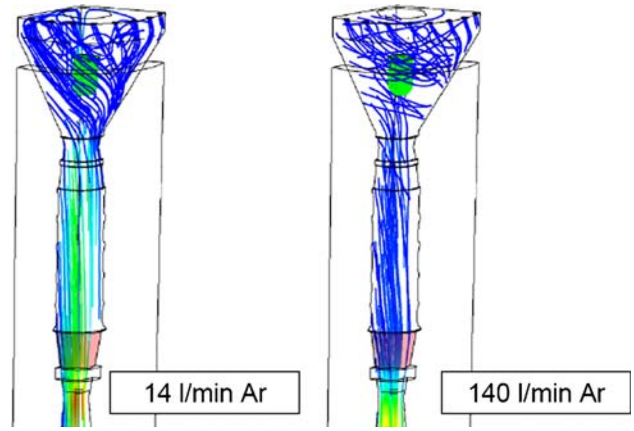

Fig. 4 Comparison of gas flows at 14 NLPM and 140 NLPM showing similar gas flow patterns

electrodes (cathodes) reside there is a vortex that trails behind the gas swirling in the chamber as it passes by each electrode. The location of the vortex and the path it takes to the bore follows roughly same path as the arc as it travels from the electrode to the bore entrance. It can be deduced from this that the vortex and the arc path are related. Figure 3 shows the arc path and a cutaway of the gas flow pattern halfway downstream of the first electrode. Additional confirmation came from images of the pressure and streamlines in this same region. Attempts at producing an image of the vortex itself were unsuccessful due to inability to isolate the streamlines and any resulting images were too congested with the streamlines to make out the vortex within.

Since arc length is a major determining factor in arc voltage and resulting arc power any significant alteration of this vortex would also result in changes to the performance of the gun. Any future design considerations that may result in alteration of gas flow, such as a change in component geometry, can then use the model to ensure that this flow pattern remains unchanged with respect to the vortex.

The next relationship resulted from looking at the entrance of the bore and how the arcs enter the bore away from the walls. Just downstream of the electrodes the vortices dissipate and the overall flow in the chamber consolidates into a single swirling flow. At this transition point is a second small vortex along the chamber wall. This second vortex can also be seen in Fig. 3 above the electrode trailing edge vortex and serves to reflect the gas flow inward and away from the chamber walls. The resulting affect on the arcs drives them to the center of the bore entrance and thus the walls are spared any impending contact or proximity to the arcs. This was especially true when the Lorentz force was added to the arc model. If this were not the case then the high voltage potential alone could abrade the chamber and bore walls.

Yet another observation made was that despite operating the model at various gas flows and current levels the gas flow pattern remained fairly consistent. Figure 4 shows the comparison of gas flows at two very different gas flows.

At the lower flow rate of 14 slpm the swirl pattern appears more pronounced, partially due to the higher number of streamlines used to define the flow, but the direction of flow past the electrodes is very similar and in fact produced a nearly identical arc path as a result. Note that the velocity coloration of the streamlines is not to the same scale. These two runs were at the same arc current and additional runs with different arc currents produced similar results.

What can be concluded from this is that the gas flow patterns can be dealt with independent of the arc model such that just using a simple heat source could be used to work on geometry changes without the need to run the entire comprehensive model. This made using the model to alter the gun geometry more feasible in that only the gas flow portion of the model need be run and so long as the critical areas of gas flow patterns were maintained the end result would not adversely affect the operation of the gun. The critical area being bounded by the region near the tips of the electrodes to the end of the gun bore before the nozzle that defines the path of the arcs.

Without having a comprehensive model the fact that the gas flow could be modified independent of the arcs would not have been discovered.

2.3 Examination of Diatomic Gasses

Diatomic gasses, Nitrogen and Hydrogen, have been used in plasma guns to boost performance, but at a price—gun hardware life. In addition guns like the Sulzer Metco 9 MB require a change in hardware (gas ring) to accommodate operation with nitrogen. As a preliminary examination the CFD model of the Triplex Pro 200 was run with just nitrogen as the plasma gas.

The Triplex Pro 200 Gun is capable of operating with small amounts of Nitrogen and/or Hydrogen to boost enthalpy. Instrumentation connected to the gun at Sulzer Metco during coating development and gun testing detected the presence of instability with the arcs as nitrogen flow is increased in proportion to argon. Curiosity then set in as to the cause of the instability and drove the desire to run the model with nitrogen only as a worst case scenario.

When the model was run with pure nitrogen the simulation failed to reach convergence indicating the presence of instability. Instability could result from an error in the model or give an indication that the actual solution is not stable. This was an interesting development as attempts to achieve high nitrogen flows with the plasma gun itself show the arcs become very dynamic, with fluctuating voltage between the three arcs, and eventually forces a shutdown of the system for this reason. As to whether the model is failing to reach convergence for the same reason is not known, but there is certainly coincidence driving even more curiosity.

