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Plasma Transferred Arc Welding—Modeling and Experimental Optimization

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Plasma transferred arc (PTA) welded coatings are used to improve surface properties of mechanical parts. Advantages are the high reliability of the process and the low dilution of substrate and coating material. Processing of surfaces by PTA welding is restricted at the time to flat horizontal position. Furthermore, industry is interested in the development of strategies for coating with PTA in constraint position as complex three-dimensional (3D) parts could be then easily processed as well. Under commercial aspects, the process design can be optimized to increase process efficiency and to reduce heat input during the welding process. Process optimization involves the determination of guidelines for PTA welding in constraint positions as well. Modeling the process gives an alternative to reduce the experimental effort to optimize the welding process. Results of simulation studies of the PTA welding process are given in the present work. It will be shown that coating conditions can be optimized by varying plasma gas flow, heat input and heat flow, process speed, or powder injection with regard to welding in constraint positions. The defined controlling of the PTA welding allows modification of process management with less experimental effort and to develop coating strategies for processing in different positions. In experimental investigations, the developed coating strategies are confirmed by producing PTA coatings in constraint position as well as complex 3D parts.

Keywords fluid flow, heat transfer, numerical modeling, plasma transferred arc welding, process optimization

1. Introduction

Plasma transferred arc (PTA) welding represents an efficient process to improve the surface properties for corrosion and wear protection (Ref 1, 2). The advantage of this technology is drawn by the high freedom in powder material, which allows a better fit for purpose cladding. An example of technological application of the PTA welding process is the coating of crushing rolls in the mining industry with nickel (Ni) alloys with inserted tungsten melt carbide (WSC) (Ref 3).

Processing of surfaces by PTA welding is restricted at the time to flat horizontal position. This means that damaged parts have to be dismounted to be processed. Furthermore, industry is interested in the development of strategies for PTA coating in constraint positions as complex three-dimensional (3D) parts could be easily processed as well. Process modeling is an important tool to develop process strategies for PTA coating in constraint positions and to generate complex geometries, as the influence of the process parameters (plasma power, gun position, injection conditions, and substrate) and the material on the heat input and the coating geometry can be specified. By means of process modeling simulation results can be visualized and assessed. This allows specifying optimized process parameters with regard to heat input, dilution, and welding in constraint positions.

1.1 Experimental Setup

In the PTA process two independent arcs are used. A pilot arc is formed between a nonconsumable tungsten electrode (cathode) and copper plasma nozzle with an inner diameter of 2 mm (anode) in the welding torch. A plasma gas (Ar, He, Ar/He, or Ar/H_2 mixture) flows coaxially to the tungsten electrode in the copper nozzle and is ionized by the applied arc energy. A second arc (transferred or plasma arc) is then established between the tungsten electrode and the workpiece. The resulting temperature in the transferred arc is between 10,000 and 15,000 °C. There is no direct contact between the copper plasma nozzle and the workpiece, and no arc is burning. The energy released by the arc is influenced by arc current and length. Powder is fed into the plasma through injection nozzles and is subsequently heated by the arc. Shielding gas for protecting the area around the plasma from oxidation is fed through a large outer nozzle. Figure 1 shows the principle of the plasma transferred arc process.

Main parameters of the PTA process are the current of the pilot and the transferred arc, the flow rate of the plasma, the shielding, and the powder carrier gas (Table 1). The gas flow rate and the gas type have a significant influence on the heating and melting of the coating material during the PTA process. Additionally, the powder feed rate and the process velocity influence the resulting properties of the coating.

