Subtractive processing and surface integrity of additive manufacturing materials

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Received 28 December 2023
Revised 2 January 2024
Accepted 2 January 2024

Abstract

Purpose – As an advanced manufacturing method, additive manufacturing (AM) technology provides new possibilities for efficient production and design of parts. However, with the continuous expansion of the application of AM materials, subtractive processing has become one of the necessary steps to improve the accuracy and performance of parts. In this paper, the processing process of AM materials is discussed in depth, and the surface integrity problem caused by it is discussed.

Design/methodology/approach – Firstly, we listed and analyzed the characterization parameters of metal surface integrity and its influence on the performance of parts and then introduced the application of integrated processing of metal adding and subtracting materials and the influence of different processing forms on the surface integrity of parts. The surface of the trial-cut material is detected and analyzed, and the surface of the integrated processing of adding and subtracting materials is compared with that of the pure processing of reducing materials, so that the corresponding conclusions are obtained.

Findings – In this process, we also found some surface integrity problems, such as knife marks, residual stress and thermal effects. These problems may have a potential negative impact on the performance of the final parts. In processing, we can try to use other integrated processing technologies of adding and subtracting materials, try to combine various integrated processing technologies of adding and subtracting materials, or consider exploring more efficient AM technology to improve processing efficiency. We can also consider adopting production process optimization measures to reduce the processing cost of adding and subtracting materials.

Originality/value – With the gradual improvement of the requirements for the surface quality of parts in the production process and the in-depth implementation of sustainable manufacturing, the demand for integrated processing of metal addition and subtraction materials is likely to continue to grow in the future. By deeply understanding and studying the problems of material reduction and surface integrity of AM materials, we can better meet the challenges in the manufacturing process and improve the quality and performance of parts. This research is very important for promoting the development of manufacturing technology and achieving success in practical application.

Keywords Additive manufacture, Superalloy, Surface integrity, Additive-subtractive manufacture, Unconventional machining

Paper type Literature review

This research is funded by the National Natural Science Foundation of China (No: 52205493) and Aeronautical Science Fund (No: 20230016038001) and supported by the Fundamental Research Funds for the Central Universities.

Journal of Intelligent Manufacturing and Special Equipment
Emerald Publishing Limited
e-ISSN: 2633-660X
p-ISSN: 2633-6596
DOI 10.1108/JIMSE-12-2023-0014

1. Introduction

1.1 Definition and development of additive manufacturing

1.1.1 Definition of additive manufacturing. Additive manufacturing (AM), also known as 3D printing, is an emerging technology that adds materials layer by layer on top of a digital model to form a physical object (Lu and Li, 2013). In the process of increasing materials by layer, each layer has an independent control instruction, and the specific pattern of that layer is formed according to the specific content of the instruction. This is also the core of AM, which the work is built and added in sequence (Lu, 2022). According to whether 3D printing technology is directly used in the production process, 3D printing technology can be divided into direct 3D printing technology and indirect 3D printing technology (Sun and Luo, 2021). Based on digital models or electronic data sources, AM technology can produce almost any form of object (Gu, 2022).

The invention of AM technology has greatly improved the manufacturing and production process of items. It is an accelerator of technological innovation and is also called a key technology for manufacturing products (Lu, 2020). This makes product production more innovative and personalized, in line with the development trend of the manufacturing industry. As AM continues to become more popular, combined with advanced information technologies such as cloud manufacturing and big data, it can promote the upgrading of the manufacturing industry, thereby promoting the transformation of traditional manufacturing into intelligence, personalization and socialization (Zhang and Yang, 2021). Especially in high-precision fields such as national defense, aerospace, new energy and biomedicine, the use of AM technology can achieve technological breakthroughs and promote rapid industrial development (Wang, 2013).

