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Editorial

Additive Manufacturing of Metallic Components for Hard Coatings

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Metals additive manufacturing is a new concept of fabrication that consists of depositing material layer-by-layer in a very precise and automatized way. This manufacturing technique, also known as 3D printing, has the advantage of producing complex "customized" geometries according to each sector requirements [1].

Additive Manufacturing (AM) can reduce the number of intermediate fabrication steps in comparison with traditional manufacturing techniques. According to previous studies, components can be produced up to 80% faster with this technology. In addition, the fabrication of AM components does not generate waste, and for this reason, the parts have a lower cost (especially for expensive alloys and materials), and the manufacturing technique is more sustainable [2].

Large and important transport companies, such as Boeing and Ford, are pioneering the incorporation of additive manufacturing capabilities. Consequently, many large- and medium-sized companies have already started using metal AM to achieve a competitive advantage. In the coming years, it is projected that more industrial SMEs will adopt metal 3D printing to stay in the market. There are several providers in the Spanish market that offer various solutions for metal fabricators, such as Moebyus Machines, Leon3D or Triditive, among others. In the last two years, the growing number of suppliers has allowed the SMEs industry to invest in this technology since the benefits of AM are evident [3].

Advantages of additive manufacturing [4]:

- Time to market: Additive manufacturing allows projects to be developed faster than ever before. Printing a 3D design the same day that it is created reduces the development process that could take days or even months.
- Save cost: Injection molding machines for prototyping and its production processes are large investments. The AM process enables the creation of parts at a lower cost than traditional machining.
- Mitigate risk: This is the ability to verify a design before investing in a molding machine. It is much cheaper to 3D print a prototype than to redesign or modify an existing mold.
- Flexibility and creativity: This is the ability to develop ideas and quickly discover what is not working. This accelerates the R&D process and leads to an ideal solution. AM also allows an engineer or "product manager" to make rapid advances in the initial stages of product development, working under the motto, "trial and error".

Some experts even mention the Fourth Industrial Revolution, which could benefit different economic sectors. Although its market share is still small, the forecast for upward growth is practically incalculable [3].

Potential applications of additive manufacturing include aerospace, defense, or automotive materials. Elements for the medical sector and a variety of consumer goods, such as instruments or electronic devices, can also be produced. The freedom of design and production is very broad, and it is expected to be extended to many more industries and sectors in the future [5–7].

Currently, three technologies have been earmarked for hard materials additive manufacturing: Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Direct Energy Deposition (DED) [8].

Selective Laser Melting (SLM): This additive manufacturing technique consists of the deposition of a thin layer of powder (generally metallic powder) in a container. Once this powder layer is deposited, a laser beam melts previously selected areas that quickly solidify. Then, the powder container moves down so that a new layer of powder can be deposited at the top. This process is repeated as necessary until the desired geometry is achieved. The most commonly used metals in SLM systems are steels and titanium alloys, although nickel and aluminum components have been also fabricated by SLM. These raw materials must be spherical, which restricts the number of times they can be used. SLM-manufactured components usually have high density; however, the porosity level depends on the SLM equipment used. The greatest advantage of this manufacturing process is its capability to manufacture components with geometries close to the initial design [9].