1.2 Modeling

The setup for the model is equivalent to the experiments (Fig. 1). The pilot arc is established between the noncon-

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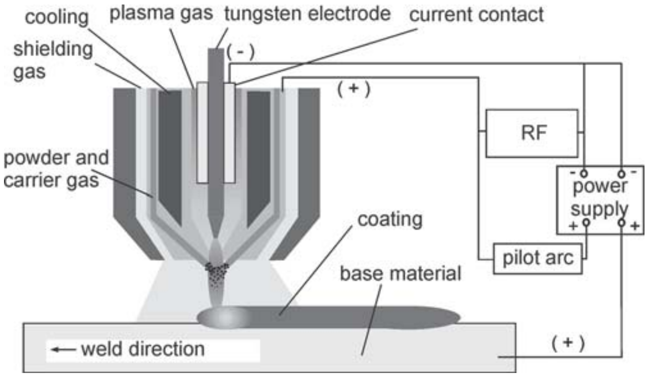

Fig. 1 Principle of the plasma transferred arc process (Ref 4)

Table 1 Process parameters for PTA welding

Parameter	Value
Pilot arc current, A	10-50
Plasma arc current, A	70-170
Pilot arc voltage, V	20
Plasma arc voltage, V	20
Plasma gas flow rate, slpm	1.5
Powder feed rate, g/min	8-20
Powder	Ni
Coating direction	Flat, constraint
Powder gas flow rate, slpm	0.4
Process speed, mm/s	10-90
Substrate	S335JR

sumable tungsten electrode and the copper plasma nozzle (anode); the transferred arc is formed between the tungsten electrode and the substrate. In the model, a relative meander-like motion between the plasma torch and the substrate is used. Single lines with an offset of 1 mm were applied on the steel surface (Fig. 2). The geometry of the base material was 20 by 10 mm, and the thickness was between 1 and 10 mm. Simulations were done for the welding on a flat as well as in the vertical position. The energy input by the pilot and the transferred arc is considered as well as the heating, melting, and solidification of the feedstock material and the substrate.

The energy input of the two separate arcs was done by a simplified tube model with regard to a constant voltage drop between the cathode and the anode. The arc energy input depends in first calculations only on the current density *j* and the electrical conductivity σ of the plasma gas based on Ohm's Law (Ref 5), whereby the current density depends on the arc current and the arc diameter. In the first investigations, the arc diameter was set to the internal diameter of the nozzle (2 mm). The calculation of the heat input into the base material is based on heat conduction and radiation at the interface between heated plasma gas and substrate. Due to the inserted power in the plasma arc a temperature field of the gas can be determined. Due to this simple assumption recombination and further physical processes are regarded in the authors' simulation studies only due to temperature-dependent parameters. Kinetic effects are negligible in the basic assumption, according to Ref 6; the main contribution to the heat flux comes from electron condensation and heavy particle conduction. With this simplification, heating, melting, and solidifying of powder and substrate material can be calculated. Electromagnetic effects and the dynamic behavior of the arc root attachment during arc movement are not considered in this model.

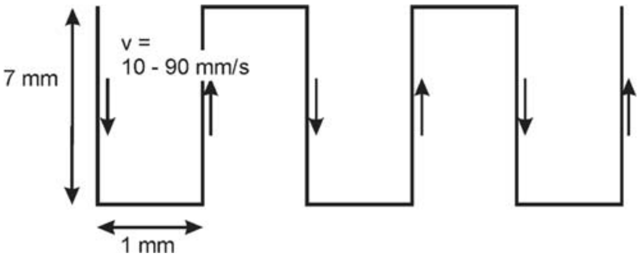

Fig. 2 Coating strategy

The theoretical basics of the process are reported in Ref 7. They can be described by the fundamentals of the dynamic flow of a viscous fluid regarding external heat and material sources. The mathematical model to explain the motion of the plasma gas and the molten material is based on the Navier-Stokes equation for the laminar, incompressible, and viscous flow regarding the temperature-dependent material properties and external forces (e.g., gravitation). Further, the energy transfer to the plasma gas, to the material, and to the substrate can be calculated based on the conservation of energy. The temperature of the material can be calculated with regard to melting and solidification and external heat sources (pilot arc between cathode and anode nozzle, transferred arc between cathode and substrate), heat conduction, and the internal energy.

