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Plasma transferred arc additive manufacturing of Nickel metal matrix composites

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ABSTRACT

This paper analyzes the geometric stability and microstructure characteristics of metal additive manufacturing parts using plasma transferred arc with Metal Matrix Composites. The technology used to enhance the capabilities of a plasma system to create an additive manufacturing system is described. Geometric stability, microstructure porosity and cross-sectional hardness analysis of the additive manufacturing parts are discussed. This work confirms that the new capabilities of the system allow building a 3D printed part of nickel-base metal matrix with tungsten carbide particles for wear resistance. The results will lead to the development of large-scale additive manufacturing parts for industrial purposes.

1. Introduction

Additive Manufacturing (AM) is the process of joining material to make parts from a 3D model, layer by layer [1]. Before 2009, AM was referred to Rapid Prototyping (RP) [2]. Its history can be tracked to 1986, when C. Hull filed the first patent for three-dimensional objects [3]. Vis-á-vis Metal AM, the first patent can be traced to 1925, where R. Baker proposed a method to use electric arc welding for making decorative articles by layers [4]. In 1971, Akira U. patented an apparatus for building circular vessels from welded metal deposition [5]. By 1974, the Thyssen company embarked on plans for constructing components made only of weld metal. They were able to build a 72 tons multilayer weldment by a method called "Shape Welding" [6].

For this particular research, a Plasma Transferred Arc Additive Manufacturing (PTA-AM) process is proposed. This technology can be considered as a Directed Energy Deposition (DED), more specifically a Free Form Fabrication System [7]. It uses a plasma arc as energy source to melt Metal Matrix Composites (MMC). The arc is constricted using a water-cooled small diameter copper nozzle that allows a reduced arc diameter but an increase in the power density compared to other arc welding processes. Although other systems supply metal powder in a variety of ways, such as off-axis powder injection with ceramic tubes [8–10], for PTA-AM it is delivered through ports in a coaxial nozzle. The Kennametal nozzle and all modern PTA hardfacing torches have powder delivery through the internals of the nozzle. This system is commonly used globally and it is an excellent adaptation of current technology into 3D printing technology allowing the equipment to be multi-functional. The use of powders makes the process more flexible in terms of the alloys that can be deposited [11]. In the literature, research in DED has focused on Wire Arc Additive Manufacturing (WAAM). Gas Metal Arc Welding (GMAW) and its particular form of Cold Metal Transfer (CMT) technology has been used to produce thin-walled structures and analyze the thermal history, microstructure, and mechanical properties [12–15]. Other authors uses micro lasers, micro-plasma and thin wires to analyze geometrical properties in thin-walled structures [16,17]. There is one technology commercially available for direct metal fabrication related to PTA-AM in the Materials and Electrochemical Research (MER) Corporation. This company has developed a Plasma Transferred Arc-Selective Free Form Fabrication (PTA-SFFF) equipment used to make 3D metal parts of Ti6Al-4V and the refractory alloys Mo-Re and Ta-W [7]. In comparison, this work presents development of Tungsten Carbide (WC) based MMC AM parts assuring particle homogeneity and increasing wear resistance to extend component life. The AM system that has been developed in house

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is currently capable of building parts assuring WC homogeneity and hardness suitable for the mining, oil, and gas industries.

2. Experimental methods

The equipment used is a Starweld PTA 300 M from Stellite Coatings equipped with a Kennametal Excalibur torch. This system has previously been used for metal cladding of components. The system comprises of 4 main parts. The PTA enclosure is were the controller, and all the valves and electronics are located (Fig. 1A). The Excalibur torch is at the transition point where the metal powder is carried by the argon and melted by the plasma arc (Fig. 1B). For AM purposes, a three axis table was adapted. It should be noted that the torch is fixed and the build platform moves according to the AM part geometry.

The build platform is the location where the substrate is mounted to print a part (Fig. 1C). That platform can move in the build space of 365 mm × 170 mm × 300 mm through its X, Y, and Z axes, respectively (Fig. 1D). A real-time DSP-Based system is used with a Computer Numerical Control (CNC) interface to control the table movements by the G-Code standard RS-274NGC. The printing process starts with a 3D model in Standard Tessellation Language (STL). The model is converted then to layers by the slicer software CURA to generate the first set of G-code instructions under the standard RS-274. Before running the code to print the part, a parsing of the code is needed to convert the G-code to its extended version RS-274NGC. This language has many capabilities beyond those of RS-274 and it is the type of data that the PTA-AM table uses to coordinate the movements required to print the parts.

