Chapter 36
Additive Manufacturing for Circular Manufacturing: Trends and Challenges—A Survey in Japan, Norway, and India

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Abstract Circular manufacturing such as product remanufacturing, refurbishment, and repair is a key element in promoting a circular economy, whereas enhancing its resource-efficiency-increasing-effects is often dictated by the critical process of material surface restoration. One of the key technologies that enable effective material surface and geometry restoration is additive manufacturing (AM). This study presents, firstly, a survey of the existing industrial usage of AM in circular manufacturing, which includes applications of re-coating, cladding, and thermal spray. The survey was mainly conducted in three countries, namely, Japan, Norway and India. Secondly, the study presents a review of research and development of the applications of metal 3D printing—an advanced AM. Challenges hindering the promotion of AM applications in circular manufacturing are laid on a process-to-process basis. In general, such challenges include advancement of process automations, design for restoration, quality enhancement of metal 3D printing-based restoration, and cost reduction of the process applications.

Keywords Circular manufacturing · Remanufacturing · Material surface restoration · Additive manufacturing

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36.1 Introduction

Increasing the resource efficiency of economies is one of the keys in promoting a sustainable society. To increase the resource efficiency, promotion of material saving, material recycling, and prolonging the product/component lifetimes are indispensable. In recent years, activities prolonging the product/component usage time have become increasingly important. Such activities specifically include product remanufacturing, refurbishment, repair, and direct reuse (RRRDR), and are alternatively called value-retention processes (VRPs) (UNEP-IRP 2018). In this paper, we call these activities wholly as circular manufacturing. They attract attentions because they offer not only the opportunity to achieve significant environmental impact reduction, but also to create economic opportunities for cost reduction, value-retention, and employment opportunities (UNEP-IRP 2018).

Promoting circular manufacturing is quite challenging in developing process technologies, system technologies, and business management and policy arrangement (GIS RIT 2017; Matsumoto et al. 2016). This study focuses on the process technologies for RRRDR specifically for remanufacturing which enables high-value retentions. The process technologies indispensable for remanufacturing include techniques for disassembly/assembly, cleaning, inspection, material restoration, reliability assessment, and so on (GIS RIT 2017; Matsumoto et al. 2016). Among these technologies, material restoration technologies are the highlight of this study, with specific focus on additive manufacturing (AM). The material restoration critically influences the remanufacturing's effects on prolonging product/component lifetimes and thus, the effects of enhancing resource efficiency. The surface of the materials of used products/components can contain fracture, fatigue, wear, corrosion, etc., which need restoration for remanufacturing. The term AM is used, in some cases, to specifically indicate 3D printing, but in general, AM also includes techniques as welding, thermal spray, cladding, laser engineered net shape, cold spray, and so on. This study uses the term AM in the latter sense. At the same time, the study distinguishes 3D printing from other AM techniques.

This study conducted a survey of AM techniques that are used and can be potentially used in remanufacturing. It also explored the challenging issues in the techniques. The first survey was on the AM techniques used in remanufacturing today, based on visits and interviews with industries mainly in Japan, Norway, and India. The subsequent survey was focused on metal 3D printing that has been researched intensively in the last decade. The industrial applications today are mostly limited to new product/component manufacturing, however, the technique has already started to be applied in remanufacturing, and demonstrates a great potential that field in the future (GIS RIT 2017; Matsumoto et al. 2016). This study surveyed the applications of the metal 3D printing largely based on literature review. It further conducts an exploration of the challenges on the techniques.

The rest of this article is organized as follows. The next section outlines the challenges in process technologies of remanufacturing, and specifies the importance of material restoration technologies in the field. Section 36.3 summarizes the AM techniques used in today's remanufacturing, and outlines the challenges in the application of these techniques. Section 36.4 presents a review of the applications of metal 3D printing in remanufacturing, along with a summary of the challenges on the techniques. The final section summarizes the main points of the article.

36.2 Material Restoration in Remanufacturing

RRRDR prolong the usage duration of products and components, and thus contribute to saving materials and energy in manufacturing. In RRRDR, remanufacturing can retain the highest value of products and components; its process typically consists of: disassembly, cleaning, component inspections, restoration of components and materials, reassembly, and testing (Fig. 36.1). More importantly, remanufacturing restores the products (used products) to the original, as-new condition and performance or better (UNEP-IRP 2018).

