Strategic Action Line LI5: Innovative Production Processes

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Abstract The objective of this chapter is to describe the strategic action line related to innovative production processes (LI5). In particular, this chapter proposes research and innovation priorities across various aspects both related to conventional and non-conventional processes, such as: digitization of conventional production processes in order to improve their interactions and handle different types of processing, even by means of hybrid processes; the growing role of additive manufacturing and its ensuing challenges in terms of both design and production; processing of standard and innovative materials, or materials with meso/macro geometries, including also nano- and micro-manufacturing. In addition, process innovation also needs to take the shape of innovation in support of re- and de-manufacturing processes, to start with, through to the development of bio-inspired transformation models.

Keywords Smart materials · Bio-intelligent manufacturing · Consolidated manufacturing · Micro-nano processes · Additive manufacturing

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1 Introduction

Manufacturing processes must be the focus of innovation in manufacturing, since they influence the competitiveness of the country-system and provide capital assets for the domestic market or for exportation. This improves global performance in terms of efficiency, sustainability, reconfiguration, flexibility and resilience.

In particular, Italy should become a leader in building manufacturing facilities to be able to address various types of needs, including: management of a large variety of products at different stages of the life cycle; regeneration, reuse, repair of products, components, materials; increase in process efficiency to manufacture high-value and highly complex products.

Research and innovation to promote the digitization of consolidated manufacturing processes have come to the forefront in recent years, but there is still scope for further developments, as consolidated processes continue to represent a large portion of manufacturing processes as a whole.

At the same time, it is essential to study the development of innovative processes with a view adapting them to industrial contexts and improving the interactions that make different types of processes (hybrid processes) manageable. These improvements should focus on a manufacturing system that processes both standard and innovative materials, as well as meso/macro geometries even on a nano or micro scale. Process innovation has always focused on transformation processes for production, and should now support first of all re- and de-manufacturing processes, and the development of transformation models inspired by biological systems.

Against this background, this strategic action line aims to define research and innovation priorities for the development of innovative manufacturing processes that can help the manufacturing system implement the necessary transformation to meet the social and technological challenges illustrated below (Fig. 1):

Process innovation: in order to remain competitive, conventional processes will need to implement digital transformation in combination with technological improvement. This involves adopting systems that can develop solutions to improve productivity, flexibility and sustainability, including through real time process control solutions and process management by way of adaptive control systems. In the short term, these technologies will be just marginally replaced by alternative technologies, as they achieve high surface finishes and geometric accuracy. However, the growing demand for increasingly complex products with lower production volumes is leading to the development of unconventional technologies such as Additive Manufacturing, laser, micromachining, electro -physical and chemical processes and innovative assembly processes, as well as hybrid processes consisting in a combination with traditional technologies, which needs to overcome lead times, volume and cost limits in order to compete in terms of efficiency with traditional processes.

Materials innovation: innovation in materials should be geared towards greater durability, environmental sustainability, possible reuse/recycling, zero/low CO2 emissions. Manufacturing processes should produce and use these innovative materials in typically industrial volumes and time. The concept of generative design is

