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Feasibility Study of an Extrusion-based Direct Metal Additive Manufacturing Technique

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Abstract
A new extrusion-based additive manufacturing technique is described in this paper together with the main components of the machine capable of carrying out the process. Innovative characteristics of the machine are the fixed extrusion head and the workpiece moving thanks to a 5-axis parallel kinematics handling system, allowing the capability of inclining the part during the material deposition and consequently avoiding support structures. The extrusion head and nozzle have been designed in order to be able to extrude high viscosity mixtures with low polymeric content. Preliminary tests prove that a good final density can be obtained after de-binding and sintering and that it is possible to achieve a good bonding of extruded and deposited wires in case of AISI 630 stainless steel.

Keywords: Direct metal deposition, Fused deposition modeling, Metal injection molding, Parallel kinematics

1 Introduction

This paper describes the feasibility study of a new additive manufacturing (AM) technique based on extrusion of a feedstock made of metallic (or ceramic) particles and a polymeric binder. After the analysis of the state of the art in the significant additive manufacturing field and a description of the main parts composing the designed machine, some preliminary tests are presented on one of the most critical issues of this new process, which is the feasibility of a continuous link among the extruded and deposited wires. Also other considerations are drawn on the suitable nozzle design and on the achievable material density after sintering.

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2 State of the art

The proposed technology makes part of the so called “Direct-metal techniques” that can be classified as “Laminated manufacturing”, “Powder bed processes” and “Deposition processes” (Karunakaran, 2012). Laminated manufacturing is the simplest additive method, but requires bonding of a stack of planar metal sheets (Himmer, 1999). Joining methods such as adhesive bonding, brazing, ultrasonic welding and diffusion bonding could be used, but any of these methods requires long processing times for each layer making the technology only suited for objects with relatively thick layers.

A powder bed fusion technology is a layered manufacturing process where each layer is made by first spreading a uniform layer of powder inside a container and then joining the particles of the layer that will be part of the workpiece using the motion of a tool along a programmed 2D trajectory. This tool may be a laser beam (SLS, Selective Laser Sintering) (Roppenecker, 2012) (Agarwala, 1995), an electron beam (EB) (Gong, 2012), or another source of energy. Electron beam melting (EBM) and selective laser melting (SLM) (Murr, 2009) are nowadays preferred to sintering processes because of the superior mechanical properties of the manufactured parts.

Binder jetting is a class of binder based powder bed processes (Lipson, 2005), (Williams, 2011). Among the powder bed technologies, binder jetting is quite fast and the least expensive. One limitation of binder jetting for metals is the maximum achievable relative density. In a very recent work on binder jetting of copper (Bai and Williams, 2015), a maximum relative density of 86% has been obtained with a fine powder granulometry (15 μm), but typical values are well below 80%.

Directed energy deposition processes allow to avoid the inherent inconvenience and the encumbrance of handling a powder bed. As for powder bed technologies, a source of energy such as a laser beam (Armillotta, 2013), an electron beam (Jamshidinia, 2012) or an electric arc (Anzalone, 2013) can be used. In these cases, the powder is injected through a coaxial nozzle over the manufactured object, which progressively grows, layer by layer. A less expensive, simpler and very popular deposition technology is extrusion, frequently called Fused Deposition Modeling (FDM). In this process, a filament is extruded through a nozzle. The filament, usually made of plastics, is fed to the nozzle by means of a controlled torque and pinch system.

Material extrusion (or FDM) is the most popular deposition process for plastic objects, but can hardly be used for advanced ceramics or metals. A recent review of extrusion based AM is given by (Turner, 2014). Intense research is being developed worldwide in order to increase the applicability of material extrusion AM through the development of new materials (Roberson, 2015). Some authors have proposed the original FDM system for depositing a precursor filament of green ceramic (Jafari, 2013) or a mixed metal/plastic filament (Masood, 2004). When the percentage of ceramic component in the mixture is small, compared to the polymeric component, conventional FDM machines can be used (Kalita, 2003). However, some limitations are typical of this process: the advantage of using a precursor filament is balanced by problems during its preparation and fabrication. The frequent buckling failures during the extrusion phase cause the process interruption The backpressure encountered during the deposition limits the powder volume fraction in the filament, reducing the possibility of successful sintering of the produced part. Due to these problems, the FDM concept has been transformed by some authors, using a ceramic clay or a metal slurry as a starting material (Li, 2006) instead of a plastic filament and replacing the torque and pinch system with a piston or screw injector (Bellini, 2005) (Li, 2010). However, the use of a melt loaded with metal or ceramic particles still has some limitations, especially in terms of the minimum diameter of the extrusion nozzle. According to the Hagen–Poiseuille equation, a minor decrease in nozzle diameter dramatically decreases the flow rate and requires considerably greater pressures to extrude the particle filled polymer melt. For very small nozzle diameters and for viscous feedstock (with low binder percentage, less than 25%), even a complete nozzle clogging can be expected, due to particle agglomeration (Lewis et al., 2006). The extrusion head can be powered up, but this solution would increase its weight