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WAAM and Other Unconventional Metal Additive Manufacturing Technologies

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ABSTRACT

The paper presents an overview of metal additive manufacturing technologies. The emphasis is on unconventional emerging technologies with firm background on welding technologies such as Ultrasonic Additive Manufacturing, Friction Additive Manufacturing, Thermal Spray Additive Manufacturing, Resistance Additive Manufacturing and Wire and Arc Additive Manufacturing. The particular processes are explained in detail and their advantages and drawbacks are presented. Attention is made on materials used, possibilities to produce multi-material products and functionally graded materials, and typical applications of currently developed technologies. The state-of-the-art on the Wire and Arc Additive Manufacturing is presented in more detail due to high research interests, it's potential and widespread. The main differences between different arc additive manufacturing technologies are shown. An influence of processing parameters is discussed with respect to process stability and process control. The challenges related to path planning are shown together with the importance of post-processing. The main advantage of presented technologies is their ability of making larger and multi-material parts, with high deposition rate, which is difficult to achieve using conventional additive technologies.

Key words: *Wire arc additive manufacturing; Ultrasonic additive manufacturing; Friction additive manufacturing; Thermal spray additive manufacturing; Resistance additive manufacturing*

1. OVERVIEW OF AM OF METALS

Additive manufacturing technologies have experienced increased research interests and development lately, which can be seen by a high number of scientific publications, machines and products that are used in industry and everyday life. A big push in this direction was made with development and accessibility of modern controllers, CNC machines and robots. Nowadays different welding and weld cladding technologies are combined with CNC machines or robotic manipulators to make additive manufacturing systems with unique capabilities. Together with development and maturity of additive manufacturing processes the standards evolved related to terminology, data formats, design rules and qualification guidance [1, 2].

Additive manufacturing processes are classified according to ISO/ASTM 52900-2017 into single step and multi-step AM processes [3]. The standard divides the processes according to fusion and adhesion of similar and dissimilar materials and it deals with metals, ceramics, polymers and composites. A more comprehensive map of additive manufacturing processes can be found on 3dprintingmedia.net [4].

Fig. 1 shows the division of different metal additive manufacturing processes. The main difference between these AM processes is in technological aspect in producing the part, in the form of material used (powder, powder in filament, wire, tape) and different needs for post processing. The most common industrial AM technology is Powder Bed Fusion (PBF) Selective Laser Melting (SLM) and

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Electron Beam Melting (EBM), which enable the production of complex geometry parts with high resolution and quality, but are limited to producing smaller sized parts (Fig. 2). EBM machines are less widely spread, but possess certain advantages in processing highly reactive materials, such as titanium alloys, due to processing in vacuum. PBF processes are using Titanium alloys, Nickel based alloys and Cr-Co materials to produce aerospace products, turbines, medical and dental equipment and parts for automotive industry. Direct Energy Deposition (DED) methods are Laser Metal Deposition (LMD-Wire, LMD-Powder), Electron Beam AM (EBAM-Wire) and Wire and Arc AM (WAAM)