The commercial software Fluent (Ref 8) was used to determine the influence of the heat sources, the process parameters, and the thermodynamic properties on the coating geometry and the temperature field within the arc, the coating, and substrate material. The thermodynamic properties of the selected materials have been taken from literature (Ref 9, 10).

2. Simulation Results

2.1 Gas Flow Behavior

As a first step, the gas flow behavior during PTA welding is calculated to optimize flow conditions and to determine gas flow rate and energy input. Figure 3 shows the influence of the plasma gas flow rate on the velocity within the arc. In these investigations, the arc power was set to 4.0 kW. An increase in the gas flow rate from 0.5 to 5.0 sLpm leads to an increase in the plasma gas velocity. In the case of a higher plasma gas velocity a more directional flow to the substrate occurs.

Due to the higher gas flow rate during a constant arc power, the energy density with the arc is reduced. This leads to a decrease in the maximal arc temperature (Fig. 4). Due to the simplified arc model, arc constriction with increasing flow rate is not regarded. In the case of a lower plasma gas flow rate, a larger volume of gas is heated. Additionally, for a higher plasma gas flow rate a more directional gas jet is formed. This directional gas jet leads to a higher temperature gradient near the substrate surface and a higher heat transfer to the substrate.

The higher velocity due to the higher plasma gas flow rate will lead to a higher velocity of injected particles and to a shorter interaction time of particles in the arc, which reduces particle temperature. For the next simulation studies, the plasma gas

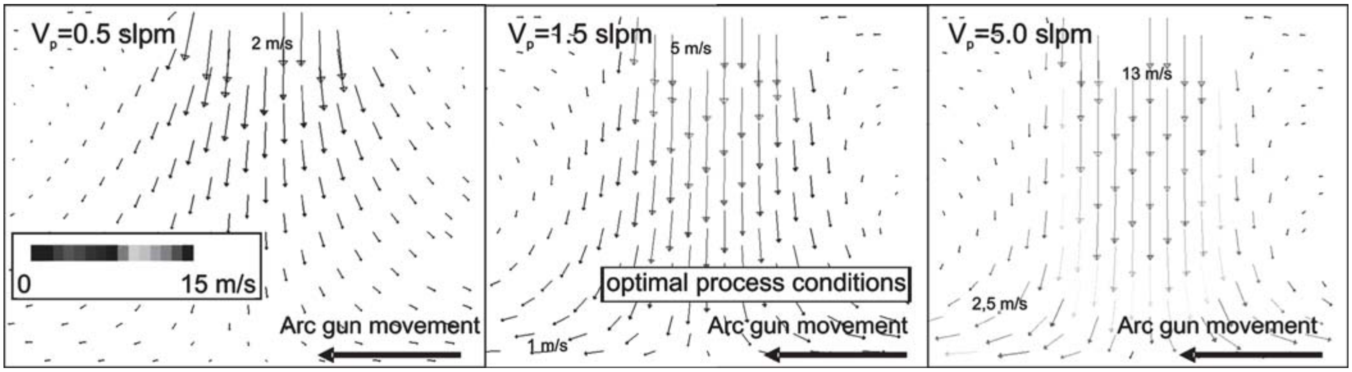

Fig. 3 Velocity distribution, variation of plasma gas flow rate, plasma power = 4.0 kW

