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特集 溶接プロセス予測モデルの最前線

The Front Line of Modeling Heat and Mass Transfer in Arc Welding Processes*

アーク溶接プロセスにおける熱および物質輸送モデルの最前線*

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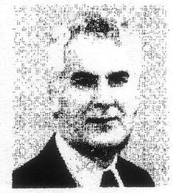

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はじめに

アーク溶接は多くの複雑な物理現象を含んでいる．アーク溶接における熱および物質輸送現象のより良い理解はプロセスの最適化や溶接品質の改善に不可欠である．溶接で生じる現象の予測は実験に代わるもう一つの手段として捉えることができ，コストを抑えるとともに厳しい溶接環境から溶接士を保護し得ることが可能になる．さらに，数値計算モデルは実験によって得られ難い複雑な輸送現象も明らかにすることができる．ここでは，アーク溶接プロセスのモデル化をテーマに取り上げるが，工業に幅広く普及しているGTA溶接とGMA溶接を中心に議論を展開したい．

GTA溶接のモデル化

溶融池あるいはアークプラズマにおける熱および物質輸送のモデル化については数多くの研究論文の中でよく議論されてきた．溶融池モデルでは最近のトレンドとして3次元化が挙げられる．著者らは添加ワイヤの送給を考慮に入れたGTA溶接の3次元溶融池モデルを構築している[30)]．Fig.1は温度場と流動場の横断面図である．最高温度がアーク中心近傍の溶融池表面とワイヤ表面に見られる．溶融池後方への熱重畳のために，溶融池前方の等温線が後方の等温線に比べて明らかに密になっていることが解る．なお，溶融池形状は流動場に示されている．一方，もう一つの最近のトレンドは，陰極-アークプラズマ-陽極を同時に解く統合モデル化であろう．著者らは完全溶込みを考慮に入れた2次元の統合モデルを構築している[32)]．Fig.2に温度場のみを示すが，時間とともに溶込みが増加し，アークスタート後2秒では部分溶込みであったものが4秒では完全溶込みに達していることがよく理解できる．完全溶込みの場合，溶融池裏面が形成されるために表面のくぼみが増加していることが解る．

GMA溶接のモデル化

GMA溶接のモデル化は溶滴移行，アークプラズマ，溶融池の3つの部分に分かれて発展してきた．溶滴移行のモデル化では，静的釣り合い理論(SFBT)とピンチ不安定理論(PIT)が適用されてきたが，電流変化にともなうグロビュラーからスプレーへの移行形態の変化を表現できなかった．このため，流体力学を応用した数値計算モデルが現在の主流になっている．一方，溶融池に関してはGTA溶接の場合と同様に3次元化が最近のトレンドであり，特に，アーク圧力ばかりでなく溶滴移行による溶融池表面の変形を考慮に入れたモデルが発表されている．アークプラズマに関しても，GTA溶接の場合と同様，溶滴移行-アークプラズマ-溶融池を同時に解く統合モデル化が最近のトレンドである．Fig.3は著者らによる2次元統合モデルの計算結果例である[54)]．ワイヤ端での溶滴の形成・離脱，アークプラズマ中での溶滴の移動，溶滴と溶融池との相互作用が時間とともに進展していく様子を見事に予測している．

その他

近年，ソリッド自由造形(SFF)のモデル化が進みつつある．ソリッド自由造形には添加ワイヤを含むGTA溶接プロセスを応用したタイプやGMA溶接を応用したタイプがあるが，これらのモデル化は，上述のGTA溶接モデルやGMA溶接モデルに多層モデルを組み合わせることにより実現可能であると考えている．一方，今後の展開として，溶融池サイズ，残留応力，金属組織を予測し，かつ溶接プロセスパラメータの最適化をはかることが重要であり，これらを実現するには，熱的，流体的，機械的，化学的モジュールモデルを統合した溶接の完全プロセスモデル化が必要であると考えている．最近，このような取り組みがなされつつある[57)]．また，溶接モデルのほとんどはビード・オン・プレート溶接を対象にしているが，最近，V形溶接継手で特徴づけられるGMAすみ肉溶接の3次元定常モデルが紹介されている[58)]．