It may be possible to ''freeze'' action during the model's convergence process if the arc instability is the cause of the model's lack of convergence by simply looking for relative minima and maxima of arc voltage or a related key indicator. The author has done this with simpler CFD models in the past, but is not sure whether this will work with such a complex model. It is left as an exercise for the future if the opportunity arises.

3. Experimental Modeling

Further development of the Triplex Pro 200 Plasma Gun is in the early stages, using the comprehensive model as the development platform rather than making changes to an actual gun and testing. Some of the work done to date represents the potential of using modeling to improve the performance. The model is a godsend when it comes to actually learning what is happening inside the gun.

3.1 Enhancement of Gas Flow for High Velocity

The current Triplex Pro 200 Gun design is capable of a very wide range of operating conditions from high enthalpy to HV. Extension of the operating range to even higher/lower gas flows and velocities may be possible if the gas flow pattern in the region where the gas is injected into the rear chamber can be optimized for a broader range of flow capability. To start this development task consideration was given to increasing gas flows and velocities.

Using the knowledge that the gas flow only portion of the comprehensive model can be used to change the gun geometry so long as the critical gas flow pattern is unchanged an experiment was conducted to determine how effectively this method would enable development of new gun geometry. The gas flow only model was set up with a simulated heat source and run with an argon flow considerably higher than currently used. Figure 5 shows the resulting gas flow pattern represented as streamlines. At high gas flows the incoming gas concentrates into more confined jet streams which are considered undesirable as they do not consolidate as well as when the gas flows are lower. In addition the buildup of back pressure upstream of the gas ring becomes excessive. The aim of the experiment is to alter the rear gas flow pattern to produce a more diverse gas flow pattern where the gas enters the rear chamber versus the current flow. The gas flow pattern downstream of the electrodes must remain unchanged in reference to normal gas flows, as indicted in Fig. 3, so as not to alter the arc paths and resulting voltages, etc.

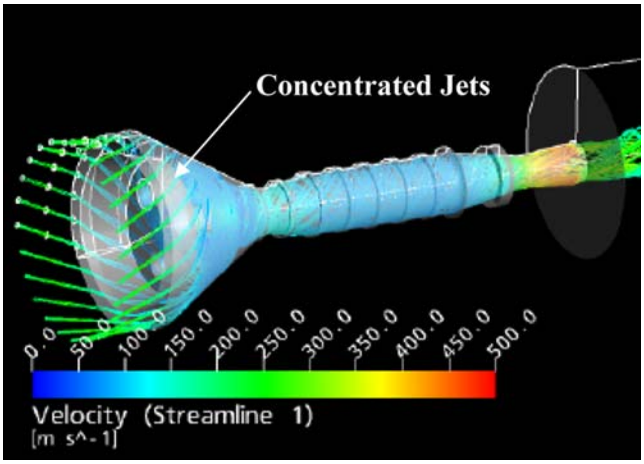

Fig. 5 Initial rear chamber gas flow pattern at high argon flows

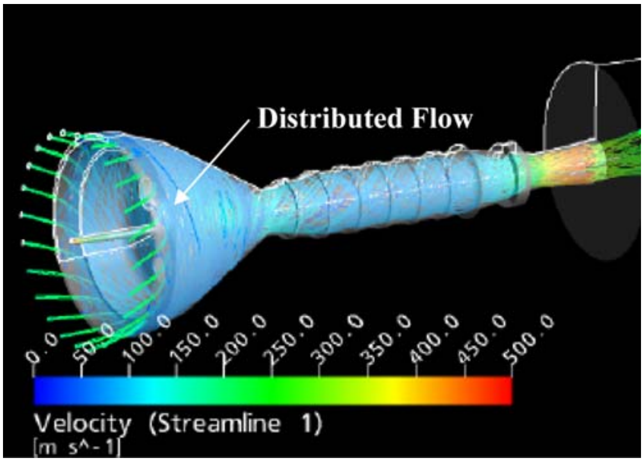

Fig. 6 Final gas flow pattern after changes to the rear chamber geometry

A series of changes to the geometry of the gas ring, electrode insulator, and the bell shaped first neutrode section were tested in the model specifically designed to spread the gas flow from the gas ring jets uniformly into the rear chamber. After only five model runs an optimal solution was determined that resulted in a more even flow of gas into the chamber while maintaining the same gas flow pattern from the region of the electrodes out past the exit bore of the nozzle. Figure 6 shows the resulting gas flow pattern, again represented as streamlines.