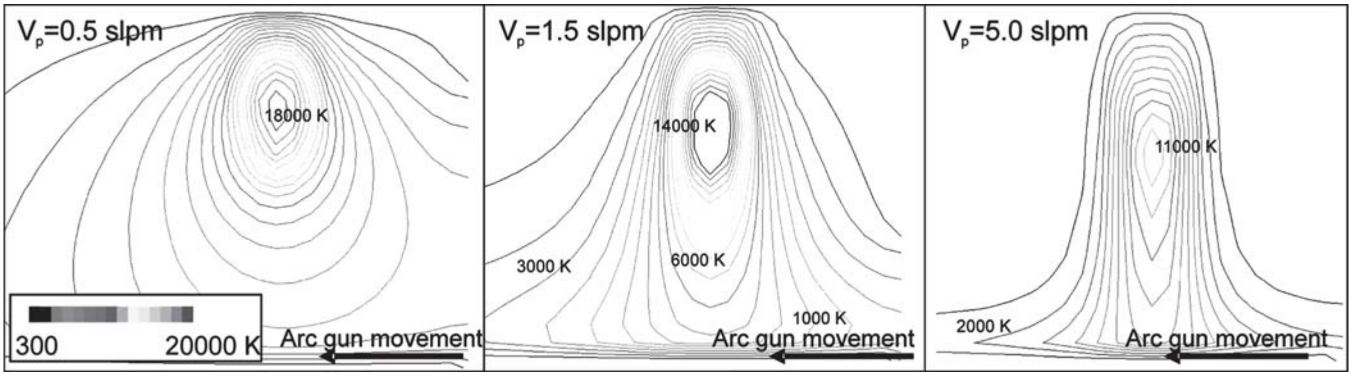

Fig. 4 Temperature distribution in the plasma, variation of plasma gas flow rate, plasma power = 4.0 kW

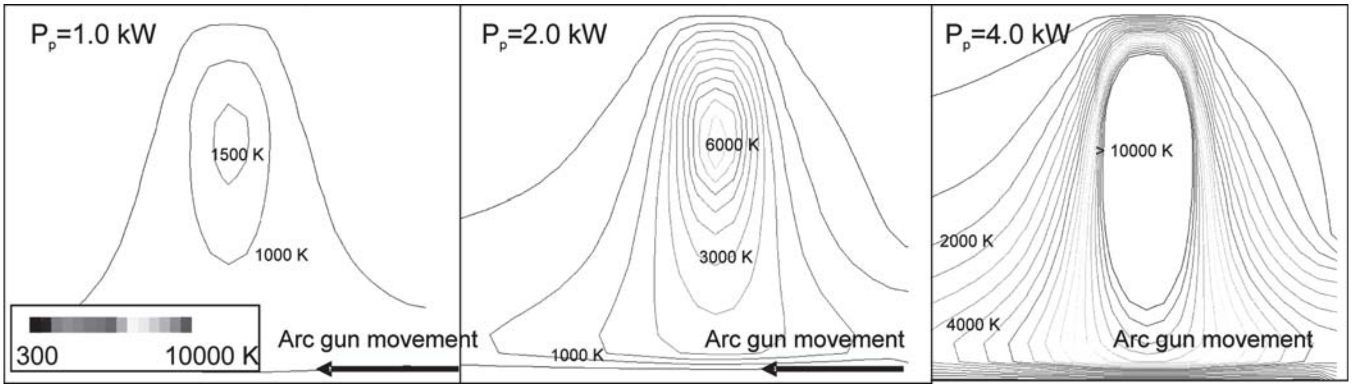

Fig. 5 Temperature distribution in the plasma, variation of plasma power, plasma gas flow rate = 1.5 slpm

flow rate was set to 1.5 slpm. With this flow rate and a plasma arc power of 4.0 kW, the temperature within the arc is about 10,000 K and the plasma gas velocity is about 5 m/s. Arc power influences the temperature distribution within the transferred arc during the constant plasma gas flow rate of 1.5 slpm as well. A higher power leads to a higher temperature in the plasma arc and a higher temperature gradient near the substrate (Fig. 5). In the case of very low plasma power (Figure 5 left), only heating of the plasma gas by the pilot arc (established between tungsten electrode and nozzle) occurs. Nevertheless, it can be seen that with low energy input no transferred arc can be established. The resulting temperature for this parameter with less than 1500 K is too low for melting injected powder material. The substrate temperature increases with increasing arc energy. With the model used, the plasma gas velocity distribution within the arc strongly depends on the gas flow rate and is nearly independent from the arc energy.