おわりに

アーク溶接プロセスのモデル化において，そのトレンドは間違いなく統合モデルであり，そして，その究極のゴールが3次元完全プロセスモデルである．これらの実現に向けてパラレル処理や非構造メッシュなど新しい計算手法が有効であろう．最後に，コンピュータ技術の発展と数値計算科学のさらなる追求は，モデル化の実溶接プロセスへの輝かしい貢献に繋がっていることは間違いない．

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1. Introduction

Arc welding processes, in which the metal parts are heated by the intense heat of the arc and fused together either with or without a filler metal, are widely used in the manufacturing industry. Recently, welding principles have been applied in solid freeform fabrication (SFF). Arc welding combines many complex physical phenomena. A better understanding of heat and mass transfer in arc welding is essential for process optimization and quality improvement. A numerical predication of the welding properties provides an alternative to the actual experiments that could cut costs and avoid the welder's exposure to the harsh welding environment. Moreover, mathematical modeling reveals some complex transport phenomena that may be impossible to obtain by experiment.

Gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) have been two of the most dominant welding processes in industry. Some modeling efforts have been put on other arc welding processes such as plasma arc welding[1]. However, the majority of the modeling research has been focused on GTAW and GMAW. To limit the scope of this paper, GTAW and GMAW based welding processes will mainly be discussed. Also, the intent of this paper is not to review all the recent developments in the modeling of arc welding processes.

2. Modeling of GTAW

2.1 Heat and mass in the weld pool

GTAW is an arc welding process that uses an arc between a non-consumable tungsten electrode and the weld pool. In view of the significant effect of the weld pool convection on the microstructure and properties of the resultant weld, numerous investigators have attempted to calculate the heat transfer and fluid flow in the weld pool of GTAW[2-15]. Most of these investigators have used either the flat-surface assumption[2, 3] or the stepwise approximation[4, 5] for the weld pool surface. A boundary-fitted coordinate was used to describe the irregular pool surface shape[6, 25, 50, 57].

For GTAW, convection in the weld pool is driven by a combination of forces that include surface tension force, buoyancy force, electromagnetic force, and arc drag force. Kim et al.[6] investigated the effect of various driving forces on heat and mass transfer in GTA weld pool. In most cases, the fluid flow and heat transfer in the weld pool are controlled by the surface tension force[7]. It is indicated that arc drag force also plays an important rôle affecting convection in the weld pool[2, 3]. Choo[8] and Chankraborty[9] considered turbulence in the simulation of fluid flow in GTA weld pools and showed it can affect the pool depth significantly. The surface active element was proved to affect the flow pattern in the weld pool and was used to increase the depth of penetration[10].

In addition, some works have been conducted on the heat transfer and fluid flow in the GTA weld pool with full penetration. The full penetration is complicated by the coupling of the free surface on the bottom of the pool, the top pool surface deformation, and the temperature distribution. Fan et al.[11] simulated the dynamic movement of the molten pool from partial until full penetration. Cao[12] incorporated full penetration, and free top and bottom surfaces in a three-dimensional (3D) steady model. A 3D transient model was developed by Zhao et al.[13] to investigate the dynamical behaviors of a fully penetrated GTA weld pool with surface deformation.

2.2 Transport phenomena in arc plasma

Modeling heat transfer and fluid flow in the arc plasma of GTAW has been well documented[14-16]. These studies all dealt with the arc plasma between a tungsten electrode (cathode) and a water-cooled copper plate (anode). The anode was represented as a flat surface. It has been observed that the surface of the weld pool becomes markedly depressed at high current levels, and the assumption of a flat surface is no longer valid[17, 18]. Although Choo and Szekely[19] presented a model of high current arcs with a deformed anode surface, the specified weld pool shapes have been approximated as a stepwise one, and the cathode tip shape was limited to be flat-ended. Experimentally, Lin and Eager[18] measured the arc pressure with different electrode shapes, and showed that the sharp cathode produces a higher arc pressure than the blunt one. That is, the cathode shape is an important factor influencing the welding arc characteristics and the transferring phenomena on the base plate. It should also be emphasized that in most studies on heat transfer and fluid flow in the arc plasma, a current density profile has to be assumed over the surface plane of the cathode[19, 20], and it has been found that the theoretical predictions are sensitive to the current density at the cathode [16]. The model without any assumption of the current density at the cathode surface was presented in[21-23]. The distribution of current density was calculated with the combined arc plasma-cathode system. The anode temperature and the distribution of arc pressure and current density along the anode surface were investigated in[22, 23]. Further, Fan et al.[24] used a similar model to describe the heat and mass transfer in the pulsed GTA welding arc. Using a boundary-fitted coordinate, Kim et al.[25] addressed a pointed tip cathode and a pre-deformed weld pool surface; the current flux and the heat flux to anode calculated for various cathode and anode shapes were compared.