1.1.2 Development of additive manufacturing. AM has become a key topic of research at home and abroad (Rabinarayan and Goutam Kumar, 2021). The American consulting firm McKinsey is very optimistic about the development of AM and even publicly stated that in the next five years, AM technology can be said to be one of the 12 major disruptive technologies as well as reviewing manufacturing's 40-year development history and prediction of its future direction of AM in its journal (Yan *et al.*, 2020). China has also set its sights on AM technology. When the Chinese Academy of Sciences was discussing the "14th Five-Year Plan", it included an industrial blueprint for AM. This shows that it has a strong interest in AM technology (Guo *et al.*, 2020a). There are also many scholars who have explored the development overview of AM at home and abroad and analyzed the application basis, application fields and development trends of this technology (Liu and Wang, 2017). At the same time, they have also done some research on the cultivation of talents in the industry. Some research (He *et al.*, 2017). Joint organizations such as the World Economic Forum believe that in the next 10 years, AM technology will be widely promoted and applied and also pointed out that this technology also plays a certain role in the prevention and control of the current COVID-19 epidemic (Jia, 2021).

At present, our country's manufacturing industry can be said to be facing internal and external troubles. Our country's manufacturing industry lacks high-end manufacturing equipment and products lack innovation at home while the competition in the international manufacturing industry abroad is fierce. It is unable to fully master the advanced technology. Therefore, using emerging technologies to improve, transform and upgrade the manufacturing industry require the support of our country (Qi and Zhang, 2017) Although AM is currently very popular in China, there is still a certain gap between the domestic AM technology and the international top technology (Xu *et al.*, 2020) while most manufacturing companies are still not familiar with AM technology. Most of the manufacturing companies are in the stage of understanding without truly mastering of the technology. Even if the technology is already being applied, it is only in the primary application stage that has not yet been developed and applied in depth (Qiu *et al.*, 2020). Therefore, according to the current development status of AM in China and combined with China's national conditions, it is necessary to plan for AM technology and include the industry in the ranks of powerful nation of manufacturing (Wang *et al.*, 2018a).

With the increasing popularity of additive technology and the exploration of emerging technologies, the demand for additive technology will increase significantly in the future, and it will also become a driving force for the development of our country's emerging industries (Zhou *et al.*, 2021). There will be more and more market shares for 3D printing, and they will even penetrate into all aspects of our lives (Li, 2017). In this way, the application scope and industrial scale of AM technology will be greatly expanded and AM, subtractive manufacturing and other material manufacturing will gradually form a "three-thirds of the world" pattern in the manufacturing value chain (Gao and Ye, 2021). In particular, AM will play an important development role in our country's industrial manufacturing.

1.2 The significance of metal additives

1.2.1 Metal additive manufacturing. Metal AM is the most important branch of AM technology (Zeng and Liu, 2016; Li *et al.*, 2017a). It is a new manufacturing technology based on metal powder/wire material, using high-energy beam (laser/electron beam/arc/ion beam, etc.) as a tool, based on computer 3D CAD data model, using the principle of discretion-stacking. Under the control of software and numerical control system, the material is melted layer by layer to manufacture high-performance metal components (Yang, 2019a; Chang *et al.*, 2021).

1.2.2 Metal additive manufacturing technology. Metal 3D printing technology usually uses high-energy beams as input heat sources to print parts layer by layer by melting or sintering metal powder (Zhou and Chan, 2016; Sun, 2021). According to the different input high-energy beams, metal 3D printing technology can be divided into selective laser melting technology (SLM), electron beam selective melting technology (EBSM), laser three-dimensional forming technology (LSF), electron beam fused filament deposition technology (EBFF), Electric arc additive manufacturing technology (WAAM), (Du *et al.*, 2022) etc. They are shown in Table 1. At present, the research and application of printing technology using laser as input heat source is relatively in-depth, and it is mainly used for printing metal powders such as titanium alloy, cobalt-chromium alloy, stainless steel, (Chen and Chen, 2017; Guo and Zhang, 2022) etc.