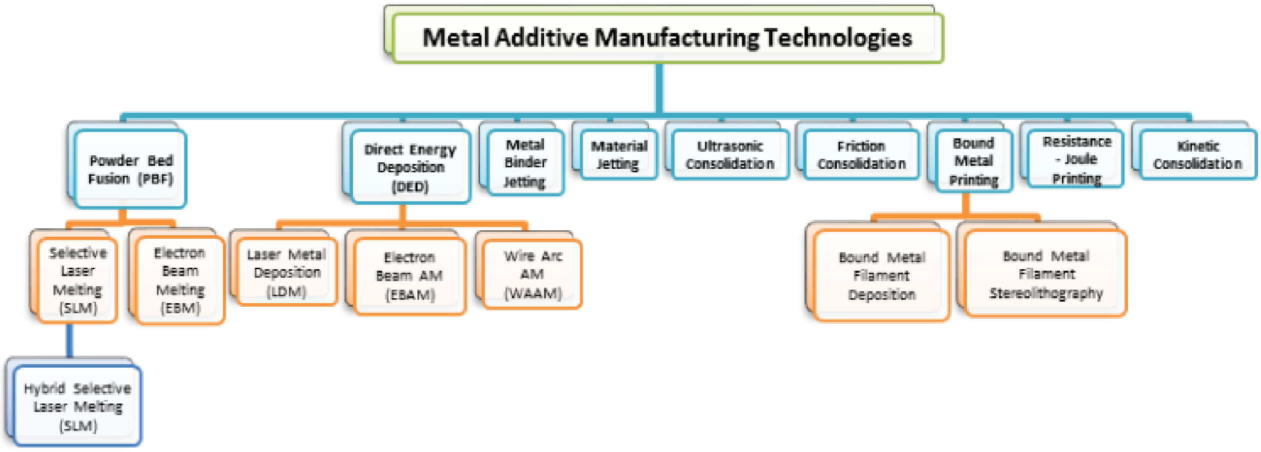

Fig. 1 *Schematic presentation of metal AM technologies*

The common aim of this technologies is to enable production of bigger parts at smaller resolution and are especially useful for repair of components. he key materials that are used in DED technologies are Titanium alloys, Nickel based alloys, Stainless Steels, Aluminum Alloys and Cr-Co materials. Typical applications are aerospace products, products for automotive industry, turbines for power plants, and repair of different metallic products. Bound Metal Printing consists of Bound Metal Filament Stereolithography (BMFS) and Bound Metal Filament Deposition (BMFD). In BMFD metal powder in filament is extruded through the nozzle to form a green part. In second stage a sintering is done to get the final properties of the part, which could be further improved with post processing heat treatment, if materials are suitable for it. The typical materials used are copper alloys, nickel alloys, stainless steels, tool steels and titanium alloys for instance. The processes are suitable to produce precision engineering parts, prototypes and products used in automotive industry.

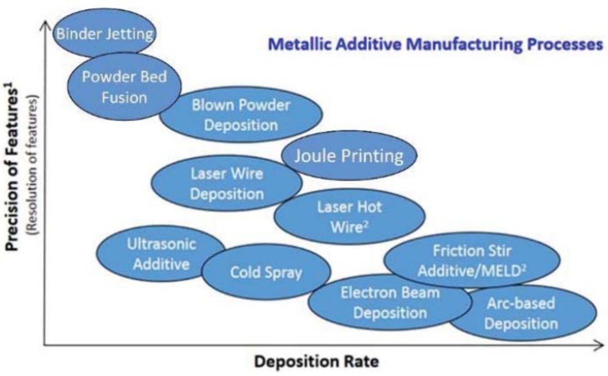

Fig 2. *Resolution and part complexity versus part size of main additive manufacturing technologies* [9]

Binder Jetting (BJ) is another technology that has high manufacturing readiness level and high potential for niche products. It enables production of complex parts with high resolution at lower costs, which gives a potential for industrial mass production. The process is done in powder bed, where joining of powder is done with binding agent to form a green part. This part is further processed by sintering and other post-processing technologies. The typical materials used are tungsten-carbide, tungsten, cobalt-chromium, steels, stainless steels, bronze and nickel based alloys for instance. Their main applications can be found in automotive industry, medical industry, precision engineering, production of prototypes, in arts and design [5–8].

2. ULTRASONIC AM (UAM)

Ultrasonic AM is based on ultrasonic welding of metals and sheet lamination process, where filler material in the form of sheets or tape is used for deposition. Joining of materials is achieved by relative motion between two sheets of metals under the action of force. This movement is producing friction between the contacting surfaces, which heats the materials from 35 to 50% of melting temperature and enabling cleaning of surfaces in contact, which produces sound metallurgical bond. Fig, 3 shows schematic illustration of ultrasonic weld formation during ultrasonic AM [10]. At the beginning after the contact between surfaces (Fig. 3-1) the compressive deformation of materials in contact occurs (Fig. 3-2), which produces heating of contacting surfaces and formation of micro-asperities on the top sheet surface (Fig. 3-3). Fig. 3-4 shows the early stage of welding between contacting sheets. In the next stage, bonding takes place (Fig. 3-5) with crushing of micro-asperities, shear deformation of materials and plastic flow of material, which leads to further temperature rise and expansion of welded area. In the last stage (Fig. 3-6) the weld interface is formed with interfacial and recrystallized microstructure [10].