2.2 PTA Welding in Flat Position

Further investigations were done to determine the influence of the energy input and the heating and cooling during the coat-

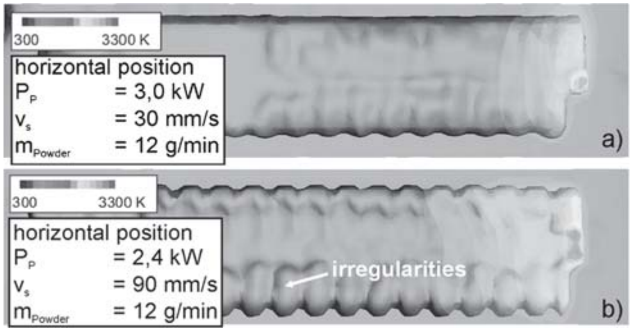

Fig. 6 Geometry of PTA welded Ni coating on a substrate. Temperature field (a) arc power 3.0 kW, process speed 30 mm/s; and (b) arc power 2.4 kW, process speed 90 mm/s

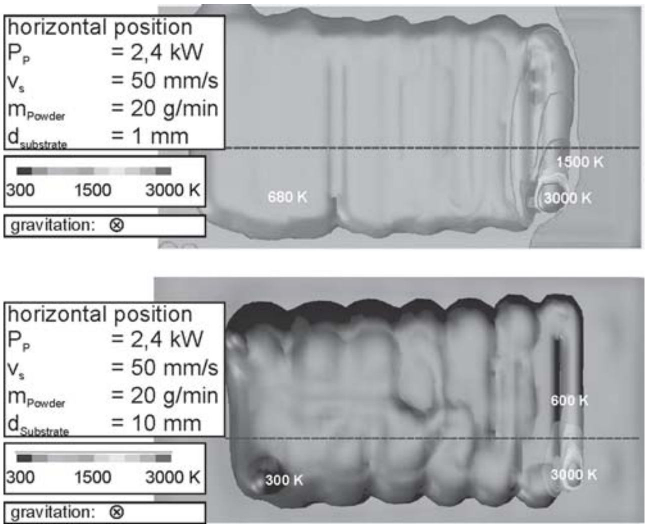

Fig. 7 Geometry of PTA welded Ni coating on a substrate: (a) substrate thickness, 1 mm; (b) substrate thickness, 10 mm

ing process and the temperature of the coating in flat welding positions. Figure 6 compares the surface geometry of two PTA welded coatings generated in horizontal position with differences in the energy input. With a plasma arc power of 3.0 kW and a process velocity of 30 mm/s (Fig. 6a), a flat surface is formed. If energy input is reduced to 2.4 kW and process speed is increased to 90 mm/s (reduced energy input per unit length), a rough surface with weld bead irregularities is formed. The higher process speed leads to a fast solidification of the coating material, and single weld beads can be identified (Fig. 6b).

Heat transfer to the substrate influences the cooling of the coating and the resulting geometry. In the case of a higher substrate thickness, more heat can be accumulated by the substrate during the coating process. Figure 7 compares the surface geometry of PTA welded coatings on substrates with different thicknesses. With a thinner substrate (Fig. 7a), significant heating of the substrate during the coating process occurs. The larger melt pool and the higher coating temperature leads to difficulties in handling the melt pool and the flow of the molten material. In the case of a substrate thickness of 10 mm (Fig. 7b), the temperature field is less expanded due to the higher heat capacity of the substrate. Additionally the reduced coating temperature increases the viscosity and the surface tension and reduces the size of the melt pool as well.

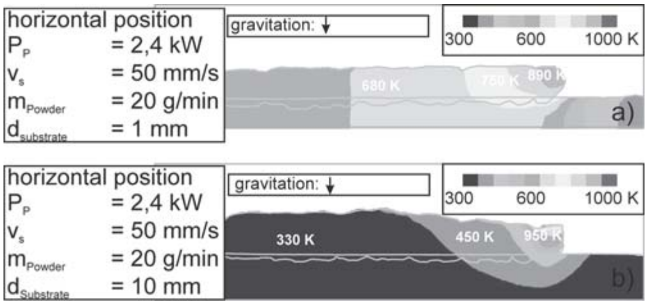

Fig. 8 Cross section of PTA welded Ni coating on a substrate: (a) substrate thickness, 1 mm; (b) substrate thickness, 10 mm

The corresponding cross section (along the dashed line shown in Fig. 7) is given in Fig. 8. For the thinner substrate, coating and substrate temperature is reduced from about 1000 K near the melt pool to about 600 K in the cooled area. This is about 300 K higher than for the thick substrate. Additionally, the higher heat capacity and the lower coating temperature of the thicker substrate slightly reduce the dilution as well.