- Electron Beam Melting (EBM): This process is based on the layer-by-layer deposition of metal spherical powder that has been selectively melted by the controlled incidence of irradiation from an electron beam as energy source. The process takes place in a closed vacuum container, allowing the additive manufacturing of materials with a strong oxygen affinity, for example, titanium alloys. In addition, this technique is advantageous since the use of additional inert gases and subsequent thermal treatments are not necessary. This is because the raw material and container have previously been heated during the process. The raw materials used are mainly spherical metal powder, and the typical alloys used are cobalt, nickel, or titanium. Furthermore, in situ metal matrix composites can be obtained by an in situ reaction. Currently, the additive manufacturing of cements or ceramics components using this technique is emerging. The density of the samples fabricated with EBM is higher than for SLM samples due to the higher energy density of the electron beam in comparison with the laser beams of SLM. However, the precision and surface finishing of the EBM manufactured components are worse than in SLM [10].
- Direct Energy Deposition (DED), also called laser cladding: In this process, a raw powder material is sprayed and directly melted on the substrate surface or the previous deposited layers with a minimal dilution. During this fabrication, only a thin layer of the substrate (or the previous deposited layers) is melted, obtaining a layer thickness around 50 µm and 2 mm. This continuous layer-by-layer deposition results in a coating fabrication process, and consecutive layer-by-layer deposition results in an additive manufacturing process. In the initial stages of the development of direct energy deposition, the samples are mainly used to improve the component characteristics or already manufactured materials or to restore their components. In addition, this process can also be used as a complement to other manufacturing technologies to solve porosity problems, thermal distortion or manufacturing difficulties in small, localized areas. In addition, this system can eliminate errors that may occur in other additive techniques. However, one of the most important differences compared to other additive manufacturing techniques is the possibility of using non-spherical raw material. This raw material can be metallic or ceramic, and since most ceramic powders have no spherical shape, this makes it possible to manufacture metal matrix composites or inclusive cement components [11].

Metal matrix composites and cements can be considered hardmetals due to their high hardness, strength and toughness. These hardmetals are generally used in aeronautic, automotive or machine tooling sectors as hard coatings to obtain components with a high wear or corrosion resistance [12].

Hardmetals have become an important part of modern industrial development. In the 1920s, they were applied for the first time as wire drawings, and since then, the variety of applications has only broadened, e.g., metal cutting or the fabrication of aluminum cans.

Moreover, hardmetals are used to make several tools utilized in the mining, gas, oil and forming industries.

However, traditional hard materials manufacturing involves a lot of fabrication problems; for instance, titanium machining tools suffer deformation and wear damage due to the low thermal conductivity of the titanium alloys, which prevents the correct dissipation of the generated heat during the processes. The higher chemical reactivity of the titanium alloys causes the chips, formed during the tooling process, to easily weld to the tool surfaces, which results in an increment in the edge-holding size. For this reason, 3D additive manufacturing can be a good alternative for tool manufacturing [13,14].

Traditionally, standard powder metallurgy is used to fabricate hardmetal parts, where the created green parts present 55% of theoretical density (TD), which can reach up to 100% TD when sintered in inert atmospheres under vacuum. Powder Injection Molding (PIM) allows complex parts to be produced, such as cylindrical shapes by extrusion, whereas simple traditional parts, such as cutting inserts or dies, are made by uniaxial pressing. Although the fabrication of cooling channels for drills and milling cutters is possible, the complexity of the internal morphologies and outer geometries of the tools can only be reached with a long process of green machining and finishing [15].

Powder metallurgy also involves issues, for example, the evaporation of the metallic binder at high temperatures. Hardmetals sintering occurs above the eutectic temperature (1310 °C) within the W-C-Co system (liquid phase sintering). If the temperature further increases, the liquid phase also increases since more C and W can be dissolved within Co; nevertheless, an evaporation of the metallic binder can also take place. If temperature continues going up (above 2800 °C), the decomposition of WC into W2C and C can disintegrate the tungsten carbide, which is the hard phase. Furthermore, safety procedures specify that cobalt is a Cancerogenic Mutagen Reprotoxic (CMR) material; therefore, special requirements are necessary to handle this material [16–18].