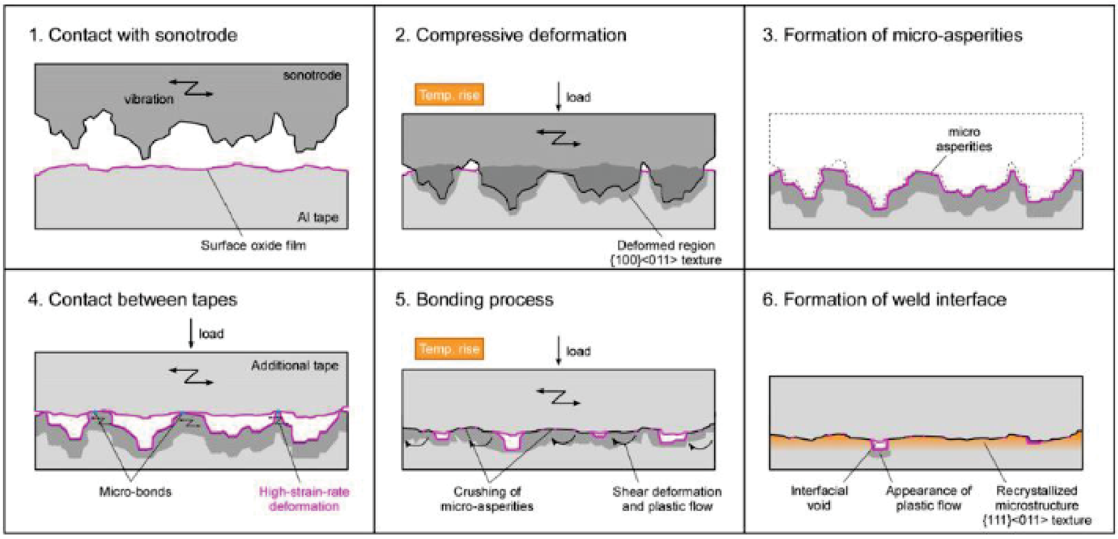

Fig 3. *Schematic illustration of ultrasonic weld formation during ultrasonic AM* [10]

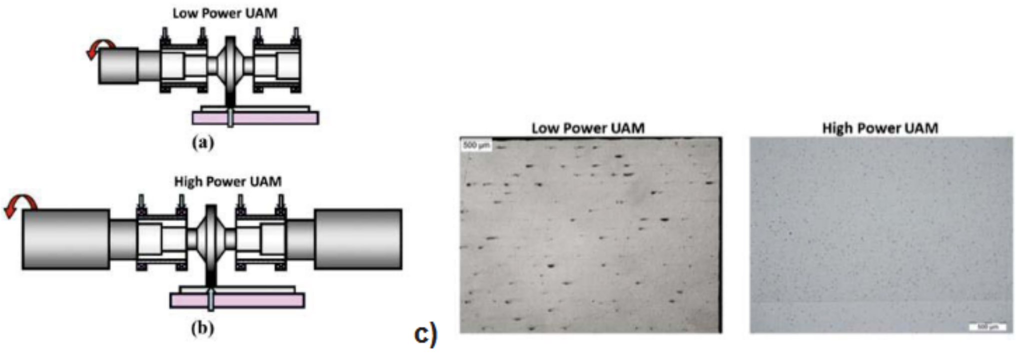

Fig 4. *Power designs used in UAM a) a low-power and b) a high-power additive stage.*
c) Macro sections showing comparison between Low and High Power UAM. [10]

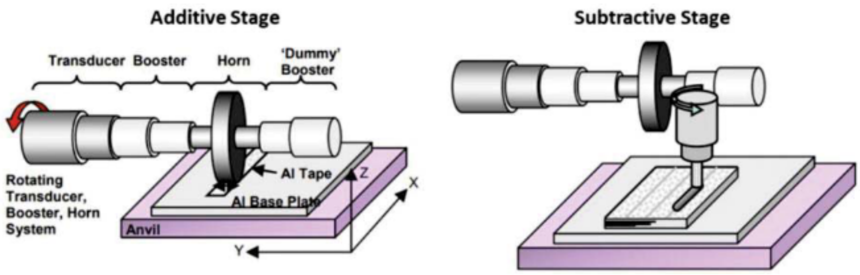

Fig 5. *Additive and subtractive stage during ultrasonic AM [10]*

During the process bottom sheet is fixed and filler sheet is usually moving at approx. 100 m amplitude and at ultrasonic frequency of 20kHz. The Fabrisonic Company is the pioneering company that brought this technology to market. Their Ultrasonic AM machine consists of CNC milling center equipped with ultrasonic sheet deposition stage. Two ultrasonic stages are available, a low-power and a high-power additive stage (Fig. 4). The high-power stage consists of second ultrasonic transducer with higher capacity, which improves the UAM tool amplitude and power levels. Additionally, higher forces can be applied during UAM, therefore improving the joining process during the UAM, thus remedying interfacial voids that may occur during low-power UAM (Fig. 4c).