1.2.3 The application of metal additive manufacturing.

(1) Forming parts that are difficult to manufacture traditionally

In the manufacturing field, some parts have complex shapes and long preparation cycles. They cannot be produced using traditional casting and forging processes or suffer large losses. Metal AM technology can quickly produce parts that meet requirements and has the advantages of short processing cycle, low manufacturing cost and no need for tooling and molds (Xiong *et al.*, 2021; Wan and Chen, 2020).

The special-shaped waterway mold design time through metal 3D printing is reduced by 75%, manufacturing manpower is saved by 50%, the injection mold production cycle is shortened by 14% and manufacturing costs are reduced by 16%.

(2) Preparation of high-cost material parts

Metal materials are indispensable and important materials in the manufacturing field. However, there are many problems in the actual processing process, such as titanium alloys, high-temperature alloys, ultra-high-strength steel and other materials that are difficult to process, have high processing costs and have low material utilization rates, long processing cycle, etc.

Metal additive manufacturing technology		SLM	EBSM	LSF	EBFF	WAAM
Output heat source		Laser	Electron beam	Laser	Electron beam	Electric arc
Material form		Powder	Powder	Powder	Fuse	Fuse
Working environment		Inert gas	Vacuum	Inert gas	Vacuum	Atmospheric environment
Technical feature	Part dimension	Middle and small scale	Middle and small scale	Large and middle scale	Large scale	Ultra-large scale
	Sophistication	Extremely complex	Extremely complex	Complex	Complex	Complex
	Surface quality	Excellent	Good	General	Bad	Terrible
	subsequent process	No processing	No processing	Light processing	Light processing	Much processing
	Manufacturing efficiency	Low	Middle	High	Higher	Highest
	molding precision	Excellent	Excellent	Good	Middle	Bad
	Special mold	None	None	None	None	None
Processing materials		Titanium alloy, superalloy, copper, aluminum alloy, magnesium alloy, hard alloy, cobalt-chromium alloy, as well as Cu-Su, W-Ni, Ni-Al and Nh-Ti-Si intermetallic compound materials and some gradient materials				

Source(s): Table courtesy of Du *et al.* (2022)

Table 1.
Comparison of five metal additive manufacturing technologies

Pratt & Whitney, one of the largest aero-engine manufacturing companies in the United States, applied AM technology to the development of nickel-based alloy and titanium alloy components for engines. The results show that it not only achieved performance consistent with current materials, but also greatly shortened the manufacturing cycle. The manufacturing accuracy of complex geometric structures has been improved; raw material consumption has been reduced by 50% and the BTF ratio of the engine (the ratio of raw material mass to final component mass) has been reduced from 20:1 in the traditional process to less than 2:1, effectively improving Improve the quality of components and reduce manufacturing costs (Zhang *et al.*, 2022a).

(3) Rapid prototyping of small batches of non-standard parts

AM is very suitable for personalized customized production and small batch production. Metal AM technology can be used to tailor precision components for patients for implant surgeries (Cheng and Chang, 2018; Liu, 2018).

Through the precise control of 3D printing technology, these implants can effectively realize the simultaneous reconstruction of the external contour and internal structure to meet the high match with the patient's local anatomy. Among them, the biocompatible titanium alloy material is an important processing material. Printing porous structure implants with this kinds of material can better integrate with human tissues. On the other hand, metal AM technology can also be used to tailor precision components of implant surgeries for patients. For example, South China University of Technology has successfully developed personalized auxiliary guides for surgical operations by using laser selective melting technology (SLM) (Shichao *et al.*, 2021).

(4) High-performance forming to repair damaged parts

The forming and repair of high-cost parts is also a prominent advantage of metal AM technology. In the past, only surface coating repairs could be done on damaged parts, and the repair process involved many steps, including some additional steps such as processing, polishing, testing, etc. It was also restricted by the repair time limit and took a long time. Parts that are slightly damaged can only be replaced. Metal AM technology can quickly form and repair any missing or damaged parts.