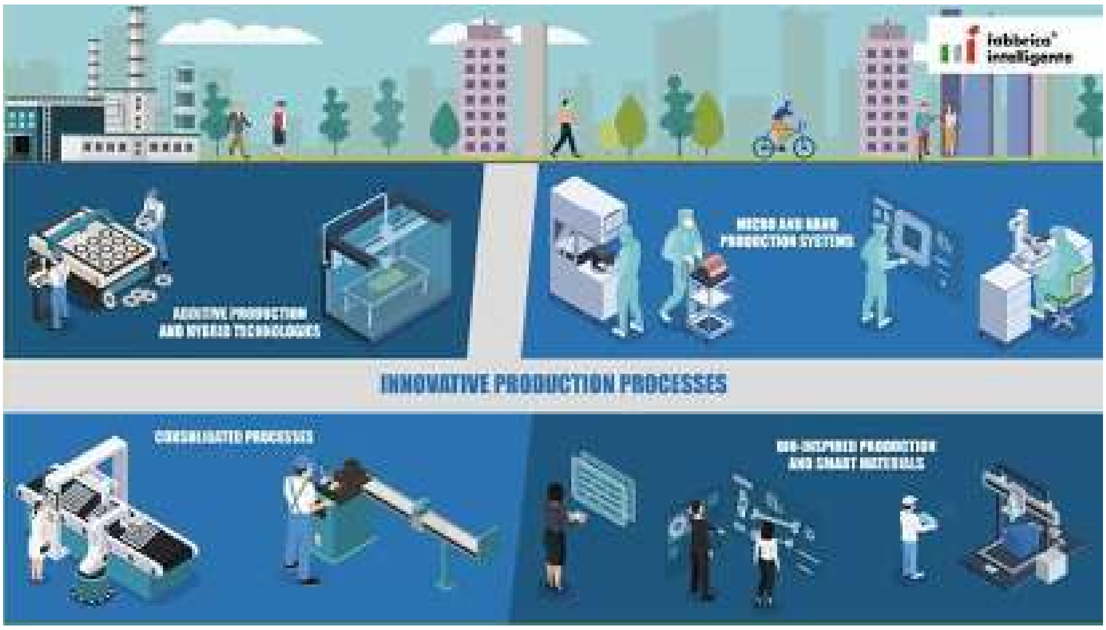

Fig. 1 Strategic Action Line 5—Innovative production processses

also important. Generative design involves the integration of the properties of these materials in the manufacturing cycle of a component right from the design stage, by developing databases and software tools that include material, process, product performance and life cycle modifications to enhance the advanced modeling and characterization tools of the manufacturing process.

New production paradigms such as biological transformation: a new concept of manufacturing inspired by biological systems found in nature is currently spreading at European level (Byrne et al., 2018). Biological and bio-inspired principles, materials, functions, structures and resources are expected to be increasingly used and integrated in manufacturing, in order to obtain intelligent and sustainable technologies and manufacturing systems (Cainelli et al., 2020).

Four research priorities have been dedicated to the first paradigm. They focus on the innovation of consolidated processes, processes for additive manufacturing, hybrid processes and micro processes. Distinct research priorities have been dedicated to the second and third paradigms, which are in fact cross-topical.

Expected impact: innovation of conventional and non-conventional processes; reduction and reuse of waste materials through innovative processes; increased flexibility and resilience of manufacturing processes; increased performance in terms of volume of work and productivity of innovative processes; reduction of energy consumption; redesign of the manufacturing cycle of a component based on the choice of new materials, new geometries and new manufacturing processes; integration between consolidated and innovative manufacturing processes, improvement of the tools necessary for the simulation of manufacturing processes; reduction of set up and cycle times with shorter time-to-market; improvement of manufacturing processes' sustainability.

The research and innovation priorities of the strategic action line on Innnovation Production Processes are:

PRI5.1.—Technologies, processes and materials for additive manufacturing
PRI5.2.—Bio-inspired technologies and manufacturing processes
PRI5.3.—Innovation of consolidated manufacturing processes
PRI5.4.—Manufacturing processes through hybrid technologies
PRI5.5.—Manufacturing and processing of innovative materials
PRI5.6.—Processes, products and functionalities on a micro scale

2 PRI5.1 Technologies, Processes and Materials for Additive Manufacturing

On a domestic front, Additive Manufacturing (AM) has been recognized as one of the enabling technologies of the Industry 4.0 plan defined by the Minister of Economic Development, because of the benefits it offers in terms of strategic aspects such as design digitalization, supply chain transformation and high flexibility and freedom in the manufacturing of high-value innovative products. In addition, there is a growing interest on the part of domestic, European and international industry for the development of AM technologies to manufacture metal components and components reinforced with polymeric matrix fibers. In these areas there has been a rapid and important technological development from systems limited to rapid prototyping, to systems that can support small series manufacturing of functional components and final parts.