Additional images were used during the analysis of model results, too many to incorporate into this article. As evidence of the unchanged gas flow, Fig. 7 shows roughly the same gas flow pattern as that depicted in Fig. 3, including the extent and location of the vortices. The modified geometry also results in a more uniform pressure

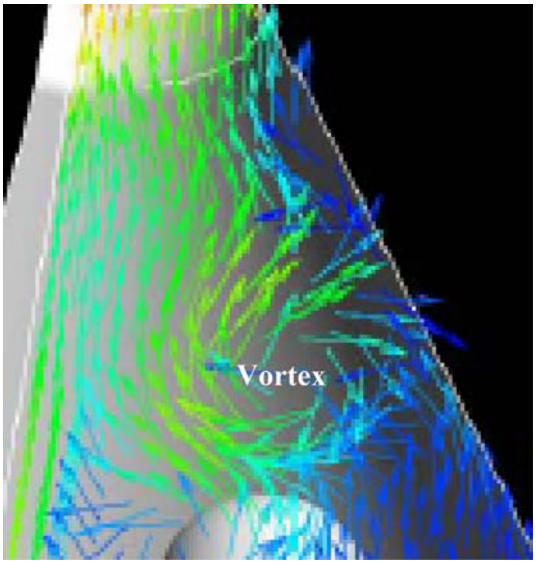

Fig. 7 Cutaway slice of gas flow pattern after changes in rear geometry

distribution within the chamber and a lower pressure drop for gas entering the chamber. Depending upon the results of actual testing this modification may see production sometime in 2007. If the testing is successful this modification will serve as another validation of the model.

3.2 Nozzle Development

One of the benefits of the Triplex Pro 200 Plasma Gun cited previously is the ability to tailor different nozzles for different applications (Ref 9). By taking advantage of developing nozzles in the comprehensive model provides an opportunity to discover and use all the potential of this gun platform, as well as quickly learn what will and will not work in terms of physical limitations. Currently only the 5.0 mm internal diameter HV nozzle has been modeled with the gun while the real gun is supplied to customers with a total of three nozzles including the 5.0 mm. In addition, about 12 other experimental and developmental nozzles have been built and tested with reasonable success. Still a lot more potential exists to explore axial injection, liquid injection, more aggressive HV nozzles, etc.

Coupled to nozzle development for the shaping of the plasma plume will be the need to model the injection or introduction of powder particles so that both injection and shaping of the plasma plume can be optimized simultaneously. If the plasma plume is shaped to permit better injection of particles into the plume and help trap the particles therein then improvements in deposit efficiency, process efficiency, and even coating property variation can be expected.

4. Future Development

A number of next steps are proposed to further use and develop the model along with the Triplex Pro. The most notable omission from the ‘‘working’’ model is powder injection. Sulzer Innotec and Sulzer Metco have been jointly developing a model component that incorporates injection of solid particles into a fluidic stream over a wide range of velocities from subsonic to supersonic. As mentioned previously, other work has been done at the research level to simulate powder injection into a plasma plume (Ref 2) and in cooperation with all this research particle injection is in process of incorporation into the comprehensive model to enhance the capability of the model. The only issue is the computing power needed to run the model. Again the ability to define subsets of the model once the relationships are known will hopefully help to ease the computing burden.

Another potential area for investigation and possible enhancement of the gun design itself is in how well the arc paths can be controlled inside the gun bore. If the gas flow and arc paths are interdependent as the research done to date strongly suggests, then it is certainly feasible to further develop gas flow patterns that can provide even greater arc stability, longer arc lengths for higher voltage, and even better use of the arc energy in terms of heating the gas with reduced loss to the chamber and bore walls. This could also lead to more flexibility in the choices and flows of gasses that can be used.

Long term this comprehensive model can be used to develop new guns from scratch with improved operating conditions. Currently most plasma guns lose a substantial amount of their energy input to the cooling water. Even a small reduction in this energy loss will improve the efficiency and effectiveness of a process gun.

5. Summary and Conclusion

The use of comprehensive modeling has been shown to provide valuable insight into the inner workings of a plasma thermal spray process gun. The design and performance of the Triplex*Pro*™ 200 plasma gun has already benefited from this effort and additional improvements are in the pipeline.

Coupling the modeling of the gas flow and arcs together has shown some indications of dependencies between the gas flows and arcs suggesting that the arcs can be further controlled through modification of the gas flows.

The addition of particle injection to the working model will further provide opportunities to enhance and develop the gun to new performance levels not currently achieved by any thermal spray process.

Acknowledgments

The authors want to express appreciation to Marc Heggemann and Reto Waeger of Sulzer Innotec for their patience and diligence in producing the considerable number of model images that were required to conduct this research program.

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