Remanufacturing is employed in various product areas, the main areas being aerospace, heavy-duty and off-road equipment (HDOR), automobile parts, machinery, electronics and IT, and medical devices (Table 36.1).

Continuous research and development (R&D) enhance remanufacturing. It is specifically needed to assure the quality of remanufactured products and to control the costs at a reasonable level. Each of the processes shown in Fig. 36.1 requires technological development; nevertheless, while the techniques for these processes are

Fig. 36.1 Remanufacturing process

Table 36.1 Product areas of remanufacturing and market scales in the US and Europe

Product area	Production in US International Trade Commission (USITC) (2012) (Billions USD)	Production in Europe Eurpoean Remanufacturing Network (ERN) (2015) (Billions Euro)
Aerospace	13.0	12.4
HDOR	7.8	4.1
Auto parts	6.2	7.4
Machinery	5.8	1.0
Electronics and IT	2.7	3.1
Medical devices	1.5	1.0
Retreaded tires	1.4	–
Consumer products	0.7	–
Rail	–	0.3

important, technologies for inspection and material restoration are especially important for products for which material deterioration significantly affects the product performance and reliabilities. Such products include those in aerospace, HDOR, machinery, and automobile parts sectors.

Hence, this study investigated material restoration processes in remanufacturing, focusing on the conduct of a survey of AM techniques in these processes. Surveys in the industry were mainly targeted at the sectors of aerospace, HDOR, and automobile parts.

36.3 Conventional Additive Manufacturing Techniques Used in Remanufacturing

36.3.1 Survey Method

To investigate the material restoration processes in present remanufacturing, an author visited and interviewed nine firms to survey the process. Most of the firms were Japan-based companies. The product areas included: automobile parts, HDOR, aerospace, machinery, and power-generating facilities.

36.3.2 Application Cases

Oftentimes after usage of a product, the components incur surface damages. In some cases, the damages can be restored by scraping off the damaged part, a method categorized under subtractive manufacturing. Nonetheless, the technique is applicable when the depth of the layers to scrape off is within the range of tolerance. In other cases, the damages are restored by making up the part, under what is known as AM. AM techniques used in present-day remanufacturing include welding, cladding, and thermal spray.

The automobile parts sector is one of the sectors in which remanufacturing is observed actively. AM is used in the sector. The sector, however, is oftentimes associated with a relatively strong cost constraint, originating from the principle that the price of the original products in this sector is relatively lower than those of other sectors such as aerospace and HDOR. Figure 36.2 shows a case of AM being applied in automotive parts remanufacturing. Here, the company is a third-party remanufacturer of engines. The figure shows the process of restoration of damage on the surface of an engine crankcase. The damaged part is, first polished, then cladded by arc-welding, and then is finished by polishing. Cladding by welding is also used to restore component breakage. Figure 36.3 shows a case of another company. The drive shaft in the figure had broken splines, restored by cladding. These AM processes are a key in remanufacturing; however, they rely heavily on manual work, and thus, as

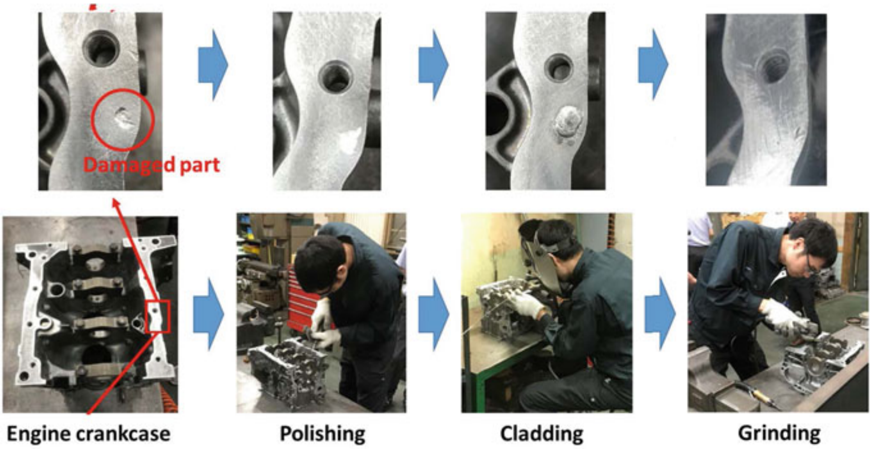


Fig. 36.2 Restoration of the surface of crankcase in automobile engine remanufacturing

Fig. 36.3 Restoration of splines of automobile driveshaft by cladding

labour wage increases in these countries, these processes become less economically feasible. This is the reason why component restoration is less done today.