2.3 Three-dimensional modeling of GTAW

The arc movement introduces three-dimensionality in the weld pool. Such effects were addressed by Kou and Wang [26]. Zacharia et al.[27] considered the same configuration but included a number of additional effects, such as the curvature of the weld pool free surface and a turbulence model. Dutta et al.[28] considered the non-axisymmetric boundary conditions in the calculation of Lorentz forces for moving GTAW. Reddy et al.[29] used the finite element method to simulate three-dimensional (3D) heat transfer in pulsed GTAW; the fluid flow in the weld pool was not included in the model. Cao[12] and Zhao[13] present 3D models to simulate surface deformation using a boundary-fitted coordinate.

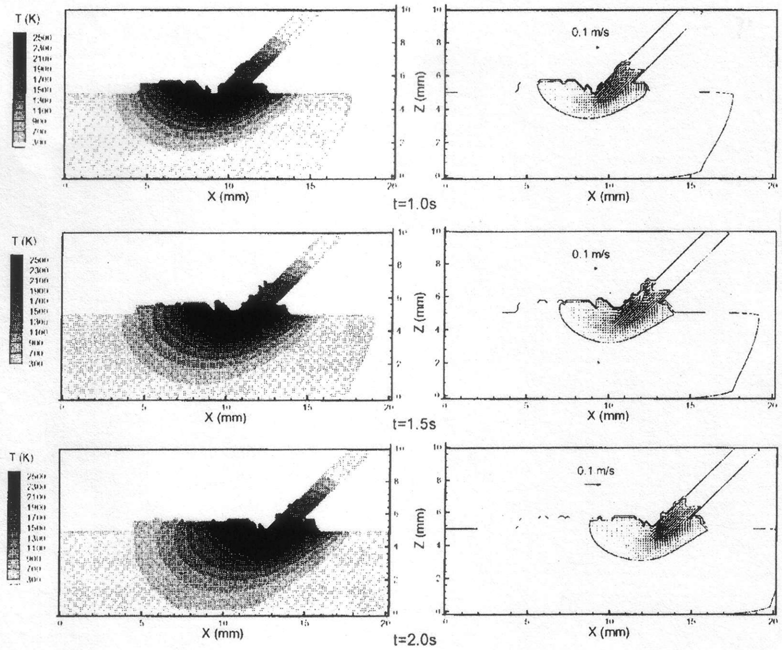

Fig. 1. Temperature and velocity distributions for GTAW with feeding wire

Fan and Kovacevic[30] present a 3D dynamic model describing the GTAW with feeding wire. The problem is complicated by the following physical phenomena: wire moves in the feeding direction and moves with the heat source; the feeding wire interacts with the free surface of the weld pool; and the volume of the weld pool is increased due to the addition of wire. Figure 1 is the side view showing the temperature and velocity distribution. The highest temperatures appear on the surfaces of the base metal and wire that are near the arc center. The shapes of isotherms in the leading part of the weld pool are much thinner than the isotherms in the trailing part due to the heat accumulation in the trailing part. The solidus temperature is drawn in the velocity distribution to show the boundary of the weld pool. The rate of increase in the weld pool size decreases as the time increases, since the pool size is closer to its quasi-steady state condition.

2.4 Unified models

The studies of heat transfer and fluid flow in the weld pool have been an area of active research and have made great progress in recent years. For the effective usage of these models on weld pool, accurate information about the welding arc influencing the molten pool is a prerequisite. The transport phenomena of arc plasma are critical because they yield critical information on the arc pressure, arc drag force, and heat input to the workpiece. Unified models including cathode, arc plasma and anode are believed to be the trend for the modeling of arc welding processes.