Fig. 5 shows the process of UAM with two stages. At the additive stage the ultrasonic metal weld cladding is used to produce near-net-shape parts from similar or dissimilar materials. In the following subtractive stage, CNC milling is done to shape the features on part between the material deposition and to finalize the component geometry.

The main benefit of UAM is the possibility of joining similar and dissimilar materials. This enables production of multi-materials components and components with functionally graded properties. The key materials used in UAM are aluminum alloys, copper alloys, tantalum, tungsten, metal matrix composites and similar. Typical applications of UAM are the production of heat transfer devices, with smooth and accurate channel geometries, which are done in the subtractive stage. Multi-materials products that can be cladded can be used as protection laminates for electronic shielding in aerospace applications, like Satellite Radiation Shielding Solutions, for production of sensors for Aerospace Health Monitoring, to make transition joints, composite structures with particular properties and others (Fig. 6).

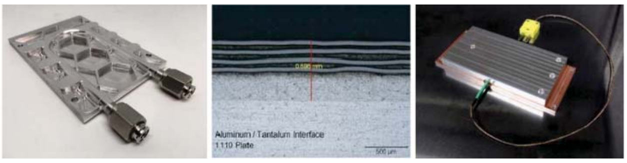

Fig 6. *Typical applications for UAM are a) heat exchangers, b) laminates for electronic shielding in aerospace applications, c) sensors [11]*

3. FRICTION BASED AM (FBAM)

Friction based additive manufacturing technologies can be divided into technologies that uses friction stir technologies or friction surfacing technologies. According to Fig. 7 we can distinguish friction stir AM by feeding a material in a) powder form or in b) rod feedstock. Friction stir AM can also be done as sheet lamination process (Fig. 7c), where sheets of similar or dissimilar materials are weld cladded sheet after sheet. A rotational frictional surfacing can be used for frictional AM (Fig. 7d). An additive composites with functionally graded variation of composition can be produced using a special technique of friction stir AM (Fig. 8) and Friction Stir Processing can be used for modification of deposited material, additively added by cold spray AM [12, 13].

During friction based AM the materials are deposited by thermo-mechanical stirring of a rotating tool to induce high temperature via severe plastic deformation. Stirring of materials during deposition of particular layer forms fully dense and homogenous structures, with refined microstructure. Such microstructure is without any fusion or solidification defects such as cracks, micro-voids and porosities. The process can be used on open-atmosphere and is not sensitive to the operating environment or material surface condition. Due to lower heat input during friction based AM the products has lower values of residual stress and distortion as compared to the fusion-based AM. Severe plastic deformation of compressed materials could produce superior and isotropic strength and ductility, as well as superplastic properties of materials. These processes enable higher deposition rates, while achieving lower products resolution and part geometric complexity. Friction based AM process are one step processes that does not require post-processing such as hot isostatic pressing (HIP) or sintering to improve the quality of the deposited material [13, 14].

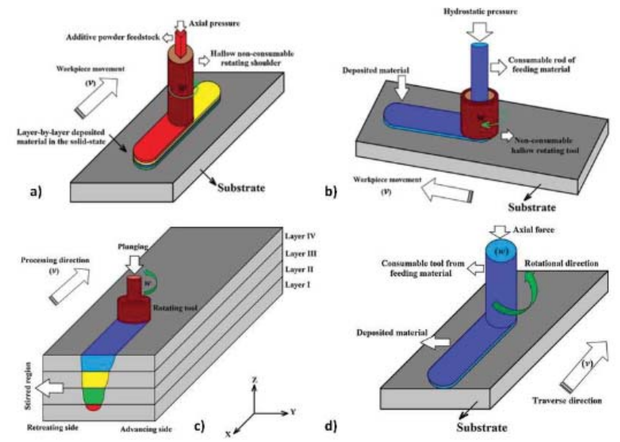

Fig 7. *Friction based additive manufacturing friction stir AM by feeding a) powder, b) rod feedstock, and c) as sheet lamination process and as d) rotational frictional surfacing AM [13]*