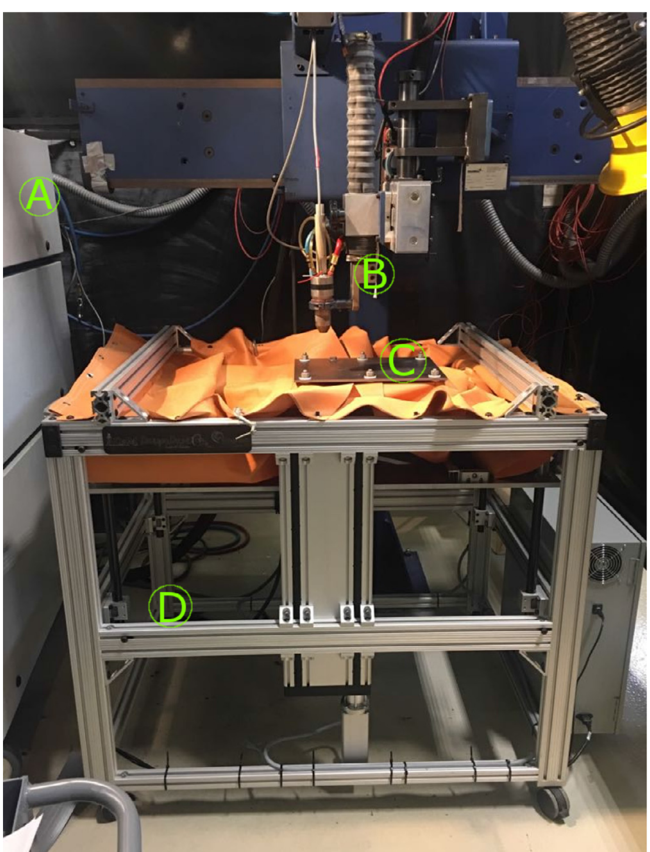

Fig. 1. PTA-AM system. PTA Enclosure(A), Excalibur torch(B), build platform(C) and build space(D). Explanations are provided in the text of the paper.

For the MMC, a DURIT 6030 40% NiCrNSi Nickel Alloy with 60w% of WOKA 50115 WC particle concentration was used. Table 1 shows the configurations used for the AM experiments. In the initial pilot run the process parameters were restricted to the lower end of the capabilities in order to assure the successful run. The system has the capability to increase these parameters for other purposes e.g. achieve higher speeds. The selected values were based on Wolfe (2010), to ensure the Tungsten Carbide particles' homogeneity inside the MMC [18].

3. Results and discussion

Two 3D printed parts made of DURIT 6030 Nickel Alloy with 60wt% of WOKA 50115 were obtained from the experiments. The first objective was to confirm the hypothesis that the manufacturing process will be feasible for AM purposes. Although the machine is capable of printing larger parts up to 150 mm, for the purpose of experimental validation for this paper, two test artifacts were chosen. A pyramid with 60 degree angles and total height of 50 mm was selected to show some degree of overhang. A cylinder with a 50 mm diameter and 30 mm height was determined to exhibit annular capabilities. Fig. 2 shows the results of the two printed parts in which geometric stability is achieved. The pyramid's printing time is 13 min and the cylinder has a 2 min printing time. Both shapes have a layer thickness of 750 µm.

One particular problem in common overlays used in the hardfacing industry is the settling of WC particles due to their high density. In this study, a cross-sectional analysis of the cylinder 3D printed part was obtained in order to have more insight about the effects of the PTA-AM process in the microstructure evolution. It can be shown that WC particle homogeneity is kept constant due to the rapid solidification rate of the layer-by-layer additive manufacturing process (Fig. 3). This rapid solidification occurs because of the very low building rates that allow the nickel matrix to prevent settling of the heavier WC particles.

In the CAD model, the nominal value of the total height in the cylindrical part was 30 mm, compared to the real value of 32 mm, which was measured through the microscopic evaluation of the part. The nominal value of the wall thickness of the model was 3 mm. The measured shell thickness average is 4.7 mm with a standard deviation of 0.339 mm, taken over 63 discrete locations through the build. The porosity was measured using a false colour technique with image analysis software Clemex 9.0 at seven locations. The average porosity from the seven sections is 0.40%, with a standard deviation of 0.161%. The porosity in the microstructure is due to the lack of metal fusion inside the matrix, as well as internal porosity intrinsic to the tungsten carbide. It was observed that the porosity increases on the latter layers of the AM part. This characteristic is highly correlated to heat management in the build, particularly an effect known as heat buildup. It is known that travel speed contributes to higher residual stresses and distortions within the build [19]. Thermal modeling before beginning building is suggested to reduce porosity. Finally, for the WC hardness, ten random locations inside particles from the cross-section were selected. The

Table 1
Plasma Transferred Arc AM Parameters.