As mentioned above, most investigators have concentrated on representing weld pool behavior on the one hand and the modeling of welding arc on the other, with relatively little attention being paid to the interfacial regions. Haidar[31] presented a unified treatment of the arc, the anode, and the cathode, and included a detailed account of the sheath effects near the electrodes; the free surface of the anode was handled using the volume of fluid (VOF) method. The whole region of the stationary GTAW process, namely, tungsten cathode, arc plasma, and stainless steel anode is treated in a unified model by Tanaka[2] and Ushio[3]. The predicted weld shape, heat intensity, and current density as a function of radius at the anode agreed well with experimental results. However, the anode surface deformation and the effect of full penetration were not addressed.

Fan and Tsai[32] developed a unified model to describe the transport phenomena in GTA welding with full penetration. In the modeling of the welding arc, a pointed tip cathode that fits with the actual situation is addressed. The distribution of current density that is determined primarily by the welding current and cathode shape is calculated with the combined arc plasma-cathode system[21]. In the modeling of the molten pool, the heat transfer and fluid flow of the weld pool have been calculated at different welding times until a full penetration occurs, considering the influence of electromagnetic force, buoyancy force, arc drag force, and surface tension. In the modeling, difficulties associated with the irregular cathode shape, the deformation of top and bottom weld pool surfaces, and the moving liquid-solid interface have been overcome by adopting a boundary-fitted coordinate. The two-way interaction between the welding arc and the molten pool is considered: the free surface shape used

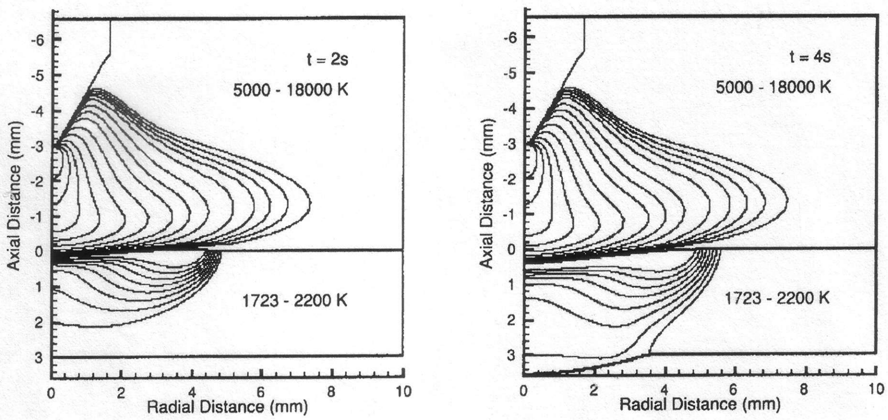

Fig. 2. Temperature contours of welding arc and molten pool with full penetration.

in the modeling of the welding arc is transiently deduced from the computed result of molten pool, while the surface profile of the molten pool is distorted by arc pressure, buoyancy, and surface tension forces acting on the weld pool. In addition, transport phenomena from the welding arc, such as arc drag force, heat flux, and current fluxes, are introduced into the molten pool in terms of boundary conditions on the interface. Here, we only show the temperature contours calculated for the welding arc and molten pool in Figure 2 as an illustration. In the region of the welding arc, the typical bell shape of arc periphery is clearly observed. In the region of the molten pool, the radial outward fluid flow transport heat from the center of the weld pool to the periphery; the shape of temperature contours shows the significant influence of the fluid flow on the temperature distribution. It is also indicated that the top surface depression increases due to the free bottom surface when the workpiece is fully penetrated.