2.3 PTA Welding in Constraint Position

Compared with the PTA welding process in flat position, in the constraint position the gravitational acceleration has an influence on the fluid flow and the coating geometry. Simulation studies of welding in constraint position were done. In the simulations, the process speed was varied between 50 and 100 mm/s, the powder feed rate was set to 20 and 40 g/min. The higher powder feed rate was chosen with regard to a constant ratio of powder feed rate to process speed. Constant process parameters were the substrate thickness of 1.0 mm and the arc power (2.4 kW).

In the case of a process speed of 50 mm/s and a powder feed rate of 20 g/min, the molten material is strongly influenced by gravitation. With this parameter, the melt flows in the direction of gravitation (Fig. 9a). Reducing the energy input per unit length by increasing process speed from 50 to 100 mm/s (Fig. 9b), the temperature of the coating and the size of the melt pool is slightly reduced. With the reduced energy input, the molten material solidifies faster and the flow of material with gravitation is strongly reduced. Due to the gravitational force in both cases, the molten coating material flows downward, so that overlapping of subsequent steps is homogeneous and the seam shape is very smooth.

The corresponding view across the coating (along the dashed line in Fig. 9) can be seen in Fig. 10. A higher input per unit length (Fig. 10a) causes a larger melt pool and a higher melt pool temperature. Solidification time of the molten material is longer, which results in a flow of the molten material downward in the direction of gravitation. The geometry becomes even, but the coating expands too much over the substrate (left side of the coating). The lower energy input with higher process speed reduces the solidification time and the material flow. The penetration profile is very irregular, too. A reduction of the energy input per unit length reduces the penetration depth.

3. Experimental Evaluation

Experimental investigations of PTA welding in constraint position were done to compare the results with the simulations and to optimize the process model. The experimental setup is equivalent to Fig. 1; the process parameters correspond to values given in Table 1.

In Fig. 11 coatings are shown generated with different parameters in flat and constraint welding positions. It can be seen that for welding in flat position (Fig. 11a) the geometry of single weld beads are visible. With welding in constraint position with nearly identical parameters (current slightly higher than 80 A, Fig. 11b), the solidification time is too long, the molten material flows downward with gravitation, and the resulting coating geometry is very inhomogeneous with pores. A lower arc current (60 A, Fig. 11c) reduces the melt flow downward with gravitation; single overlapping weld beads can be observed.

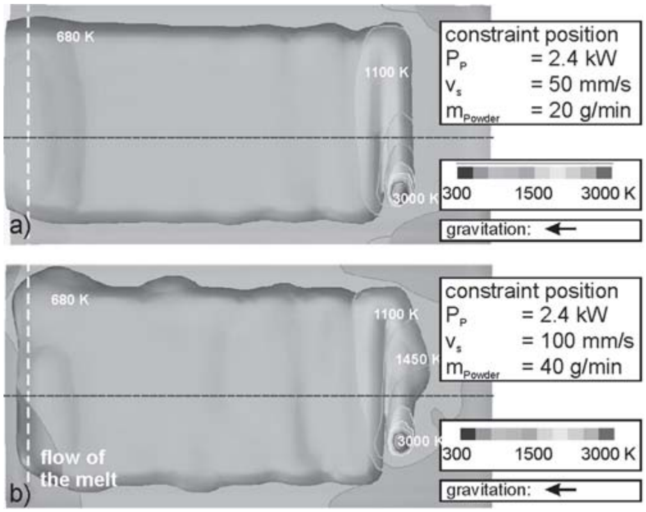

Fig. 9 Simulated geometry of a PTA welded Ni coating in vertical welding position with different process parameters. Temperature field (a) 2.4 kW, 50 mm/s; (b) 2.4 kW, 100 mm/s