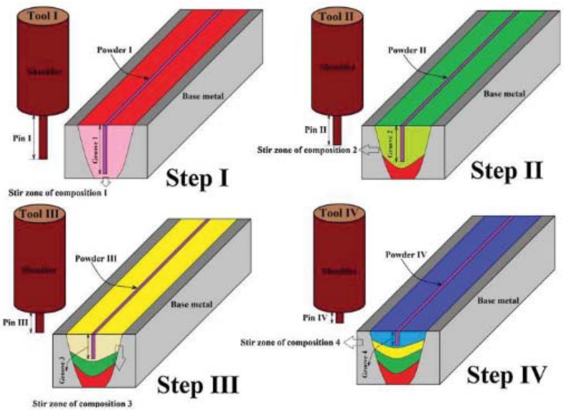

Fig. 8. *A special technique of friction stir AM for producing functionally graded material composites [13].*

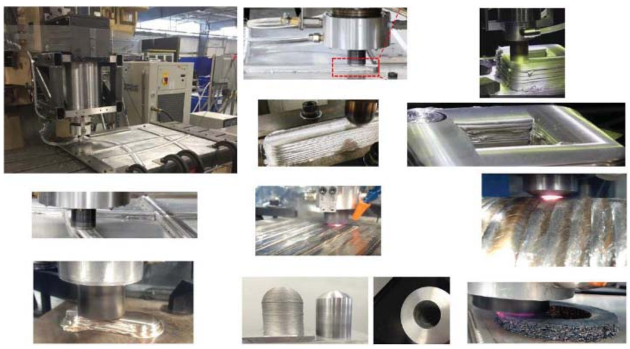

Fig. 9. *A few products made using friction stir AM by feeding materials* [13]

The key materials used in friction based AM are aluminum alloys, copper alloys, titanium alloys, magnesium alloys, stainless steels, mild steels and nickel based super alloys for instance. Typical capabilities of FBAM include additive manufacturing, coating applications, component repair, metal joining, custom metal alloy and metal matrix composite billet production and part fabrication (Fig.9). Component repair can be made of cast, wrought or forged materials. The process can make repairs of wear, cracks, or other applications where material must be replaced or removed.

4 RESISTANCE AM – JOULE PRINTING

A very favorable new technology that will soon be industrially available is "Joule Printing". The technology is a wire DED AM technology based on resistance welding technology i.e. "joule heating". Their advantages are lower energy consumption and low heat input (1.4 -1.6 Wh/cc), which heats the filler material up to mushy state by avoiding formation of the melt pool. The process enables production near-net-shape products, with high deposition speed (5 - 10 kg/hr), which is 2-10 times faster than DED-Powder and similar to DED-ARC, while the resolution is compared to DED-Powder [9]. Manufacturing can be done in demanding environments, with high material efficiency, using commercially available welding wires, while are the obtained material properties between wrought and cast metal [9]. The key materials that are used in Joule Printing are titanium alloys, tool steels (H13, P20), stainless steels, nickel based alloys, mild steel, copper alloys, aluminum alloys, refractory materials (Tantalum, Molybdenum, Niobium), precious materials (gold, platinum, palladium, silver), Zirconium, Hafnium. [15] Joule printing produces full strength, full density, near net shape parts from a big set of materials. With it, different tools can be manufactured from tool steels, dies with conformal cooling channels for shortening cycle time in die casting and injection molding (Fig. 10), multi-material parts, and parts with functionally graded materials.

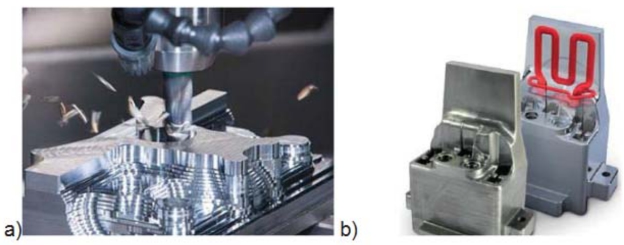

Fig. 10. *Examples of Joule printing: a) tools made of H13 tool steel and b) tools with conformal cooling channels [9]*