3. Modeling of GMAW

3.1 Modeling of droplet formation and detachment

GMAW is an arc welding process that uses an arc between a continuous, consumable electrode and the weld pool. Due to the wide use of GMAW in industry, numerous models have been developed to study the metal transfer process[33-41]. A theoretical description of droplet formation in GMAW is complicated by the following effects: the dynamic nature of droplet growth, thermal phenomena in the wire, and heat transfer from the arc. Two major models developed to describe the droplet formation are the static force balance theory (SFBT)[33] and the magnetic pinch instability theory (PIT)[34]. Models based on SFBT are usually used for the prediction of droplet dimensions at low currents in the globular model of metal transfer. Allum[34] investigated the PIT and found good agreement between predicted and experimental droplet dimensions at currents corresponding to the spray transfer. However, both the SFBT and the PIT have been unsuccessful in predicting the transition from the globular transfer mode to the spary transfer model with an increasing arc current. Kim and Eagar[35] compared predictions both from SFBT and from the PIT with the experimental measurements for the droplet diameters and suggested modifications for the SFBT to include the effects of the tapering of the electrode tip in the spray transfer model. Nemchinsky[36] developed a steady state model to describe the equilibrium shape of a pendant droplet, accounting for surface tension and magnetic pinch force. A simple approximation for the current density distribution in the droplet was used. Simpson and Zhu[37] developed a one-dimensional model considering the forces acting on the droplet. The model made the predictions of droplet shape as a function of time. Haidar and Lowke[38] and Haidar[39] developed a time-dependent two-dimensional (2D) model for the prediction of droplet formation that included the arc. The surface tension, gravity, and magnetic pinch forces were considered; the model did not consider the arc drag force. Further, Choi et al.[40-42] considered the effect of the welding arc under the assumptions of a uniform and linear current density on the droplet surface for globular, spray and short-circuit transfer modes and pulsed-current GMAW. However, the work did not include a description of thermal phenomena; rather, it assumed that the droplets were isothermal. Wang and Huang et al. [43] simulated the transition from the globular to spray transfer mode by assuming a Gaussian current density distribution on the free surface of the drop. Wang and Hou et al. [44] predicted the geometry of the melting interface. However, the model assumed electrical and thermal fluxes along the droplet and ignored the effect of Marangoni and the drag effects on the droplet surface.

3.2 Transport phenomena in molten pool and arc plasma

Compared with the GTA welding pool, however, the GMAW molten pool is less studied from both experimental and theoretical aspects due to the interaction between the droplet and base metal. The impingement of molten metal droplets into the weld pool in GMAW affects the shape of the free surface and the convective heat transfer in the weld pool. Tsao and Wu[45] presented a 2D stationary weld pool convection model for GMAW that assumed the weld pool surface to be flat, and took into account the thermal energy exchange between the metal droplets and weld pool. In a study by Fan and Kovacevic[16, 17], the droplet formation, detachment, and transport phenomena are considered together with the weld pool. An approximation was used to get the current density and heat distribution along the surface profiles of the droplet and weld pool. Wang and Tsai[48] used another non-isothermal model to simulate the droplet impingement on the weld pool surface and the consequent fluid flow in the weld pool. While their paper focused on the interaction between the droplet and the weld pool, the mechanism of droplet formation and detachment was not studied.

In GMAW, the simulation of arc plasma was more challenging since the anode (droplet) and cathode (molten pool) are free surfaces; furthermore, the effect of droplet flight in arc plasma had to be addressed. Compared with GTAW arc plasma, the modeling of GMAW arc plasma was far less addressed. A 2D steady-state mathematical model was developed by Jonsson[49] to predict electric potential, temperature, and velocity. However, the electrode was assumed no melting, so the effects of the electrode shape and droplet on the arc plasma were not considered.

3.3 Three-dimensional modeling of GMAW

Using boundary fitted coordinates, Kim[50] presented a 3D quasi-steady model for the moving bead-on-plate GMAW process. The size and profile of the weld pool were predicted, but the dynamic interaction between the droplet and the weld pool free surface was not considered. Ushio and Wu[51] approximated the effect of the droplets on the weld pool as a constant force acting on the weld pool free surface; although, the impingement process is not a continuous process. The transient development and diminution of the weld pool at two periods after the arc ignites and extinguishes were analyzed quantitatively by Wu and Yan[52]; the time for the weld pool shape to reach the quasi-steady state and the time for the weld pool to solidify completely were predicted. Wu's model assumed the surface of the molten pool to be flat. Wang and Tsai[53] used the VOF algorithm to simulate the impingement of droplets in 3D moving GMAW; the size of the droplet was pre-determined, and the distribution of the heat and current density on top of the surface were assumed.