In recent times, other strategies have been researched in order to avoid the fabrication problems of hardmetals. Hard coatings can be manufactured on the surface of components to obtain hardening surfaces with a high wear resistance, maintaining the advantages of fabricating softer materials. Some techniques, such as physical and chemical vapor deposition, have been successfully used to manufacture these coatings with ceramics, cements or metal matrix composites [19]. However, laser cladding or laser electron beam techniques are more versatile in manufacturing complex components of Ti, Fe or Ni alloys [20]. One advantage of the additive manufacturing of coatings is the possibility of manufacturing the component and the coating with dissimilar materials in a single step. Currently, some traditional coatings manufacturing techniques have been used for additive manufacture components, for example: thermal spray, HVOF, cold spray or friction stir deposition [21]. In this way, coating deposition methods, such as cold spray, have recently been applied to additive manufacturing, as well as in its conventional mass production of high-quality metals, alloys and metal matrix composites (MMCs) coatings [22]. Additive Friction Stir Deposition (AFSD) is another solid-state AM process in which the feed material is thermally treated and deformed to enable its deposition, leading to wrought-like mechanical properties and microstructures in the as-printed state [23]. However, in all cases, the amount of materials that can be used for additive manufacturing is small, and the development of these techniques is still emerging.

Even though hardmetals are of high interest for their possible applications in AM processes, it is remarkable that they were included in the very early tests performed by Zong at UT Austin in 1992 [24] using PBF. These materials were studied for AM applications, with the conclusion that it was quite complex to utilize them. Currently, the additive manufacturing of hardmetals is achieving promising results; however, extensive research on this topic remains necessary.