5. MATERIAL JETTING

Material Jetting uses one of the thermal spray methods to make parts layer by layer. The following thermal spraying processes are known: flame spraying (conventional with wire or powder, high velocity oxygen fuel, detonation-cladding, and cold gas spraying), plasma spraying, electric arc spraying and laser spraying. These processes are generally used as coating processes to improve wear resistance, thermal resistance and corrosion resistance. During particular process materials in wire or powder form are heated and accelerated to a high-velocities where upon the impact on a working surface deform and bond together creating a firmly adherent layer. Each of before mentioned technologies produces surface coatings with particular properties and with limited selection of materials. For additive manufacturing the Cold Spray technology is generally used. The Cold Spray AM is differentiated from all other metal AM process that it is a low temperature, solid state process at which there is no melting of the filler material. Their main advantages are in usage of heat-sensitive materials, possibility to deposit almost all metals and alloys, in possibility to join dissimilar materials, in high deposition rates (up to 20 kg/h), the process induces low thermal stresses, and it could be done in air environment. The process is environmentally friendly, since it has low energy consumption, produces no toxic particles and enables the production of multi-materials components. The challenges of the process are in smaller precision and resolution of the product, material embrittlement, due to residual stresses and in possible need of post processing. Cold Spray uses pressurized carrier gas to accelerate metal powders to high velocities and when colliding with the product surface, the high kinetic energy causes plastic deformation, creating mechanical interlocking and metallurgical bonding. The particles are heated up to 600 °C, but there is no melting of the material. Fig. 11 shows two main Cold Spray systems i.e. high and low-pressure. High-pressure can spray powder at higher velocities (800-1400 m/s) whereas a low-pressure at 300-600m/s. High pressure system enables the AM of heavier and less ductile materials like steels and titanium alloys, and uses low weight gases like nitrogen or helium. Low-pressure systems are used for processing of lighter and more ductile metals like aluminum and copper alloys, which can be processed in air. High-pressure systems are more complex and expensive to operate, but can achieve higher deposition rates in production. [16]

Depending of the size of the system medium to large size parts can be manufactured. For example, a Titomic's 3-axis gantry system is capable of printing parts up to 9 m x 3 m x 1.5 m. Deposition width varies between 3 – 20 mm and the deposition accuracy about ± 1 to 3 mm. The surface finish is 10 – 50 microns, which is similar as at sand casting. The key materials that are used for Cold Spraying are stainless steels, tool steels, cobalt alloys, aluminum alloys, magnesium alloys, titanium alloys, nickel-based alloys, copper alloys, brass, bronze, tin, zinc, precious metals, invar and beside them also metallic glasses, metal matrix composites and polymers. Material costs are about half the cost of PBF powder, 1.5 to 2 times of the price of the cost of wires and 3 to 4 times the costs of billet. In important cost presents also the carrier gas. Typical applications of Cold Spraying AM are in aerospace industry (propellant tank, trust chambers, combustion chambers, rocket nozzles, fan blades, gearboxes), tooling industry (casting, forming and stamping tools), electrical industry (permanent magnets for electric motors). A few sample applications of Cold Spray AM are shown on Fig. 12 and Fig. 13. For copper parts it was established that it can retain over 90 percent of the electrical and thermal conductivity of the raw material. [16].

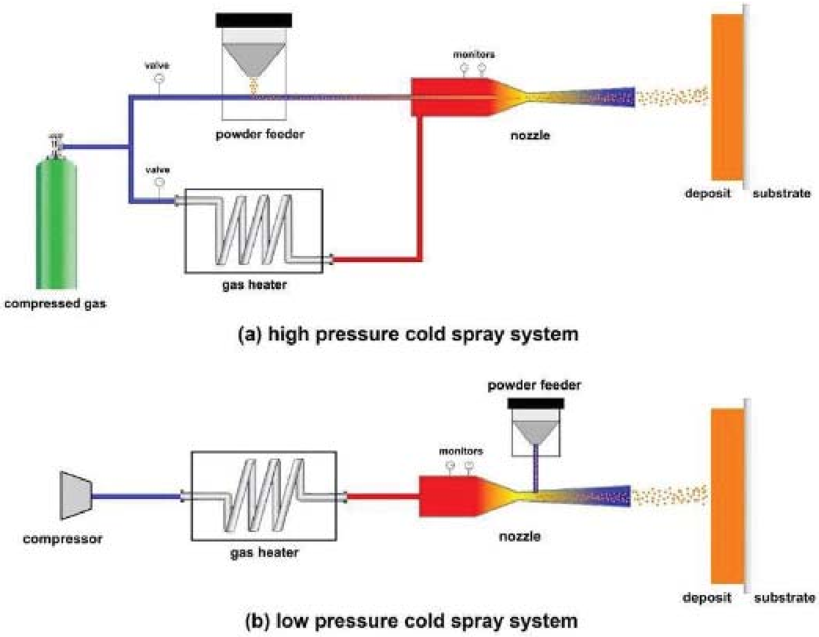

Fig. 11. *Cold Spray system a) high pressure and b) low pressure.* [16]