3.4 Unified models for GMAW

Similar to GTAW, a unified model for GMAW combines the electrode, arc plasma and molten pool. Haidar[31] presented a unified model including a detailed account of sheath effects near the electrodes, and considered the droplet formation. Fan and Kovacevi[54] developed a unified model to describe the growth and detachment of the molten droplets, the transport and interaction of the droplets in the arc plasma, and the interaction between the droplets and the weld pool. Two-way interactions between the arc-metal interfaces were also addressed: the simulation of heat and mass transfer in the arc plasma considered the developing surface profile of an electrode and the molten pool, also the effect of a flying droplet inside the arc plasma. Furthermore, the heat inputs to the electrode and the molten pool resulted from the simulation of the arc plasma. Figure 3 depicts the transport phenomena of the arc plasma while the droplet is formed, detached, and impinged on the substrate.

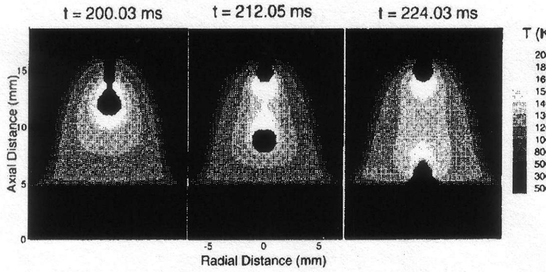

Fig. 3. Temperature contours of GMAW arc with droplet formation, detachment and impingement.

The unified models for GMAW need to be enhanced to describe other transfer modes such as spray transfer and short circuiting transfer. Spray transfer, where the droplet diameter is smaller than the wire diameter, occurs at medium and high current. Short-circuiting transfer is a special transfer mode where the molten droplet on the wire tip makes direct contact with the surface of the weld pool. It is characterized by repeated, intermittent arc extinguishment and re-ignition. The unified models should be able to predict the transition between different modes more accuratly.

So far, no 3D unified model for either GTAW or GMAW has been found in the open literature. We have discussed 3D modeling of the welding pool on the above and expect to see 3D calculations for the welding arc in the coming future, since so many arc properties are basically three dimensional. For example, the welding torch is often positioned at a certain angle to the workpiece. Even though the welding torch is positioned vertically, the phenomena of arc blow need to be resolved. Arc blow, also called arc wander, occurs when the arc stream does not follow the shortest path between the electrode and the workpiece. Arc blow can be one of two types: magnetic or thermal. Thermal arc blow, resulting from cathode and/or anode spot wandering, occurs because an electric arc requires hot zones on the electrode and the workpiece to maintain a continuous flow of current in the arc stream. Thus, the prediction of thermal arc blow is relied on unified models since the hot zones on the electrode and the workpiece are input from anode and cathode models.

4. Modeling of welding based SFF and multi-pass welding

Recently, arc welding principle has been applied in solid freeform fabrication (SFF). SFF builds up 3D objects by successive 2D layer deposition; objects are sliced into 2D thin layers, and each layer is built by various deposition or forming processes. In the process of applying GTAW with filler metal in SFF, parts are built up in a layer-by-layer fashion by feeding raw material in wire form into a melt pool that is maintained by a welding arc. For GMAW-based SFF, droplets are deposited layer by layer to build the product. As you can see, the principle of welding-based SFF is similar to the multi-pass welding. While extensive documentation and experience is available on the selection and optimization of welding parameters for the production of welds with exceptional joint quality, this information cannot be successfully applied for the SFF process since the criteria for a "good weld" and a "good prototyped layer" differ significantly. For example, the requirements for build-up height, penetration depth into the previous layer, and the ratio of these two variables are very different for welding and SFF by welding. The key issue in applying welding techniques for the SFF of metallic parts is to control the heat and mass transfer caused by molten wire or droplets onto previously deposited layers. Understanding the transport phenomena is critical to the product quality. For the extending usage of welding technologies, the research for the modeling of arc welding will have to pay more attention to 3D multi-layer welding processes. Actually, 3D models for GTAW with filler metal[30] and GMAW with droplets[53] would be used to model multiple layers. The challenge will be the solidification and re-melting of previous layers, and the maintenance of the weld surface profile. More investigation on these issues will be needed to make modeling results have a reasonable agreement with experiments.

