Thermal Effects on the MIG-SMD Parts Characteristics: A Review

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ABSTRACT

Shaped metal deposition (SMD) is a revolutionary process for fabricating near-net-shaped products by consecutive layer deposition with the aid of a welding machine. The SMD rig comprises a robot and a manipulator equipped with an inert gas welding torch. The SMD-fabricated object is frequently exposed to extreme temperature variations and rapid heating and cooling throughout the manufacturing process, resulting in a unique microstructure and morphology not seen with traditional production processes.

Among the fundamental research, there are efforts to understand thermal behavior, which is a critical component of complex systems, and its effect on product quality. This paper intends to review the many ways to study the thermal impact on the final product.

Keywords: SMD, Manufacturing process, thermal analysis

1. Introduction

To meet growing industry demands, the emphasis of additive manufacturing (AM) research has recently switched to directly creating efficient metal apparatuses, including aluminum alloys, stainless steels, titanium alloys, and nickel alloys [1]. AM of metal components may be broadly categorized into three categories depending on the energy source employed in the deposition process: laser-based, electron beam-based, and arc welding-based [2]. Laser-based additive manufacturing is renowned for its great accuracy but low energy efficiency. While electron beam-based AM is marginally more energy efficient, its use is limited due to the process's high vacuum environment. Compared to laser and electron beam-based additive manufacturing, arc welding-based additive manufacturing offers a high deposition rate and energy efficiency [3].

Additionally, AM using arc welding equipment is more cost-effective than laser and electron beam equipment.. Metal-shaped deposition (SMD) produces near-net 3D objects by layers that use melted metallic wire with an electric gas arc as a heating source. This method uses a wide range of materials and alloys. The main advantages of this method are high by to fly ratio, less human effort required, reduced time for producing components, no mold required, and complex and internal profile shapes. These advantages are due to an unconstricted building arm robot, and the design is straight from the (CAD) program to the machine. The common arc-shaped metal deposition is gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW). In GTAW and PAW-SMD [4,5], The arc is lit between the tungsten and the base metal, and each wire is separately inserted into the molten pool[5]. The welding arc is hit directly between the wire and the base metal during GMAW-SMD. The electric arc will rapidly melt the wire in this scenario, resulting in a high deposition rate[6]. Thus, GMAW-based additive manufacturing is better suited to generating medium- and large-scale metal products [8].

However, because of the increased deposition rate in GMAW-SMD, the heat input is typically more than in other procedures. The repetitive heating of GMAW-SMD components with significant heat input results in substantial distortions and residual stresses, very low geometry accuracy, and a poor surface finish. These difficulties will have a detrimental effect on the components' final form and mechanical qualities. As a result, it is critical to investigate the thermal behavior of this procedure and its influence on the components used to manage the heat input in this technology. Numerous studies have concentrated on the mechanical characteristics of surface-mount devices (SMDs) [9-20]. This paper reviews the influence of the thermal process on the final products by studying the effect of thermal behaviour on residual stresses and the deformation of the microstructure.

2. Thermal Effects on Conventional GMAW-SMD

Many aspects of metal deposition's thermal behaviour have yet to be fully understood, whether through experimental or numerical methods. As a result, numerous uncertainties have yet to be published. These errors or their sources are caused by the irregular temperature of samples within the period between the beginning and the end of the SMD process, as described by Stenback [21].

When typical MIG techniques are utilised in metal deposition processes, various issues arise, such as HI or AE issues. Metal deposition efficiency can be negatively impacted by a lack of attention to or suspicion of heat input constraints on contentious outcomes. Water calorimeter measurements have been weakened or erroneous because of the 15-second lag between the start of deposition and the measurement's conclusion [22].

However, Quentino et al. (2013) [23] emphasized the need to take heat losses into account on the backside of the weld for full penetration welding to enhance the quality of MIG-welding methods utilized in manufacturing. It was found that the thermal input during metals deposition by the MIG process was higher than that of the thermal input in the TIG process, which means that energy consumption or temperature was roughly 27.06 percent higher in MIG than in TIG [24].