WAAM and other Unconventional Metal Additive Manufacturing Technologies 59 The key materials that are used for Cold Spraying are stainless steels, tool steels, cobalt alloys, aluminum alloys, magnesium alloys, titanium alloys, nickel-based alloys, copper alloys, brass, bronze, tin, zinc, precious metals, invar and beside them also metallic glasses, metal matrix composites and polymers. Material costs are about half the cost of PBF powder, 1.5 to 2 times of the price of the cost of wires and 3 to 4 times the costs of billet. In important cost presents also the carrier gas. Typical applications of Cold Spraying AM are in aerospace industry (propellant tank, trust chambers, combustion chambers, rocket nozzles, fan blades, gearboxes), tooling industry (casting, forming and stamping tools), electrical industry (permanent magnets for electric motors). A few sample applications of Cold Spray AM are shown on Fig. 12 and Fig. 13. For copper parts it was established that it can retain over 90 percent of the electrical and thermal conductivity of the raw material. [16]

6. WIRE ARC AM

6.1. *An overview*

WAAM is Direct Energy Deposition type of additive manufacturing technology. The process is defined by the combination of welding arc as a heat source and wire feedstock. The process does not have high precision deposition such as powder bed systems but does in fact allow for deposition with exceptionally high productivity. This is the mayor driving force for big interest in WAAM in academic and industrial environment [17]. Although Baker [18] presented the first patent for WAAM in 1926, the technology has not been recognized as a viable manufacturing technology until 1990s.

Fig. 12. *Spee3D Cold Spray a) copper printed and finished part and b) Aluminum 6061 Hydraulic Camlock and c) Hermle's multi-material component. [16]*

Fig. 13. *An example of component repair using Cold Spray AM. [16]*

In comparison to other conventional metal additive technologies is WAAM a highly cost-effective option due to low feedstock and capital cost. WAAM enables the production of medium to high scale metal components, theoretically even in unlimited size, which is proven by the stainless-steel MX3D bridge [19]. It has been applied in industries including aerospace, automotive and rapid tooling. Aerospace components often have complex geometries and are made of expensive materials, which suffer from low buy-to-fly ratio. The tooling industry uses additive manufacturing (AM) to produce functional tool components [20]. In addition, it enables manufacture of functionally graded materials, such as Fe-FeAl, as shown by Shen et al. [21]. One of the most common applications of WAAM is the manufacture of large thin-walled components, such as pressure vessels. For complex-shaped parts that are often used in the aerospace industry, machining is usually employed, but WAAM can be used instead to reduce the buy-to-fly ratio [22].

6.2 WAAM systems

WAAM technology is based on existing mature welding technologies and its' systems typically consist of a manipulator and a welding power source. Most common manipulators for WAAM are industrial robots and three or multiple-axis CNC machines (Fig. 14) [23]. For the largest scale deposition, industrial robots show great promise since they can be fitted on a linear track. Additionally, multiple robots can work on a single large component.

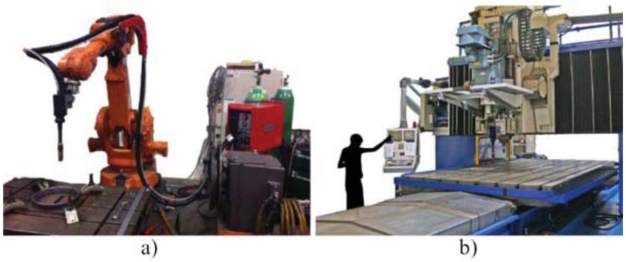

Fig. 14. *a) Robotic WAAM system and b) CNC WAAM system.*

Welding technologies that are used in WAAM are typically GMAW, GTAW and PAW. Each of these having a distinct set of benefits and drawbacks in respect to productivity, resolution and final material properties. GMAW process is the most common in WAAM. Productivity ranges from 1 kg/h to 9.5 kg/h, which was achieved with a twin wire system by Filomeno et al. [24]. This process is suitable for rapid manufacture of the largest components [17]. GTAW and PAW have a productivity from 0.5 kg/h to 2 kg/h, as shown by Martina et al. [25].