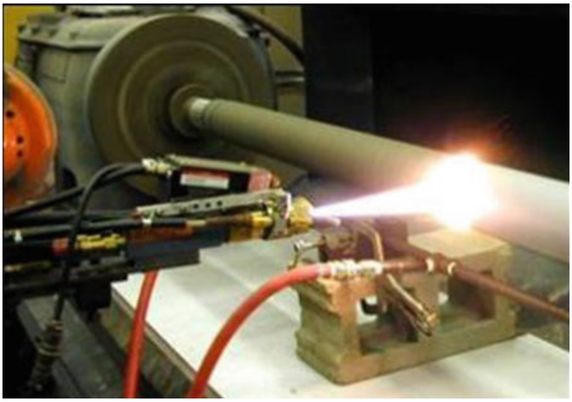
HDOR is another sector in which remanufacturing is actively conducted. Typical examples of HDOR equipment include excavators, bulldozers, backhoes, asphalt pavers, and trucks. Remanufactured components in the sector include engines, starters, alternators, turbochargers, transmission axles, hydraulic cylinders, hydraulic pumps, reduction gear equipment, and so on. Of these components, material surface restoration of hydraulic cylinder is a critical remanufacturing task. Figure 36.4 shows a case of damages (scratch and corrosion) on the inner surface of a hydraulic cylinder tube. Damage on the cylinder surface may cause leakage of lubricant oil, resulting in the functional degradation of a product. As such, restoration of the damage is important in remanufacturing. The remanufacturing process for the tube starts with an inspection of the damage. If such damage is assessed as restorable, the cylinder (tube and/or rod) is electroplated, and then the plated surface is planarized by honing. In some cases, thermal spray is used instead of electroplating. Generally, thermal spray is costlier, but because an electroplating facility needs a large initial investment, thermal spray is used when an electroplating facility is not available in a region. Thermal spray is also used in the restoration of other components. Figure 36.5 shows a case of restoration of a shaft. Besides the mentioned approaches, various AM techniques are used and researched by companies. These techniques vary from the wire-arc spray, bore spray, high-velocity oxy-fuel spray, cold spray, thin film coatings, and laser cladding.

Dies and molds are also remanufactured. Cladding by welding is used to restore the broken parts of dies and molds.

The aerospace sector is the largest sector of remanufacturing in the global market (International Trade Commission (USITC) 2012; Eurpoean Remanufacturing

Fig. 36.4 Scratch and corrosion on hydraulic cylinder tube

Fig. 36.5 Thermal spray for surface restoration of a shaft



Network (ERN) 2015). Because the components are generally expensive, remanufacturing is conducted for various components; at the same time, the quality requirements for the components are governed by high and stringent remanufacturing standards. Customarily, remanufacturing is driven in large part by the mandatory aircraft safety inspections prescribed by national aircraft certification authorities (International Trade Commission (USITC) 2012). Cladding by welding is also widely applied for remanufacturing in the sector; cladding is used to restore some broken parts of such components as compressors, burners, casing, and disks. Nevertheless, the increasingly high requirements for the performance of the components make remanufacturing in this sector difficult. Turbine blades (Fig. 36.6), for example, were previously commonly repaired, but in recent years they have not been repaired that much. In turbine blade remanufacturing, the top coating layer is first removed, and then a new layer is coated. Today, turbine blades are used to tolerate increasingly high temperatures, to increase engine fuel efficiencies. To assure the high-temperature mechanical property of the blades, a new type of additive substances is added to the substrates. However, these new materials cause chemical reactions during the re-coating process in remanufacturing that degrade the blades' mechanical properties, thereby making remanufacturing a difficult task.

Fig. 36.6 Aircraft turbine blade

36.3.3 Trends and Challenges

AM has been widely used in remanufacturing, among which cladding by welding and re-coating are the most popular. The trends and challenges in these techniques are as follows. Firstly, the cost is critical in remanufacturing. Thus, cost reduction of the AM techniques is important. As restoration processes generally rely on manual work, as described in the automobile parts remanufacturing cases, automation or semi-automation of the inspection and these restoration processes should be advanced. Cost reduction is also important because a survey in the United States revealed that AM techniques are used mostly by large companies, not much by small-and-medium sized enterprises (GIS RIT 2017). To further activate circular manufacturing, development and commercialization of affordable AM techniques is necessary.