Despite its robust growth (SmarTech Analysis estimated in 2019 a global additive manufacturing market grow over 10.4 billion dollars) AM is still not fully mature to be implemented in a manufacturing system due to its yet limited manufacturing times and volumes. In particular, the most consolidated processes for manufacturing metal parts (PBF—Powder Bed Fusion and DED—Direct Energy Deposition) are still showing considerable limits in terms of time, printable materials, high defect rate and eecomplex post process operations for the removal of supports, as mentioned by Gartner Hype Cycle 2019, which places these processes in the "Sliding into the Trough" phase. As it is mainly achieved through Material Extrusion processes, also the manufacturing of reinforced components experiences high lead times and the deposition of customizable fibers only on the plane orthogonal to the printing direction. Finally, it should be stressed that, out of habit, the geometry of a component is still currently designed in accordance with traditional processes' rules, without a full exploitation of AM's intrinsic ability to manage complex geometric shapes.

For AM to become an industrially viable technology, the research and innovation priority should set the following goals:

- **New design rules**: make the most of the AM design potential by combining the concepts of generative design, topological optimization, conformal geometries, meta and multi materials, hierarchical and functional complexity using numerical modeling software to test their performance.

- **Simulation of AM processes**: develop software to predict, correct and manage printed parts. The creation of digital twins using exceptional software tools will play an important role in reducing risks when printing parts from prototype to manufacturing. This software should make it possible to simulate the individual manufacturing process of a component and the MES (Manufacturing Execution System) that is essential to control and rationalize the AM workflows of medium/large manufacturing batches.
- **Innovative systems for AM**: new AM solutions to increase work volume and/or productivity, thus ensuring the manufacturing of at least 10,000 pieces/year. Development of innovative post-process treatments. Development of innovative solutions for in-process monitoring and control and for post-process inspection and quality control.
- **Solutions for metal AM**: new solutions for the manufacturing of complex shape metal components. These solutions should not be constrained by the geometric limits and available materials that typically affect powder bed processes.
- **Solutions for Multi-material AM**: new materials, solutions, software and machining strategies for the creation of components built according to criteria of continuous and discontinuous functionally graded materials.
- **Solutions for composite AM**: exploit the potential of AM composite materials, solutions to make manipulation of fiber alignments possible at unprecedented levels.
- **AM solutions for new industrial sectors**: based on the capacity of AM technology, study and develop solutions for entry into new industrial sectors such as clothing and footwear, oil & gas, pharmaceuticals etc.
- **Sustainable AM**: new solutions to improve process sustainability, recover and optimize specific materials such as plastic and in general all materials resulting from other manufacturing processes (second life material).

The expected benefits will be considerable: reducing waste materials and energy consumption compared to traditional technologies will improve the environmental impact of manufacturing; furthermore, new, more sustainable products can be introduced on the market if existing components and assemblies are redesigned with a view to reducing their weight and keeping the same performance. The reduction in set-up and cycle times will lead to a reduction in the time-to-market of small series, allowing Italian companies to be competitive on the global market.

Interaction with Other Action Lines

- This research and innovation priority will certainly support LI1 thanks to the economic advantages of AM in the production of highly customized geometries with minimum manufacturing volumes.
- In view of the research priorities expressed by LI2 to date, AM techniques look with interest to the issue of the recycling of materials and zero-waste AM processes, especially in the manufacturing of polymeric parts.

- Once again, exploiting improved capability to handle high product complexity in the generation of ad hoc solutions can be of support to LI3.
- Finally, as already explained in the goals, issues such as zero defect or the high-volume production that characterize LI4 can find in the AM a challenge to make this technology mature for the industrial world.