Due to the low-cost and reproducibility of numerical modeling, there are numerous forms of study on the AM process thermal behavior.[25] produced a three-dimensional finite element (FE) model to accurately forecast residual stress-induced deformations in AM based on GMAW. [26] investigated the thermomechanical behavior of a multilayer wall structure created using the GMAW-based AM process using two 3D finite element models (transient and steady-state models). In study [27] and [28], the temperature field development, residual stress, thermal stress evolution and strain distributions were examined using 3D FE numerical simulations during single-pass multilayer GMAW-based AM. [29] also investigated the temperature field and residual stress distributions in multi-pass single-layer GMAW-based AM. [30] used a secondary heat source to simulate moving induction heating in the induction-assisted shaped metal deposition process, resulting in much reduced residual stresses than in the absence of induction heating. As a result, the majority of research in this subject has concentrated on evaluating the temperature field, residual stresses, and distortions of the GMAW-SMD process using FE numerical modeling. However, the simulation ignores the real complicated fluctuation in heat condition and deposition dimension. It is not straightforward to study the effect of heat behavior on the geometry accuracy and mechanical characteristics of deposited components as predicted by FE models. As a result, detailed experimental research are required to fully understand the thermal behavior of this SMD process.[31] designed a GMAW-SMD system equipped with a passive vision sensor for observing the molten pool's shape during deposition. However, there was no significant temperature field development to analyze the effect of process factors on the appearance of the formation. Certain works use infrared (IR) thermography to monitor the deposition process's surface temperature. Seppala and Migler [32] employed infrared thermography to determine the temperature profiles of a model polymer during additive manufacturing. Measuring techniques serve as a starting point for creating strategies for controlling and modeling AM processes. Farshidianfar et al.[33] devised a closed-loop feedback controller for laser AM to maintain cooling rates while modifying the travel speed in real time. The effects of cooling rate and melt pool temperature on the microstructure of 316L stainless steel produced by laser AM were examined in [34] using the same IR imaging technique. Rodriguez et al. [35] examined the high-precision measurement of absolute surface temperatures utilizing in situ infrared imaging of melted or solid surfaces layer-by-layer during manufacture using an electron beam melting (EBM) technology. In arc welding research, infrared thermography is used to characterize the temperature and monitor the welding process [36, 37]. To our knowledge, little GMAW-SMD has been used. Bai et al. [38] used infrared photography to calibrate input material thermal characteristics in order to increase the prediction accuracy of finite thermal element analysis for GMAW SMD without directly analyzing the thermal behavior. An IR camera was used to analyze the thermal process of multilayer single-pass based on these findings. GMAW-SMD.

3. Effects of Thermal on Residual Stresses and deformation

A high-temperature gradient near the melt pool leads to unwanted product deformation and dimensional distortion, which results from rapid thermal cycling. The product is left with residual stress due to inconsistencies in thermal strain. When the product is subjected to excessive strain, it is more susceptible to fracture, which reduces component life expectancy and increases the risk of early component failure.[39].

Deformation may be determined in situ or during processing. After processing, The deformation was measured using a Confocal Laser Scanning Microscope by Roberts et al. [40]. In-situ monitoring of deformation occurred infrequently. Denlinger et al. [41] measured the substrate's free end deformation during clamping using a laser displacement sensor. Temperature measurements were taken using thermocouples placed on the substrate's bottom. We treated a thin wall and investigated the influence of a novel parameter termed the dwell duration on distortion and residual stress. Nie et al. [42] fabricated laser hot-wire additively using a similar approach that included thermocouples and displacement sensors. Furumoto et al. [43] produced a thin wall of various materials on a stainless steel or carbon steel substrate, and then utilized a strain gauge to determine the substrate's stress history. The resultant stress and stress history were studied when various powders and substrates were utilized.