One approach to reduce the cost of re-coating is to develop local re-coating processes. In re-coating, generally the coated layer is removed from the entire surface and then a new layer is coated on the substrate. However, when only the damaged part of the layer is removed and re-coated, the total cost be reduced.

Another challenge is increasing the value and the quality of restoration. Conditions of damages in products vary depending on the customers' usage of the products. As such, remanufacturers can customize the restoration depending on the usage pattern of the customers, which can lead to an increase in the value of remanufacturing and the effects of prolonging the product lifetimes.

Technological development of material restorations for new types of materials is also needed. As with the case of aircraft turbine blade repair, new types of materials can make remanufacturing more challenging. In this case, re-coating techniques that do not harm the substrate by re-coating should be developed. Product design for remanufacturing (DfReman), or material design for restoration, is equally important.

36.3.4 Application in Surface Embedded Sensors

Another potential application of AM in circular manufacturing is the development of intelligent tooling based on surface-embedded sensors. Feasibly, AM can be employed to realize surface-embedded sensors; machine tools can become smarter by perceiving their own states and the state of the surrounding environment. The key enablers for this capability include smart sensors embedded into machine tools, a system that is useful in evaluating the tool's health conditions and predicting its remaining lifetime, as well as a possible breakdown or malfunction before that (Yang et al. 2018). The system is also useful for monitoring of the manufacturing process within the tools. Martinsen et al. conducted R&D of surface-embedded sensors used in injection molding dies (Martinsen et al. 2017). In principle, pressures and temperature distributions within the mold cavities are critical parameters for injection molding of thermoplastics components, whereas in-mold sensors are highly useful for improving the manufacturing process controls. In the research, the sensors were

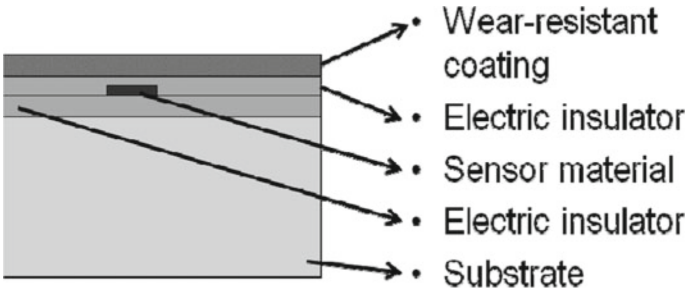


Fig. 36.7 Sensors embedded in coating layers (Martinsen et al. 2017)

fabricated on the surface of inserts on a bridge tool for injection molding using direct write thermal spray (Martinsen et al. 2017). Figure 36.7 shows the embedded sensors that were applied between layers of electric insulators. The data from the sensors were used to calibrate the process simulation of conformal cooling channels, which can enhance the analyses capabilities of the tool, process, and product behaviors, such as thermal stress, friction properties, and inlet issues (Martinsen et al. 2017).

36.4 Metal 3D Printing Applications in Remanufacturing

36.4.1 Metal 3D Printing

In a broad sense, AM refers to the process of creating an object by building something up. It is also often used as a synonym of 3D printing, which is actually a type of AM in the former sense. 3D printing is defined as the process of fabricating 3D parts through layer-by-layer deposition of materials. Metal 3D printing was first used to develop prototypes in the 1980s. As the technique improved by the early 2000s, it was employed to create functional products. More recently, companies have begun using metal 3D printing as integral part of their business processes.

3D printing has the potential to provide sustainability advantages, such as the generation of less waste during manufacturing due to it being an additive process, the capability to optimize geometries and create lightweight components that reduce material consumption in manufacturing and energy consumption in use, the increase in opportunities to repair, restore, and remanufacture due to the ability to rebuild 3D structures, the subsequent reduction in transportation in the supply chain, and inventory waste reduction due to the ability to create spare parts on-demand (Ahn 2016; Ford and Despeisse 2016). Of such advantages, the focus of this study is on the potential of the technique in increasing the opportunities for repair, restoration, and remanufacturing.