Time Horizon

Short-term goals (2–3 years):

- **New design rules**: the knowledge of design rules should be consolidated according to the different additive processes available, highlighting the current limits of technologies in the generation of complex geometries. Completing the knowledge and potential use of the design techniques available to date (topological optimization, conformal cooling, multi-material, etc.) is essential. They have certainly been extensively studied at a basic research level but they are not yet mature for concrete applications on an industrial scale.
- **Simulation of AM processes**: available multifunctional software already allows users to perform print quality checks (deformations, residual stress, etc.), orient the parts on a print area/volume, optimize the structure of the parts to take-off weight, add supports and perform what-if analyzes. However, this software is not yet mature to simulate objects that have been designed by extending the geometry of the component as far as possible, for instance for the simulation of the behavior of latex structures, multimaterials such as fiber-loaded polymers and complex materials (for example with combined mechanical and electronic properties).
- **Solutions for composites AM**: given the expiry of several patents and the degree of maturity of the technological processes that can manufacture these materials, in recent years a large proliferation of reinforced components has led to a rapid evolution of the knowledge and potential of these solutions. The near future will have to focus on the real applications of these materials in making complex components and on their real alternative to metal components.

Medium-term goals (4–6 years):

- **Innovative systems for AM**: today many companies are increasing production volumes as well as the range of printable materials, but few are the pilot projects that support process control. The new AM systems, and in particular those used in manufacturing metal components, should be fitted with integrated monitoring systems for a real-time control of the machining process in order to modify process parameters and correct any machining mistakes as well as stop the process altogether in order to reduce waste of material, time and energy for increasingly sustainable processes.
- **AM solutions for new industrial sectors**: to date, the sectors that principally use AM technology are aerospace, automotive, the medical\dental and electronics sectors. Several sectoral studies are forecasting applications in sectors such as clothing, oil & gas, pharmaceutical and architecture in the next few years.

- **Sustainable AM**: this issue is closely linked to the creation of innovative systems for AM. Both have therefore, the same time horizon.
- **Solutions for metal AM**: in many cases the consolidated PBF and DED processes for these technologies are not yet industrially sustainable. However, other more mature technologies such as Binder Jetting and Material Extrusion are being tested for their performance in manufacturing metal components. These technologies require further improvements in order to be exploitable in manufacturing real components]. At the time being they are not yet totally reliable especially from the point of view of the scale as well as of the real mechanical properties that can be obtained and exploited in the manufacturing of real components.

Long-term goals (7–10 years):

- **Solutions for Multi-material AM**: at present, this topic is strongly growing in terms of scientific research but it is not yet ready for an effective fallout in the industrial world as the main AM process (DED) is being developed as reported by Gartner's Hype Cycle. In the coming years it will be necessary to analyze and optimize the aspects related to dimensional accuracy, thermal stress, the chemical and physical affinity obtainable by mixing different materials.

3 PRI5.2 Bio-Inspired Technologies and Manufacturing Processes

Biological transformation, i.e. the systematic application of biological knowledge in improving manufacturing, is expected to be one of the next technological leaps in manufacturing processes. From a manufacturing point of view, an increase is expected in the use and integration of biological and bio-inspired principles, materials, functions, structures and resources to obtain intelligent and sustainable technologies and manufacturing systems. Biological transformation processes can develop in three separate steps: inspiration, integration, interaction.

In the first step, inspiration, biological phenomena will be translated in the design of products (for instance lighter structures), in their functionality (for instance biomechanics), in the organizational solutions (for instance swarm intelligence, neural networks). In the second step, knowledge of biology will be applied to obtain a real integration of biological systems into manufacturing systems (e.g. replacement of chemical processes with biological processes such as the use of microorganisms for the extraction of rare-earth elements from magnets). The third step will finally see a global interaction between manufacturing, information and biological systems, leading to the creation of completely new and self-sufficient technologies and production structures or the so-called bio intelligent production systems.

The impact of biological transformation in manufacturing will lead in the long term to a continuous improvement in innovation and sustainability for manufacturing processes. A systematic two-way approach would lead to new manufacturing developments, innovations and new products. It would be driven (top down) by technology and industry or (bottom up) by biology. This systematic approach should be based on the various manufacturing processes and on the different biological elements. Full potential can only be reached by combining the various strategies with data collection, digitization and the development of new processes such as additive manufacturing technologies.