Numerical models may be used to forecast residual stress and deformation. The load on nodes was simulated using temperature distributions from thermal models. Stress and displacement fields were also calculated. Mukherjee et al. [44] created a linked thermal-fluid numerical model and subsequently presented a thermo-mechanical model using ABQUS. The results indicated that layer thickness and heat input had an effect on residual stress and deformation. Furumoto et al. [45] showed that the coefficient of thermal expansion, mechanical strength, and temperature gradient all had an effect on the component's deformation, with the coefficient of thermal expansion being the determining factor. Farahmand et al. [46] built a thermoelastic-plastic model and discovered that the final tracks had a significant concentration of stress due to the rapid cooling rate and stress release from the prior tracks. This stress distribution feature has also been documented in the literature [47]. Fang et al. [48] conducted an investigation on the influence of martensitic transformation on the development of stress. The model demonstrated the stress field's impact on material characteristics, temperature-induced plasticity, and phase change temperature. Zhang et al. [49] developed a thermomechanical model for pulsed laser metal deposition using multiple beads. The highest temperature differential occurs at the interface between the depositions and the substrate, which is also the location of the thermal stresses.

4. Effect of Thermal on Microstructure and Solidification.

The temperature gradient, fluid flow, and cooling rate all affect metal solidification, affecting grain shape, orientation, and size[50,51]. Herzog et al. [52] demonstrated typical additive manufacturing microstructures, particularly unique grain shapes caused by the complicated heat cycle and rapid cooling rates. Experimentally, the microstructure may be examined by examining the thermal signature. Muvvala et al. [53] evaluated the cooling rate and microstructure of lasers operating at CW and PW power levels. Due to repeated remelting and solidification during one phase of PW laser treatment, the stacks of columnar dendrites have varying orientations. A faster cooling rate might result in severe elements segregation and the production of Laves, reducing the layer's hardness. Doubenskaia et al. [54] investigated the influence of TiC concentration on the melt pool temperature and final microstructure during the DED process. Farshidianfar et al. [55] used thermography to investigate the influence of melt pool temperature and cooling rate on the microstructure. It was shown that the cooling rate determined from thermography may be used to characterize the size of the solidification structure and the mode of solidification.

Graf et al. [56] proved that the welding orientation CMT for WAAM has a considerable effect on the temperature field in G4Si1 and AZ31 walls and tubes, respectively. The goal of this research was to examine experimental and numerical data pertaining to welding parameters and their effect on temperature increase. With Goldak's seam form and heat source identified, it was possible to correctly replicate the temperature profile of the semi-finished goods. On the basis of simulated temperatures in components, distortion, residual stresses, and connection to microstructural processes may be anticipated.

Among the several current processes, wire-arc additive manufacturing (WAAM) provides compelling advantages in terms of component cost [57], deposition rate, and buy-to-fly ratio, especially for large and moderately complicated structural components [58]. This is particularly relevant in the automobile and aerospace industries [59]. Controlling the heat input and the ensuing local temperatures and cooling rates is difficult yet critical for efficient WAAM processing of complicated structures made of aluminum alloys (also known as intrinsic heat treatment). Cooling speeds are generally in the range of 5 101–102 °C/s during WAAM [26]. Because of the iterative exposure of layer-by-layer arc welding, the intrinsic heat treatment influences the materials' microstructure and, as a result, the final mechanical properties, as recently examined by Bai et al. [60] and Oyama et al. [61]. Increased temperature exposure often leads in grain coarsening and difficulty controlling second phases (if present) and their size distribution, or, in the case of titanium alloys (e.g., +), an inhomogeneous lamellar structure [64]. In any event, the reaction to intrinsic heat treatment is alloy-dependent and requires a holistic approach aimed at microstructural correction to manage material performance. Numerous recent studies using technical and alloying-related methodologies have focused on improving mechanical characteristics through grain refinement [65–67]. The submitted research have shown that changing the polarity during WAAM is an excellent method for refining the grain structure of aluminum alloys. It has been suggested that the refined grain structure is the consequence of enhanced melt pool churning during cold metal transfer (CMT) or tungsten inert gas welding [68, 69]. Aucott et al. [71] have proposed that the stirring motion inside the melt pool results in dendritic breakup and therefore grain refining. However, determining optimal processing conditions remains challenging and is dependent on the alloy and intended component shape. Published studies do not adequately explain the microstructure optimization process enabled by intelligent polarity sequence variation.