A number of different 3D printing methods exist currently. The American Society for Testing and Materials grouped these methods into seven categories including

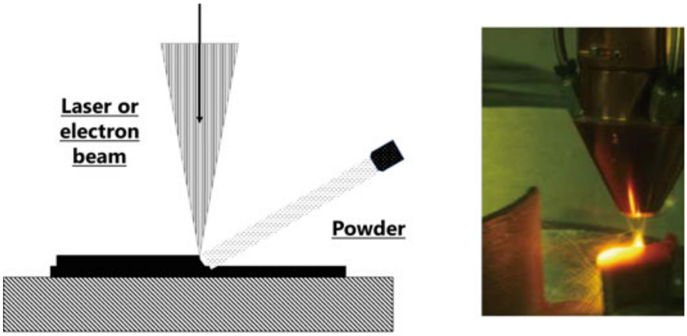


Fig. 36.8 Directed energy deposition (DED) process

binder jetting, powder bed fusion, sheet lamination, and directed energy deposition (DED). Of these, DED is well suited for remanufacturing as it can create a desired geometry along an arbitrary trajectory (Matsumoto et al. 2016; Yang et al. 2018). DED uses a focused thermal energy beam to melt and fuse materials. The typical DED process is illustrated in Fig. 36.8. Here the thermal energy beam is usually laser or electron beam. The materials added are typically in the form of the powder injected into the fusing zone with a flow of powder and inert gas through a nozzle.

36.4.2 Applications of Metal 3D Printing in Remanufacturing: A Review

Metal 3D printing applications in remanufacturing are still in an immature stage; most are in the R&D stage.

Research has been undertaken most actively in the aerospace sector. The companies and research organizations have applied DED to the repair of various aircraft components, including turbine blades, blade disks (blisks), compressor drums, compressor seals, mobiles, drive shafts, drive couplers, titanium components, etc. (Ahn 2016; Mudge and Wald 2007). Mudge and Wald, for example, reported the repair of the worn bearing housing of a gas turbine engine, cost of which was about 50% of a newly manufactured product (Mudge and Wald 2007). They also reported the repair of a drive shaft and a comparison of the repair by DED and thermal spray. The hardness and the corrosion resistance of the repaired region by DED were greater than those of the repaired region by thermal spray (Mudge and Wald 2007). Additionally, the spalling phenomenon was not observed in the region repaired by DED, whereas severe spalling appeared in the region repaired by thermal spray (Mudge and Wald 2007). Such a case, the repair cost of DED was approximately 50% that of the thermal spray (Mudge and Wald 2007).

Similarly, water turbine remanufacturing by DED has been researched. In the remanufacturing, after measurement of the amount of wear, the additive machine added the material (Stellite) directly on the worn surface, consequently prolonging the expected lifetime of the turbine (Matsumoto et al. 2016).

Remanufacturing of dies and molds is another example of DED applications. Figure 36.9 illustrates a process of remanufacturing worn-out dies. The region containing cracks was processed by pocket machining, and was restored by laser metal deposition (a DED type), and was finished by post machining (Fig. 36.9). In a case where a company applied DED to the repair of a die, the service life of the repaired die was extended by 250% (Ahn 2016). Moreover, DED-based remanufacturing can lead to extended product lifetime, shorter lead time, cost and energy savings (Ahn 2016). AM process has been applied not only to the repair of worn-out dies, but also to the remanufacture of dies for new products and processes (Matsumoto et al. 2016). There is also a study on remanufacturing dies with the hard-faced layer consisting of a wear-resistant material (Ahn 2016).

There were also application cases of other metal 3D printing techniques besides DED. Siemens Power Service, for instance, applied the powder bed fusion process for the repair of damaged gas turbine burner tips wherein the tips were machined before they were placed into the powder bed of a selective laser melting machine, and before new tips were built onto the machined surface (Fig. 36.10) (Matsumoto et al. 2016).

There are explanatory studies on assessment of energy use and environmental impacts of AM processes (Kellens et al. 2017). The merits of AM techniques, ultimately, should be judged based on not only their technical and economic advantages, but also their environmental effects.

In India, metal 3D printing is mostly looked at in the context of repairing, refurbishing, and remanufacturing old components. Examples of the regional R&D include refurbishment of railway components with laser-based DED; and repair of forging dies with the use of wire-arc AM.