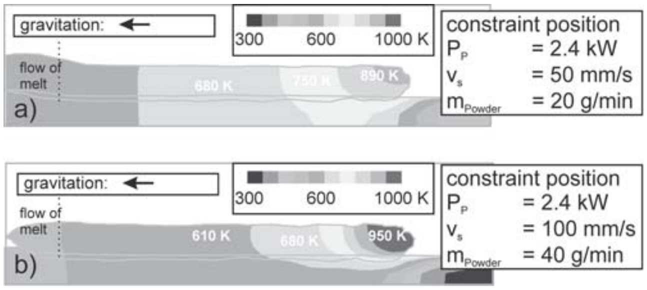

Fig. 10 Cross section of a PTA welded Ni coating in vertical welding position with different process parameters. Temperature field (a) 2.4 kW, 50 mm/s; (b) 2.4 kW, 100 mm/s

The simulation studies with the modeling method described previously can roughly represent the experimental setup. Due to the flow of molten material a better surface quality can be reached (Fig. 12).

These experimental results verify that the flow of the molten material can be reduced by reducing the energy input (confirm Fig. 9). From this it follows that in constraint position coating properties and surface geometry strongly depend on boundary conditions. Further investigations must be done to optimize the model that was used for a better agreement between experiment and simulation.

4. Summary and Conclusions

Simulation studies are reported in this paper for PTA welding by consideration of different process parameters. In the simulation studies, optimized flow conditions were determined. The influence of some process parameters during welding in the horizontal and constraint positions was calculated based on the optimized process conditions. It was shown that a thicker substrate reduces the coating temperature due to the higher heat capacity of the substrate.

Vertical welded coatings show modified properties compared with welding in flat position with identical parameters. During welding in constraint position, one must consider:

- Coating geometry is smoother.
- Molten material can flow downward in the direction of gravitation.

Reducing the energy input into the coating by a reduced energy input per unit length or a reduced arc power allows a generation of coatings with geometry that are comparable to flat welded coatings. The flow of the molten material as well as the penetration depth during PTA welding in constraint position can be reduced by a reduced energy input. A model of the PTA process was developed based on the fundamentals of fluid dynamics under consideration of conservation of energy and mass. Simulation studies on PTA welding in horizontal flat positions have shown the influence of chosen process parameters on geometry and coating thickness. For welding in the vertical position, pro-

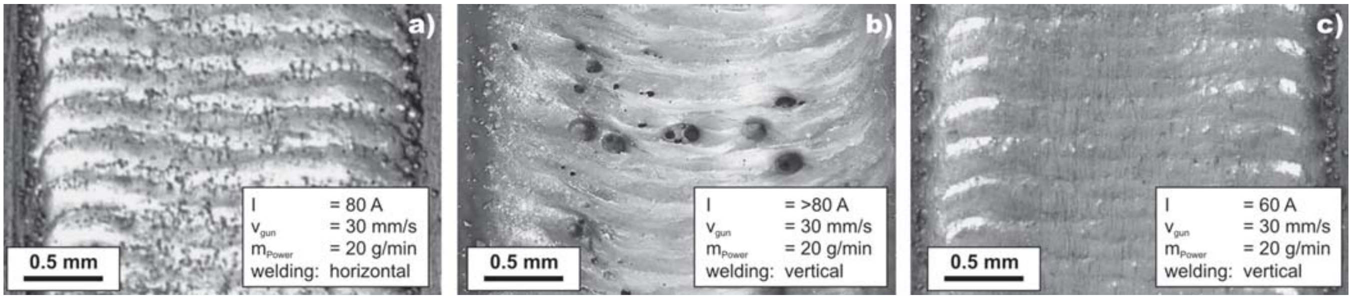

Fig. 11 PTA welded Ni coating in different welding positions: (a) horizontal; (b) and (c) vertical (Ref 11, 12)