Center gas	1 GPM
Shield gas	12 GPM
Powder gas	1.5 GPM
Powder Feed Rate	20 GPM
Pilot Current	24 A
Welding Current	48 A
Voltage	23 V
Powder Size	50–180 µm
PTA-AM Table Speed	10 mm/s

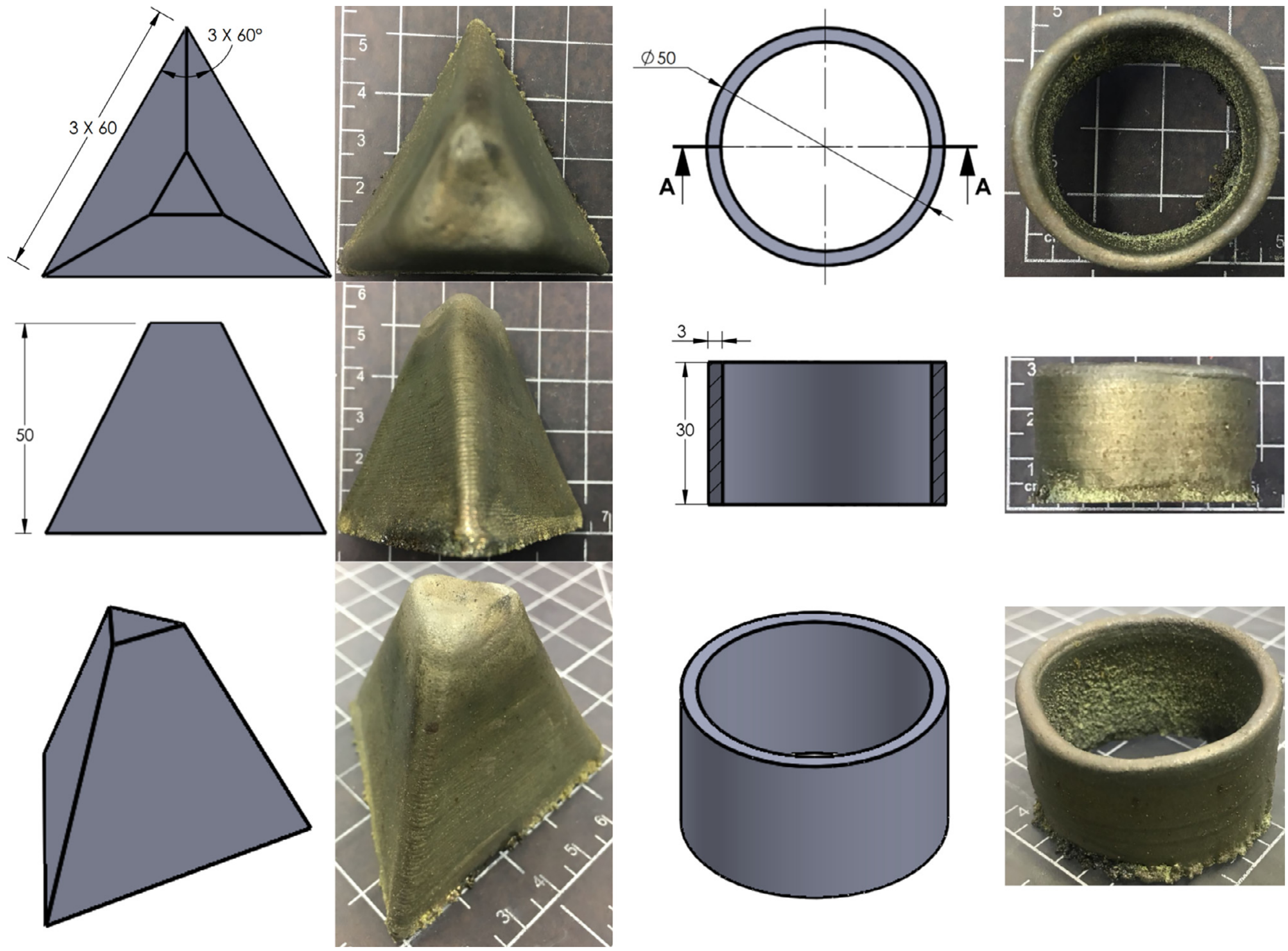

Fig. 2. Geometric Stability for a pyramid and a cylinder in mm (Top, Front and Isometric views).