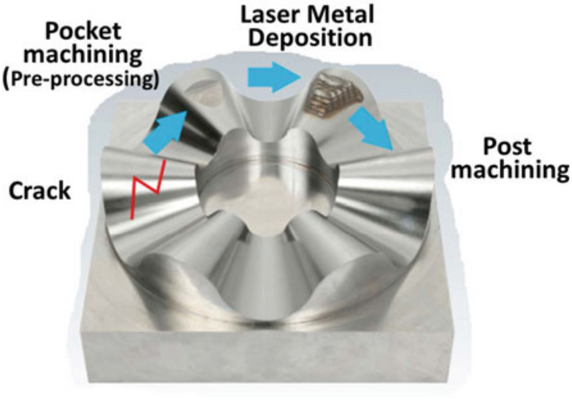


Fig. 36.9 Illustration of die remanufacturing by DED . (*Source* Okuma corporation)

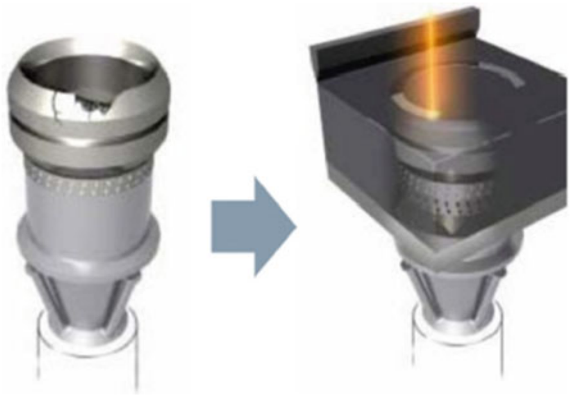


Fig. 36.10 Gas turbine burner tip repair by powder bed fusion (Matsumoto et al. 2016)

36.4.3 R&D Challenges

As earlier mentioned, the application of metal 3D printing in remanufacturing is still in the early stage of development. Nevertheless, the technology can be seen as having a huge potential in the future. Realizing such potential requires the achievement of two goals, namely, (a) improving the quality of the restored region and the interface (the border between the original part and added region), and (b) reducing the process cost.

These goals can be achieved through advancing the technological development of each of the processes for metal 3D printing-based remanufacturing. Figure 36.11 provides an outline for these processes, which include (1) condition assessment and digitization, (2) restoration process, and (3) post machining and inspection.

For the initial stage, as the objects are deformed, torn, and have other defects, it is essential to acquire the geometrical data of the object, practically through various 3D scanning methods as laser triangulation, structured light, and probing methods. The material composition and damage conditions are also inspected at this stage. The next stage is restoration, which mainly involves path planning, material definition, process parameter definition, preprocessing, and 3D printing processing (AM process). In path planning, in case the original digital design data of the product is available, the scanned data of the object are compared with the original design data using reverse engineering software, and the information is used to create the tool path plan. The restoration process is followed by post machining and inspection process, mainly consisting of tool path planning, post-processing, and post-inspection.

These processes require technological development. The major challenges of such development include:

- Material composition analysis technique

DED can deposit a wide range of materials including: tool steels, stainless steels, titanium and titanium alloys, aluminum alloys, nickel-based alloys, cobalt-chromium

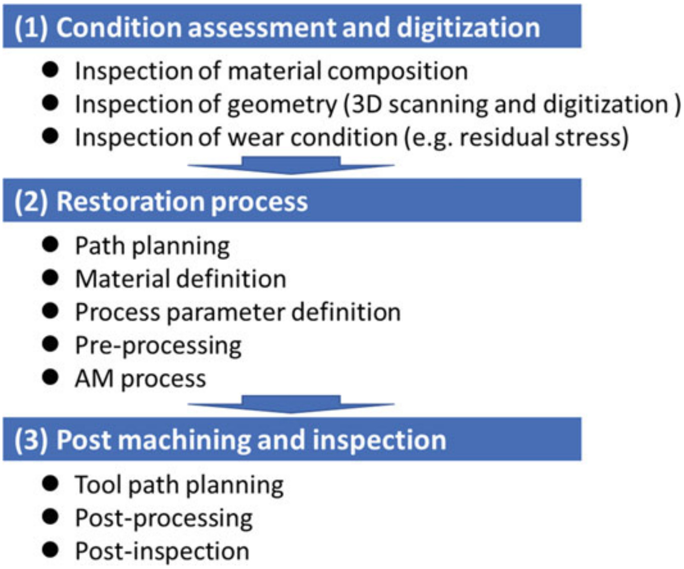


Fig. 36.11 Metal 3D printing-based remanufacturing process

alloys, copper alloys, gold and silver (Matsumoto et al. 2016). As the material composition of the region to repair is often unclear, a method for quickly analyzing the elemental composition of the materials would be essential. Developing analysis techniques such as advanced X-ray fluorescence is a challenge.