6.3 Process parameters and control

To obtain a defect free component, a set of process parameters must be controlled. The key process parameters are wire feed rate, travel speed, arc current and voltage, shielding gas flow rate and composition, deposition path strategy, preheating and inter-pass temperature [26]. The key elements in process control are linear heat input and heat conductivity of feedstock and base plate. They enable the control and prediction of cooling times, phase transitions, layer geometry and residual stresses and distortions [27]. To determine linear heat input in arc processes the arc current, voltage and travel speed must be monitored [28]. Fig. 15 shows three typical conditions that effect the heat transfer conditions in the component during the deposition. During the first layer deposition most of the input heat is conducted from the layer to the substrate. Two- or three-dimensional heat flux can be assumed, based on the substrate thickness. During tall thin wall deposition more heat is transferred to the environment through convection and radiation and smaller portion conducted to the substrate. Convection is usually natural although some authors have presented mechanisms for fast forced cooling of the component [29]. In addition to the radiation and convection, a portion of the heat is conducted to neighboring weld beads, during overlapping eld beads deposition. The cooling rate of the component after each deposited layer effects both the microstructure and layer geometry [27, 29]. Components built with WAAM show columnar grain growth, aligned transverse to the weld direction, shown in the Fig. 15. This is due to welding arc having a relatively low energy density which causes low heat gradients and low solidification rate [30]. The resulting anisotropic properties of the components should be accounted for in the component design phase or the components should be heat treated after the deposition.

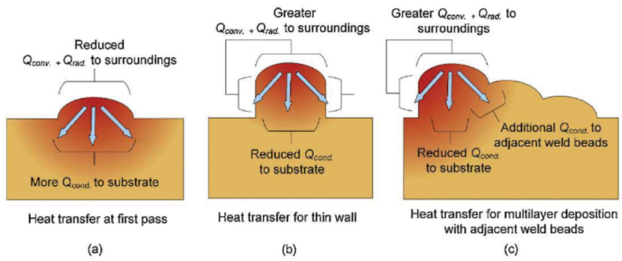

Fig. 15. *Schematic diagram of heat transfer modes: conduction (Qcond), convection (Qconv) and radiation (Qrad). Examples during a) first layer deposition, b) thin walls deposition and c) part with overlapping beads (adapted from [27]).*

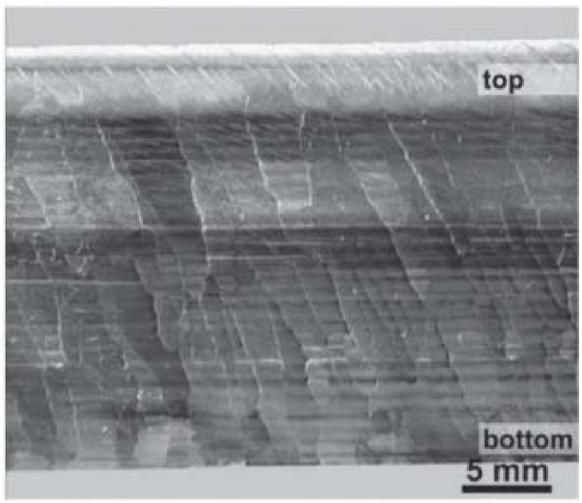

Fig. 16. *Columnar grain growth in TI-6Al-4V in WAAM component (adapted from [27])*

To improve the part accuracy and reduce the post process machining time, attention should be given to single layer geometry. A wide range of sensors can be used to determine a single bead height. In GTAW based WAAM an arc length controller can be successfully used to determine a weld bead height by monitoring arc current and voltage, as shown by Wang et al [31]. Temperature sensors have been successfully implemented in weld bead height and width monitoring applications by various authors [29, 32]. Lastly visual sensors have been widely used to monitor the surface defects and measure the geometrical deviation for feedback control. It has the advantages of rich information and high accuracy. The drawback of visual sensor is that the information in images may be blocked by the strong arc if the arc is not filtered out efficiently [33–35]. Additionally, structured light vision systems have been used to accurately monitor weld bead profiles [36–38].

7. CONCLUSIONS

The paper presents a short overview of unconventional additive manufacturing processes. Each of them possesses at least one unique properties that makes it beneficial for potential applications. The main advantage of ultrasonic AM, friction based AM and Material Jetting is the ability of making multi – material parts, since they enable solid state joining of dissimilar materials. Joule printing advantages are in high deposition speeds and relatively low cost production. WAAM enables production of medium to large structures with high deposition rates at affordable cost. All presented unconventional technologies has the ability to produce functionally graded materials and with that the possibility to reduce the use of Critical Raw Materials, sustainable products and reuse of components.

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