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References

1. Herzog, D.; Seyda, V.; Wycisk, E.; Emmelmann, C. Additive Manufacturing of Metals. *Acta Mater.* **2016**, *117*, 371–392. [CrossRef]
2. Ngo, T.D.; Kashani, A.; Imbalzano, G.; Nguyen, K.T.Q.; Hui, D. Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges. *Compos. Part B Eng.* **2018**, *143*, 172–196. [CrossRef]
3. Hernandez Korner, M.E.; Lambán, M.P.; Albajez, J.A.; Santolaria, J.; Ng Corrales, L.D.C.; Royo, J. Systematic Literature Review: Integration of Additive Manufacturing and Industry 4.0. *Metals* **2020**, *10*, 1061. [CrossRef]
4. Attaran, M. The Rise of 3-D Printing: The Advantages of Additive Manufacturing over Traditional Manufacturing. *Bus. Horiz.* **2017**, *60*, 677–688. [CrossRef]
5. Sacco, E.; Moon, S.K. Additive Manufacturing for Space: Status and Promises. *Int. J. Adv. Manuf. Technol.* **2019**, *105*, 4123–4146. [CrossRef]
6. Delic, M.; Eyers, D.R. The Effect of Additive Manufacturing Adoption on Supply Chain Flexibility and Performance: An Empirical Analysis from the Automotive Industry. *Int. J. Prod. Econ.* **2020**, *228*, 107689. [CrossRef]
7. Vasco, J.C. Chapter 16-Additive Manufacturing for the Automotive Industry. In *Handbooks in Advanced Manufacturing*; Pou, J., Riveiro, A., Davim, J.P.B.T.-A.M., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 505–530. ISBN 978-0-12-818411-0.
8. Gokuldoss, P.K.; Kolla, S.; Eckert, J. Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting—Selection Guidelines. *Materials* **2017**, *10*, 672. [CrossRef]
9. Yap, C.Y.; Chua, C.K.; Dong, Z.L.; Liu, Z.H.; Zhang, D.Q.; Loh, L.E.; Sing, S.L. Review of Selective Laser Melting: Materials and Applications. *Appl. Phys. Rev.* **2015**, *2*, 041101. [CrossRef]
10. Körner, C. Additive Manufacturing of Metallic Components by Selective Electron Beam Melting-A Review. *Int. Mater. Rev.* **2016**, *61*, 361–377. [CrossRef]
11. Thompson, S.M.; Bian, L.; Shamsaei, N.; Yadollahi, A. An Overview of Direct Laser Deposition for Additive Manufacturing; Part I: Transport Phenomena, Modeling and Diagnostics. *Addit. Manuf.* **2015**, *8*, 36–62. [CrossRef]
12. Leal, R.; Barreiros, F.M.; Alves, L.; Romeiro, F.; Vasco, J.C.; Santos, M.; Marto, C. Additive Manufacturing Tooling for the Automotive Industry. *Int. J. Adv. Manuf. Technol.* **2017**, *92*, 1671–1676. [CrossRef]
13. Sousa, V.F.C.; Silva, F.J.G. Recent Advances in Turning Processes Using Coated Tools—A Comprehensive Review. *Metals* **2020**, *10*, 170. [CrossRef]
14. Llanto, J.M.; Tolouei-Rad, M.; Vafadar, A.; Aamir, M. Recent Progress Trend on Abrasive Waterjet Cutting of Metallic Materials: A Review. *Appl. Sci.* **2021**, *11*, 3344. [CrossRef]
15. Akhtar, S.; Saad, M.; Misbah, M.R.; Sati, M.C. Recent Advancements in Powder Metallurgy: A Review. *Mater. Today Proc.* **2018**, *5*, 18649–18655. [CrossRef]
16. Processing of cemented carbides with compositional gradients by powder metallurgy: C. Colin et al (Catholic University of Louvain-la-Neuve, Belgium), *Int. J. Refractory Metals & Hard Materials*, Volume 12, No 3, 1993–1994, 145–152. *Met. Powder Rep.* **1994**, *49*, 63–64. [CrossRef]
17. Konyashin, I.; Hinners, H.; Ries, B.; Kirchner, A.; Klöden, B.; Kieback, B.; Nilen, R.W.N.; Sidorenko, D. Additive Manufacturing of WC-13%Co by Selective Electron Beam Melting: Achievements and Challenges. *Int. J. Refract. Met. Hard Mater.* **2019**, *84*, 105028. [CrossRef]
18. Yang, Y.; Zhang, C.; Wang, D.; Nie, L.; Wellmann, D.; Tian, Y. Additive Manufacturing of WC-Co Hardmetals: A Review. *Int. J. Adv. Manuf. Technol.* **2020**, *108*, 1653–1673. [CrossRef]
19. Schalk, N.; Tkadletz, M.; Mitterer, C. Hard Coatings for Cutting Applications: Physical vs. Chemical Vapor Deposition and Future Challenges for the Coatings Community. *Surf. Coatings Technol.* **2022**, *429*, 127949. [CrossRef]
20. Kumar Das, A. Recent advancements in nanocomposite coating manufactured by laser cladding and alloying Technique: A critical review. *Mater. Today Proc.* **2022**, *57*, 1852–1857. [CrossRef]
21. Albaladejo-Fuentes, V.; Martos, A.M.; Silvello, A.; Dosta, S.; Sanchez, J.; Cano, I.G. Coatings, Surface Modifications, Spray Techniques (Cold Spray, HVOF/HVAF). *Encycl. Mater. Met. Alloy.* **2022**, *3*, 451–464. [CrossRef]
22. Li, W.; Yang, K.; Yin, S.; Yang, X.; Xu, Y.; Lupoi, R. Solid-state additive manufacturing and repairing by cold spraying: A review. *J. Mater. Sci. Technol.* **2018**, *34*, 440–457. [CrossRef]
23. Griffiths, R.J.; Garcia, D.; Song, J.; Vasudevan, V.K.; Steiner, M.A.; Cai, W.; Yu, H.Z. Solid-state additive manufacturing of aluminum and copper using additive friction stir deposition: Process-microstructure linkages. *Materialia* **2020**, *15*, 100967. [CrossRef]
24. Zong, G.; Wu, Y.; Tran, N.; Lee, I.; Bourell, D.L.; Beaman, J.J.; Marcus, H.L. Direct Selective Laser Sintering of High Temperature Materials. *Proc. Solid Free. Fabr. Symp.* **1992**, 72–85.