The role of wire-based Additive Manufacturing processes in the 6Rs sustainability framework

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The role of wire-based Additive Manufacturing processes in the 6*R*s sustainability framework

By

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Abstract

In recent decades, industrial development has led to significant social, economic, and environmental impacts, including the intensive consumption of natural resources and energy, and their associated greenhouse gas (GHG) emissions, particularly in the manufacturing sector. Additionally, increased rates of products turnover have increased trash generation rates correspondingly, necessitating a rethinking of the idea of waste and, more broadly, of the end of a product's life. To solve these issues, it is vital to evaluate the product's entire life cycle instead of exclusively considering the unit-process level, and to prolong product life via value restoration, thereby closing the loop in accordance with the Circular Economy principles.

The '6*R*s' sustainability framework, including *Recover*, *Reduce*, *Reuse*, *Remanufacture*, *Recycle*, and *Redesign,* contributes to improve a product's sustainability. Additive manufacturing (AM), owing to its dual 'digital' and 'additive' nature, is critical within this '6*R*s' sustainability paradigm. AM is a broad term that refers to several advanced manufacturing methods that enable the production of a variety of free-form components, by selectively depositing material in layers. It enables the production of high-value end-use parts as well as the extension of a product's useful life and durability via (*i*) component's repair and (*ii*) fabrication of spare parts, which may be customized or made on-demand, even in a decentralized manufacturing context. Among the various AM techniques, this thesis focuses on those processes relying on the deposition of molten metal wire by means of a heat source (such as a laser, an arc, or an electron beam), which enable the rapid production of components with a low-to-medium level of geometrical complexity and medium-to-large dimensions.

The present study is aimed at evaluating Metal Wire Deposition (MWD) processes through economic, environmental, and technological perspectives. Initially, the unit-process efficiency was assessed by varying process parameters and considering both laser- and arc-based heat sources.

Thereafter, the assessment broadened towards 'cradle-to-gate' boundaries. Therefore, material production modelling was added from both primary and secondary feedstocks, as well as the post-process machining operations, since the poor obtainable surface finishing makes this step necessary for MWD processes. Integrated additive-subtractive and pure subtractive manufacturing approaches were compared while involving components produced with diverse materials. To compare the two approaches, high-resolution maps relying on inputs from a multi-criterion analysis was defined to select the optimum manufacturing approach based on metrics as CO_2 emissions, energy consumption, costs, and productivity. The primary goal was to provide predictive tools and models

involving metrics concerning emissions, energy, productivity, and costs, in order to identify the most preferable manufacturing approach as a function of the component to produce.

Afterwards, the research broadened outside of the ‘production plant’s gate’ by assessing two scenarios at the end of a product’s life, namely *Remanufacturing* through *Repair* (via a hybrid processing system including MWD coupled with machining), and *Recycling*, then discussing the benefits associated with each.

Results showed that achieving reductions in material waste and buy-to-fly ratios can render MWD processes quite attractive in terms of minimizing environmental impact. Furthermore, resource and energy consumption, along with its associated CO_2 emissions, also stand to be substantially reduced. The productivity, in terms of manufacturing time, and the costs, are contrarily strongly dependent on a given part’s size and geometry. Lastly, application of additive manufacturing for extending products’ life via *Repair* could drive the implementation of Circular Economy principles. In terms of a case study, reductions potentials for both CO_2 emissions and energy consumption were quantified, particularly when compared with a scenario whereby a damaged component is interchanged with a brand new one machined from a workpiece. After evaluating of a multiple-repair scenario, accounting for shorter lifespans of the repaired component, the afore-mentioned potentials for benefits proved to be strongly amplified.