However, these paradigms are still at basic research levels to date. Therefore, with a view to their integration into the manufacturing world, this research and innovation priority has the following goals:

- **New structures and surfaces for bio-inspired materials**: The major developments in biology-inspired material solutions can be related to a material's micro/meso structure or to the characteristics of its surface. If the function of a biological material is related to the structure rather than its properties, it is possible to replace the biological material with an artificial one without losing the key aspects of the function concerned (e.g. the structure of a bone). Conversely, it is possible to analyze a material at nano metric level by taking inspiration from the characteristics of its surface rather than its internal structure (e.g. hydrophobicity of leaves).
- **Bio-inspired design**: Nature offers examples of highly coupled solutions for complex movements, force and power distribution, controlled degradation, self-healing and regeneration. It is necessary to develop design tools that make it possible to conceive products designed to satisfy the mentioned multi-functionalities, for example by integrating mechanical and electronic parts.
- **Biological interaction and integration in manufacturing processes:** The potential for biologization in manufacturing processes, machine tools, robots, assembly systems and sensors is vast and should include environmentally friendly and anti-pollution technologies. The direct use of biological magnitudes and material in manufacturing processes (e.g. use of microbes as a lubricant in cutting operations, use of enzymes for the extraction of raw materials from waste or to carry out transformations, for example in microelectronics, microsystems and polymeric electronics) will be aimed at the optimization of processes and parameters, integration of the biological function in structures, integration of biomimetic sensors in processes as well as in robots' body mimicry.
- **Manufacturing of bio-intelligent devices:** in order to achieve the ultimate goal of bio-intelligent manufacturing, it is necessary to boost the potential of correctly applied concepts in the fields of synthetic biology, bio electrochemistry, microfluidics, bioreactors and artificial intelligence to allow the development of intelligent devices.

Interaction with Other Action Lines

- Interaction with LI1 with regard to the creation of bio-intelligent devices.
- This will pave the way towards the realization of new sustainability benchmarks in line with LI2
- Regarding LI3, study of new human–machine interfaces based on components that integrate biological structures.

- The concept of biological inspiration will be applied at various levels in current business situations, from process innovation to system innovation (LI 4, LI 6) and it will finally change the rules of next generation manufacturing management systems (LI 7).

Time Horizon

Medium-term goals (4–6 years):

- **New structures and surfaces for bio-inspired materials**: to date there are different prototypes of products or surfaces of bio-inspired parts. However they present certain critical issues that must be investigated, such as: scalability—since certain biological functions that work on a micro- or nanoscale fail on a macro scale (e.g. geckoes' adhesive property); constraints in materials—since for certain biological materials no artificial substitute is available (e.g. no man-made material can mimic a spider's web and retain its unique properties, even if its molecular structure is well known); constraints related to manufacturing processes.
- **Bio-inspired design**: the advantages drawn to date from bio-inspired product design include the possibility of changing the products' design in order to increase their performance, even if this means increasing their manufacturing complexity. It will therefore be necessary to increase both the level of knowledge and the limits of this new design concept as well as the level of digitization of the manufacturing chain, in order to be able to manage the higher levels of complexity given by the new designs.
- **Enzymatic processes**: they are mature for some specific sectors (e.g. food) and in the medium term it will be necessary to understand which ones can find their application in manufacturing (e.g. use of microbes as refrigerants in cutting operations).
- **Manufacturing of bio-intelligent devices**: promising technology in the field of micro fluidics and micro electronics in general. Future scenarios will show a development through integration of the biological with the artificial component and manufacturing processes that can achieve such integration.

Long-term goals (7–10 years):

- **Biological interaction and integration in manufacturing processes**: the transition to the design of bio-inspired processes should take place incrementally by adopting various biological solutions in the medium-long term.

4 PRI5.3 Innovation of Consolidated Manufacturing Processes

The increasing demand for customized products, with lower environmental impact and prompt and quick response to customer needs, is radically changing the organization of manufacturing systems (A graphical method for performance mapping of machines & milling tools). Despite the current evolution of innovative technologies such as additive manufacturing, chip removal will for years to come retain its role as primary technology (Agubra et al., 2016) in the higher value sectors of the Italian supply chains, together with foundry, plastic deformation and sheet metal processing (cutting, welding and bending) because they can obtain excellent surface finishes and high geometric accuracy. For example, it is expected that some sectors, such as e-mobility, will push towards an ever greater use of machine tools, given that powertrain components require high levels of precision (AMFG—The Additive Manufacturing Landscape, 2020).