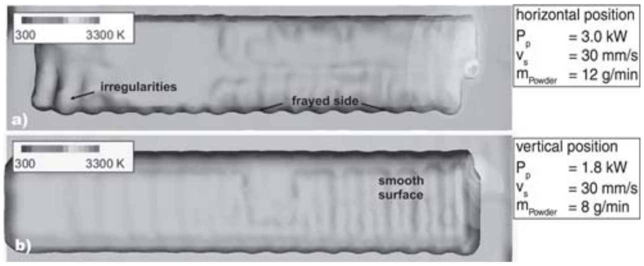

Fig. 12 Simulation of PTA welded Ni coating in different welding positions: (a) horizontal; (b) vertical

cess parameters must be adjusted according to the heat input, the heat flow, and the flow of the molten material during the welding process.

Theoretical investigations were confirmed experimentally for Ni-base alloys. The results are comparable to simulations, but the model must be optimized to reduce the remaining differences between simulation and experiment. Next simulations will be carried out to determine the influence of the process parameters such as arc current, powder feed rate, and welding velocity on the dilution, the coating thickness, and the geometry of the generated coating at different welding positions.

References

1. M. Akiyama, K. Tsubouchi, T. Okuyama, and N. Sakaguchi, Applications for Plasma Transferred Arc Welded Tools During Hot Steel Tube Making, *Ironmaking Steelmaking,* 2000, **27**(3), p 183-188
2. D. Harper, M. Gill, K.W.D. Hart, and M. Anderson, Plasma Transferred Arc Overlays Reduce Operating Costs in Oil Sand Processing, *International Thermal Spray Conf.* (Essen, Germany), March 4-6, 2002, ASM International, 2002, p 278-283
3. F. Schreiber, Mobile Plasma Powder Hand Deposition Welding: Practice Experience, *International Thermal Spray Conf.,* March 4-6, 2002 (Essen, Germany), ASM International, 2002, p 273-277
4. B. Bouaifi, F. Schreiber, J. Göllner, and S. Schulze, Eigenschaften und Beständigkeit von Plasma-Pulver-Auftragschweißungen aus hartstoffverstärkten CrNiMoN-legierten Duplex-Stählen, *DVS-Berichte,* 1996, **175,** p 425-428, in German
5. S.M. Aithal, V.V. Subramanaiam, J. Pagan, R.W. Richardson, Numerical Model of a Transferred Plasma Arc, *J. Appl. Phys.,* 1998, **84**(7), p 3506-3517
6. T. Amakawa, J. Jenista, J. Heberlein, and E. Pfender, Anode-Boundary Layer Behaviour in a Transferred, High-Intensity Arc, *J. Physics D, Appl. Phys.,* 1998, **31**(20), p 2826-2834
7. H. Oertel Jr., *Prandtl-Führer durch die Strömungslehre,* Vieweg & Sohn, Braunschweig/Wiesbaden, 2001, in German
8. Fluent 6.1 Users Guide. Fluent Inc., 2003
9. D'Ans, Lax, Taschenbuch für Chemiker und Physiker, Springer, 1998, in German
10. O. Kubaschewski, *Materials Thermochemistry,* Pergamon Press, 1993
11. J. Wilden, J.P. Bergmann, and M. Trommer, Einflussgrößen beim Plasma-Pulver-Auftragschweißen in Zwangslagen. In: Tagungsband zum 7, *Werkstofftechnischen Kolloquium Neue Materialien und Verfahren in der Beschichtungstechnik* (Hrsg.: Wielage, B.), 2004, p 214-219 (in German)
12. J. Wilden, J.P. Bergmann, and M. Trommer, Full Mechanised Cladding of 3-Dimensional Components in Constraint Position with the PPAW-Process, *International Thermal Spray Conference,* May 2-4, 2005 (Basel, Switzerland), DVS-Verlag, 2005