5. Thermal Analysis of Thin-Walled Produced by Shaped Metal Deposition

To resolve distortions and crack problems and find a way to increase the productivity and reduce the heat input substantially, double wire GMAW was produced. The thermal behaviour of metal deposition is very complex when studied, either by experimental or numerical methods, and for this reason, there are few research to understood the thermal bevahior therefore there is a need for further.

Yan et al. 2017 [72] The bypass arc significantly decreased the dimensions of the molten pool during the deposition process, including length, depth, and breadth, during gas metal arc welding (GMAW)- and double electrode gas metal arc welding (DE-GMAW)-shaped metal deposition (SMD). The volume of the high-temperature metal used in the deposited portions was reduced during the high layer deposition. After chilling each layer, the mean temperature of the deposited component was lower in the DEGMAW-SMD than in the GMAW-SMD under the same circumstances. At certain points throughout the deposition process, the temperature of the molten pool may increase dramatically, impacting the component form and surface quality. As a consequence, anticipating the molten pool temperature is crucial for improving the metal deposition process.

Numerous attempts have been made to build thermomechanical and computational models of the additive manufacturing process [73,74]. Numerous authors foresaw the effect of process variables on temperature and residual stress. S. Nikam and N. Jain [75] developed a three-dimensional finite element model for the plasma arc-based WAAM process in order to forecast the temperature history and residual stresses in a thin-walled metallic structure. Matsumoto et al. [76] also projected the temperature distribution and stress distribution inside the deposited layer using a two-dimensional finite element model for laser-based additive manufacturing. J. Yin et al. [77] proposed using a finite element model to track temperature history during laser sintering. The Gaussian heat transfer distribution has also been used successfully to forecast the size of the molten pool. Thermal modeling of the three-dimensional metal deposition process is a time-consuming and difficult operation. The model was developed, however, by simplifying the variables connected with the metal deposition process [78].

Numerous research have used the WAAM approach to develop a finite element model for a thin-walled metal deposition process [79,80]. M. Sawant et al. [81] used a microplasma arc to perform a finite element simulation of an additive manufacturing approach for metallic structures. It was observed that the developed model may be used with any filler material and substrate. They also developed a similar model for predicting the geometric shape of deposited material in terms of deposition breadth and height in another study [82,83]. M. Graf et al. [84] constructed a thermomechanical model for an additive manufacturing process based on gas metal arc welding using finite element analysis software (GMAW). Instead of simulating the complete welding process, the heat transfer coefficient for the GMAW method was determined. J. Xiong et al. [85] developed a simulation of an additive manufacturing method based on GMAW for deposition of circular thin-walled objects. The temperature history of the circular thin-walled construction was predicted at three distinct points on the substrate plate. Additionally, Montevecchi F. et al. [86] developed a finite element model for the GMAW-SMD process in order to establish the true power distribution between the deposited material and the substrate.

The majority of simulation work, according to the literature, has been undertaken for GMAW and plasma-arc-based additive manufacturing technologies. Numerous studies have been conducted to determine the effect of WAAM process parameters on the temperature generated during thin wall metal deposition.

6. Conclusion

Shaped metal deposition (SMD) is a ground-breaking technology for producing near-net-shaped components that creates near-net three-dimensional structures using layers of molten metallic wire heated by an electric gas arc. Although thermal behavior is a critical characteristic that affects the product generated by SMD, there are limited kinds of studies on its thermal behavior. Simultaneously, various researchers have investigated the thermal behavior of the AM process using numerical modeling. Due of the quick thermal cycling, a temperature difference around the melt pool is created. This results in unwanted deformation and distortion of the product's dimensions.

When the thermal behavior of metal deposition is examined experimentally or numerically, it is quite complicated. A faster cooling rate might result in severe elements segregation and the production of Laves, reducing the layer's hardness. Numerous recent studies have focused on improving mechanical characteristics by grain refining. Numerous studies have been conducted to determine the effect of WAAM process parameters on the temperature generated during thin wall metal deposition.

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