For example, aerospace parts have complex structures and high costs. Once defects or defects occur, they can only be replaced as a whole, which may cause losses of hundreds of thousands or millions of yuan. Through metal 3D printing technology, the defective part can be repaired into a complete shape with the same material and the performance after repair will not be affected, greatly extending the service life, reducing costs and downtime (Xu, 2022).

(5) Multi-material combination manufacturing

Compared with traditional manufacturing methods such as casting and forging, it is very difficult to combine different materials into a single product, but AM technology has the ability to combine different raw materials for manufacturing.

Appropriate use of AM technology for combined manufacturing of some industrial parts and using different types of metal materials for different structural parts not only greatly improve the performance of structural parts, but also reduce costs, especially the costs of expensive materials. At the same time, the advantages of AM technology for forming complex and fine structures are combined with the high-precision advantages of traditional manufacturing technology to form the best manufacturing strategy (Zhang *et al.*, 2021a).

(6) Lightweight manufacturing

The rapid and free forming characteristics of AM technology bring unlimited innovation space to product design and provide an effective manufacturing approach to achieve optimal design. Metal AM technology enable these topologically optimized innovative models to be manufactured quickly without considering manufacturing constraints.

For example, the large-scale "bionic" cabin isolation structure of the Airbus A320 aircraft is manufactured through topology optimization design and metal 3D printing. The material is Scalmalloy, a super-strong and lightweight alloy. Compared with the original isolation structure of the A320's new cabin design, the new bionic isolation structure is composed of several different components, which is not only stronger but also reduces its total weight by 45% (Xu *et al.*, 2021).

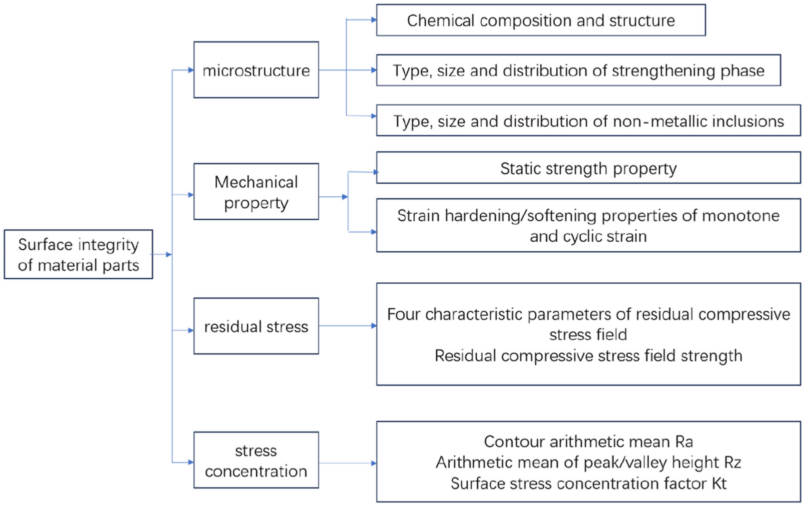
2. Surface integrity of metal additive parts

2.1 Surface integrity of titanium alloy parts

For the AM method of metal parts, the selective laser melting (SLM) method is generally used, which the laser beam fuses and melts the powder bed to form a material layer. It is mainly used for titanium alloys, cobalt-chromium alloys and stainless steel. Printing of metal powders (Zeng and Liu, 2016; Bejjani *et al.*, 2020).

Part surface integrity refers to the general term for the surface geometry and physical properties of parts after processing (He and Deng, 2015). There are many physical quantities that characterize surface integrity, as shown in Figure 1 (Wang, 2011).