Another promising welding technology used for SFF is called Plasma Powder Deposition (PPD). A transferred plasma arc exists between the torch and the substrate, and generates a molten pool on the surface of the substrate. The metal powder is fed into the molten pool by the carrier gas (argon) through the powder feeding coaxial nozzle. As the plasma arc moves forward, the molten metal solidifies to form a deposited layer. Zekovic[55] developed a model for gas-powder flow in laser-based direct metal deposition (DLMD). Compared with DLMD, PPD is more complex since the arc plasma is a high-temperature electromagnetic-induced gas flow. Similar to unified models for GTAW, the PPD modeling will be divided into two coupling steps. The first step is to simulate the arc plasma with powder. Compared with GTAW, much work needs to be done to describe the distribution of powder in the arc plasma, and the in-flight heating and melting of powder in the arc plasma. In the modeling, the Eulerian-Lagrangian approach[56] can be used to simulate the plasma-powder flow. The second step will consider the addition and the impingement of powder on the molten pool. The changing surface profile of the molten pool will be also coupled with the simulation of the arc plasma in the first step.

5. A whole-process model and advanced computational technologies

It is well known that multi-layer welding produces a higher thermal stress and distortion. PPD is capable of creating functional graded materials depending on the powder feeding system's parameters such as the flow rate and mixing rate of different powders. All of these summon a whole-process model that includes thermal, fluid, mechanical, and chemical sub-models to predict the molten pool size, residual stresses, and microstructure, and to optimize the process parameters accordingly. In the whole-process model, the temperature and fluid flow are calculated based on the thermal-fluid analysis such as the above-mentioned unified models. Thermal stress induced by the cooling rate will be calculated after the thermal-fluid analysis. The conservation equation of species to describe the distribution of chemical composition such as carbon will be added and used as an input to the microstructure evolution. The solidified microstructure from the molten pool will be predicted based on the thermal history and chemical history from the thermal-fluid-species calculations. Of course, it will take much more effort to develop a whole-process model. Recently, Caterpillar Inc. and Battelle Memorial Institute have made some progress on a loosely coupled model considering thermal, fluid, stress and microstructure[57].

The modeling of arc welding is becoming more and more comprehensive. The dynamic models such as the unified model for GMAW have already taken lots of computation time on a single powerful workstation. Fortunately, the availability of parallel computing provides an opportunity for solving increasingly complex problems. With the price of PCs declining and becoming more and more powerful, it is no surprise to see that Linux and Windows clusters have been widely applied to mathematical modeling. To cut cost and be efficient enough for industrial use, welding modeling will be moving to this direction, too. The combination of functional decomposition and domain decomposition fits very well with unified models for welding: the arc plasma model, anode model, and cathode model can be different model components. Each model component can be thought of as a separate task, to be parallelized by domain decomposition. While each component may be most naturally parallelized using domain decomposition techniques, the parallel algorithm as a whole is simpler if the system is first decomposed using functional decomposition techniques. With the power of parallel computing, the goal is to incorporate solid mechanics, microstructure evolution and fluid mechanics into one arc welding model.

So far, most of the research is about bead-on-plate welding. Using a boundary-fitted coordinate, DebRoy[57] developed a 3D steady model for GMA fillet welding that is characterized by a V-shaped joint geometry. Finer meshes were put along the interfaces among the cathode, arc plasma, and anode[25]. To gradually push the welding modeling to industry, 3D models with techniques such as unstructured mesh and adaptive mesh to handle more complicated shape will be needed. Adaptive meshing is used to refine the mesh to regions with large gradients. Thus, increased computational efficiency can be obtained without sacrificing accuracy. Typically, a fine mesh region is moving with the heat source.

6. Summary

Unified models are believed to be the trend for the modeling of arc welding processes. 2D unified models have been developed to simulate the arc and the weld pool until full penetration. 3D unified models will be needed to address the 3D welding properties such as arc wandering. 3D modeling of multi-pass welding processes with feeding wire, droplet, and powder will be also beneficial to the new welding-based SFF technologies. A tightly coupled 3D whole-process model will be the ultimate goal for the modeling of arc welding processes. Parallel computing will be more widely used in the modeling of welding processes. More advanced meshing techniques such as unstructured mesh will replace boundary-fitted coordinate and stepwise approximation to better describe the complex geometry shape. In summary, with the continuing growth in computer capability and computational techniques, and increasing effort on the research about the science of modeling, the contributions of modeling to industrial welding processes will be more and more promising.

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