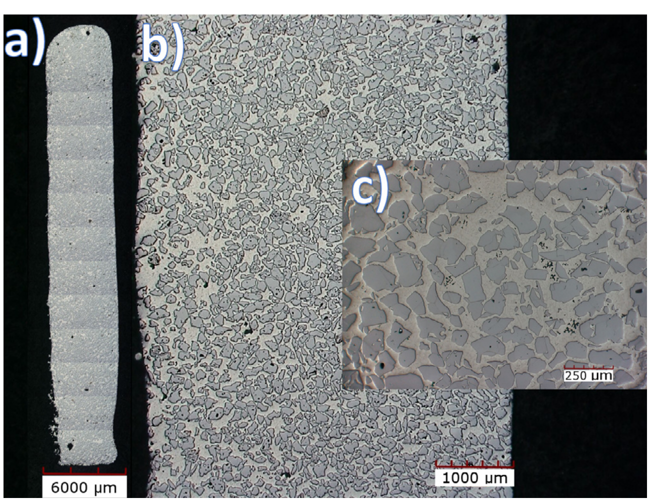

Fig. 3. 3D Printed Cross-section a) 6 mm scale, b) 1 mm scale, and c) 250 µm scale.

HRC measurement average is 63.06 HCR with a standard deviation of 0.73 HCR. This information reveals that the hardness in the microstructure aligns with the commercial hardfacing overlay results. There are no indicators in the microstructure showing growth of the WC particles. There is little interaction between the carbide and the metal matrix. Table 2 shows a summary of the result obtained.

Table 2
Summary results for geometric stability, microstructure porosity and cross-sectional hardness.

Parameter	Nominal	Measured	Standard Deviation
Height	30.00 mm	32.00 mm	–
Shell Thickness	3.00 mm	4.70 mm	0.34 mm
Porosity	–	0.40%	0.16%
Hardness	31.00 HRC	63.06 HRC	0.74 HRC

It can be observed that the variance in height and shell thickness are 6.67% and 56.67%, respectively. These differences are because of certain perturbations in the initial layers, the diameter of the copper nozzle, the initial stand-off distance of the torch and the plasma gas flow, powder flow, welding current and printing speed interactions. These allow an optimized metallic fusion in the part. To decrease these artifacts, a pre-heat routine of the substrate before printing, a decreased nozzle diameter, a standardized stand-off distance and a powder deposition characterization are proposed in a future work.

4. Conclusion

The PTA-AM technology is a high-energy DED method that uses plasma energy to melt MMC with valuable mechanical characteristic for heavy industry applications. The final goal of these work is to 3D print critical components, such as bucket teeth, crushers, shovel or cyclofeeders from a CAD Model instead of overlaying them with the MMC. A combination of steel and hard-facing powders will improve the strength, toughness, hardness, abrasion and corrosion properties of the components. Because of its high energy, the process is able to melt a variety of alloys together with tungsten carbide particles. The features that make this AM system beneficial are the possibility of high printing speeds, the mechanical properties that can be achieved with the variety of material combinations and its capacity of printing customizable parts.

Higher printing speeds will allow the system to build Large-Scale Additive Manufacturing (LSAM). Building large components in the fusion AM processes is a challenge. As shown in the microstructure analysis of the parts, buildup heat and thermal stresses can lead to porosity, distortions and warping of the parts. These effects can be reduced through thermal modeling of the process, parameter optimization, or by improving the technology of the PTA-AM through closed-loop control strategies. Addressing these difficulties will allow the system to improve its building rate. The work here shows that the PTA-AM parts homogeneity in WC particles is due to the rapid solidification because of the combination of low building rate and table speed. Future work is ongoing to optimize the combination of these factors into faster printing speeds without compromising the homogeneity of the WC particles.

The PTA-AM process presented in the paper shows promising mechanical properties, low porosity as well as excellent hardness in the microstructure proved that this technology is a suitable option for the mining, oil, and gas sectors. Although these industries are the prime focus for this ongoing research with the Ni–WC MMC materials, the potential of this technology is not limited to these sectors. Other fields such as agriculture, aerospace or automotive could benefit due to its potential large scale capabilities and broad powder material availability. Additional important features in the AM scope that need to be characterized are geometrical tolerances, thermal stresses, overhanging, in-fills, support material and small lattices. These features will be investigated as future work.

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