In order to remain competitive, consolidated processes will have to undergo a digital transformation associated with technological growth through the adoption of systems capable of developing solutions that can improve productivity, flexibility and sustainability, also by adopting solutions for real-time process control and its management by adaptive control systems (Arias-Rosales; Armendia et al., 2019; Ii & La Bioeconomia in Italia).

The goals associated with this research and innovation priority are listed below:

- **Development of Digital Twin models for tools, processes and manufacturing machines** with the aim of creating libraries and digital models to capture the physical phenomena underlying the processes and predict their behavior so as to support both their design and their execution phase. Furthermore, it is also necessary to develop adequate architectures that promote the integration of different digital models of different process components.
- **Design and development of manufacturing processes** to take into account the evolving features of machines and tools to the production needs. In particular, it is necessary to design jointly both the process and the machine that carries out production.
- **Innovative solutions for manufacturing technologies:** manufacturing processes need to be transformed to allow the processing of difficult materials (e.g. fragile, elastic materials), processing in critical environments (e.g. explosive environments, biohazard environments), increase in production rates (e.g. cutting speed), improvement of quality and reduction of set-up times. These innovations include technological machine modules (e.g. spindle, sources), tools (e.g. materials, geometries) and equipment (e.g. zero-point clamping, adaptive equipment).
- **Solutions for real-time optimization of productivity and process quality,** easy to use and install on machines with different characteristics and numerical controls. Namely, the development of adaptive control methodologies, including those based on artificial intelligence, model-based process control systems and control systems based on artificial intelligence, to improve the performance of a manufacturing system, optimize performance in terms of productivity, quality and efficiency and a use of the machines to optimize their life cycle.
- **Methods and models for process planning and product re-design**: it is necessary to develop joint product-process design models that make the most of the materials' potential (whether from a catalog or purpose designed) both to smooth work during manufacturing and to monitor performance during use. There is also a

need for process planning models designed to meet several goals, such as the cost-effectiveness and low environmental impact of machining processes, and that can produce alternative machining sequences one can choose from during the manufacturing of products, depending on the conditions of each specific manufacturing plant.

- **Solutions to reduce the environmental impact of processing,** by developing new strategies to reduce the impact of consumables (lubrication) and energy consumption of the process (modifications to machine components and choice of working parameters) and for the reduction of scraps. A second line of industrial research will address the reduction of the chemical footprint through the adoption of substances and primary materials and accessories that have higher recyclability.
- **Multi-material and multifunctional joining techniques** to ensure the coexistence of different functional responses, such as for example (homogeneous or non-homogeneous) welds with different mechanical properties (elastic and stainless), electrical properties (excellent conductivity, low contact potential) and thermal properties (good conductivity). The improvement of the features of joints should address balanced goals and respond to needs that might even be conflicting such as mechanical properties during operation and the ease of disassembly, in a circular economy perspective.
- **Innovative solutions for assembly:** development of new solutions to ensure a product's performance when precision limits are set on the components' production through solutions for tolerance compensation that may ensure high quality products through selective assembling strategies.
- **Adaptive and resilient processes**, i.e. processes that can continue production even where there are significant supply change disruptions, as it happened with SARS Covid 19 (resilience), or quickly adapt to changing market demands.

Interaction with Other Action Lines

- Technological integration, endorsed through LI4, especially for the strong level of automation already existing in companies operating in sectors such as the automotive industry, combined with the new opportunities offered by electric mobility.
- The solutions based on generative design and multifunctional joints will be related to the customization and rapid adaptation goals set out in LI1.
- With regard to strategic action line LI3, it will be necessary to study and adapt the human–machine interaction systems that incorporate new functions and new digital process models,
- The issues addressed in LI2 are obviously important for LI5, a goal of which is sustainable evolution of consolidated processes by improving their energy efficiency and environmental footprint.