- Computer-aided manufacturing (CAM) to create flexible machining path

Users of the 3D printing device expect such to create any type of geometry once the numerical data of the geometry (computer-aided design data) are input to the device. Actually, the conditions under which a certain geometry can be created are limited due to differences in shape and the materials. The processing conditions are device-specific know-how, and are accumulated as “process recipe.” In order to advance 3D printing-based remanufacturing, it is necessary to develop flexible CAM software and build a system that enables improving and upgrading the process recipe.

- Material and structural property analyses

To enhance the reliability of remanufacturing by 3D printing, further analyses and understanding of the material and structural properties are necessary. The strength of the restored region and interface is affected by structural properties of, for instance, crystallinity and crystal anisotropy. Defects such as porosity also affect the strength. However, local failure mechanisms are still not completely understood. Uncertainty in the material properties is currently a challenge for the establishment of reliable remanufacturing processes using metal 3D printing.

- Post machining planning

Post machining is required after 3D printing the damaged part to achieve the desirable dimensional tolerance, hardness and surface roughness and to ensure like-new performance. There are techniques to minimize the surface roughness, for example, through optimizing building paths, layer thickness, and powder grain size (Matsumoto et al. 2016). However, a better surface from the 3D printing process usually means a more expensive and time-consuming process. This is where post-processing comes in. Post-processing is usually a material-removing process such as cutting and abrasive processes like polishing. There exists the optimization of the combination of AM and subtractive manufacturing, but they are mainly for new product manufacturing and not designed for remanufacturing (Matsumoto et al. 2016). The challenge on this respect is to develop a sound method to combine metal 3D printing and subtractive manufacturing in an optimal way.

- Post-inspection and in-situ monitoring

In metal 3D printing, defects and variation in quality may arise in each product as it is fabricated through layer-by-layer deposition of materials; thus, post-inspection is important. An X-ray computerized tomography scan technique can be used to inspect the fabricated product; however, it is expensive and comes with a problem, wherein detection becomes difficult as the defect size becomes smaller. This issue can be resolved via development of highly precise and low-cost quality inspection techniques and establishment of an appropriate inspection standard. In addition, if the defect occurrence during the process can be detected and further reflected in the process parameters immediately, the quality of restoration can improve significantly. Development of such in-situ monitoring technique is also a challenge.

- Cost reduction of the process

Cost reduction of the process is important to expand the use of metal 3D printing in remanufacturing. Here, price reduction of the device is a challenge. The high price of powder materials today is another hindrance factor for the expansion of the applications; thus, reducing the powder cost is also a challenge.

36.5 Conclusion

The study presented a survey of existing industrial usage of conventional AM in remanufacturing and a review of R&D of metal 3D printing applications in remanufacturing. Conventional AM is widely used in remanufacturing, of which cladding by welding and re-coating are the most popular. Further promoting the usage of conventional AM in circular manufacturing essentially incorporates cost reduction and quality enhancement of AM, and associates with the challenges of advancing the automation of the restoration processes, developing partial re-coating processes, and material design for restoration.

On the other hand, metal 3D printing has been intensively researched in the last decade, with it being used initially in prototype manufacturing. The technique has great usage potential in remanufacturing in the future. Nevertheless, realizing such potential would necessitate an increase in the quality (strength) of the restored region by 3D printing and again, minimal cost. The challenges for this objective include the development of quick material composition analysis technique, CAM to create optimal machining path, increase of material and structural property understanding, development of post machining, post inspection, and in-situ monitoring techniques.

Furthermore, material surface restoration and geometry restoration processes are critical in enhancing the resource-efficiency-increasing-effects of circular manufacturing. In order for advanced AM to have a significant impact on the industry and reduction of the environmental impacts of manufacturing, R&D of process technologies outlined in this study should be realized. In addition, a product design for remanufacturing should be adopted, and a production system for smart remanufacturing, a supply chain for AM-based remanufacturing, and a business model for remanufacturing must be established. Future work includes identification of country-specific priorities of R&D in AM-supported circular manufacturing. The priority of R&D differs in different industries and product areas, and thus, the priority differs in different economies. An appropriate application of AM techniques is one of the keys in realizing circular manufacturing.

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