As a new type of metal structural material, titanium alloy has outstanding advantages such as low density, high specific strength, strong plasticity, corrosion resistance and high-temperature resistance. It is widely used in many fields such as aerospace, medical, shipbuilding, precision machinery and instrument manufacturing (Lai *et al.*, 2019). However, its high melting point, high molten state activity and large deformation resistance also cause



Source(s): Figure courtesy of He and Deng (2015)

Figure 1.
Various physical quantities characterizing the 4 parameters of surface integrity

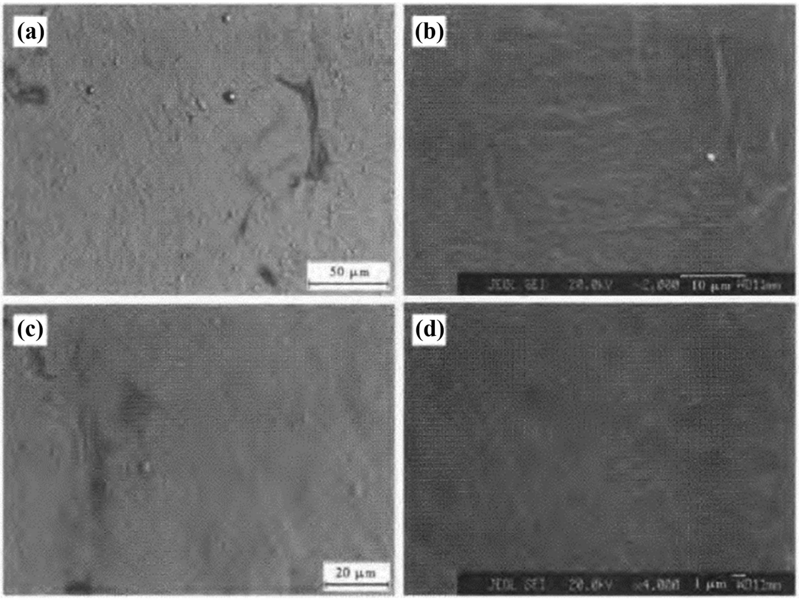
shortcomings such as low material utilization and high cost in the traditional preparation and forming process (Xiao *et al.*, 2017). In AM, due to the quality problems of raw material powder, improper selection of processing parameters and difficulty in process control, AM parts have local printing defects such as pores and problems such as the key mechanical properties that lower than forgings (Xiaoning, 2017).

The following is a detailed description of several different titanium alloys.

The structure of the Ti-6Al-4V titanium alloy formed by SLM technology shows typical epitaxial growth of coarse β columnar crystals. In Figure 2, it shows that inside the columnar crystals are lamellar α' martensite structures with different orientations and the alloy structure is $\alpha + \beta$ phase (Ren *et al.*, 2017). For this kind of titanium alloy, different scanning power, scanning speed and scanning spacing will affect its surface morphology, density and microhardness. The surface morphology and density first become better and then worsen with the increase of scanning speed and scanning spacing and the hardness decreases with the increase of scanning speed and scanning spacing (Li *et al.*, 2017b).

At present, the heat treatment process for SLM AM of titanium alloys basically follows the heat treatment procedures of traditional casting and powder metallurgy. However, based on the characteristics of the SLM process and the structural characteristics of the formed parts, the existing heat treatment procedures are difficult to meet the requirements for its mechanical properties. Therefore, a heat treatment process system suitable for SLM AM of titanium alloy construction needs to be developed (Ruyi *et al.*, 2022).

Surface treatment has a certain effect on improving the fatigue strength of SLM formed components, but most of them are still in the experimental stage and few can really be applied in actual engineering. Laser polishing and chemical polishing processes overcome the difficulty of mechanical polishing parts with complex shapes and have greater advantages in improving the fatigue performance of AM components (Marimuthu *et al.*, 2015). Traditional shot peening is a cold working technology that uses projectiles to bombard the surface of the workpiece to induce strong plastic deformation through pure physical impact to introduce residual compressive stress. It can be used to close the pores on the surface of SLM formed



Source(s): Figure courtesy of Ren *et al*. (2017)

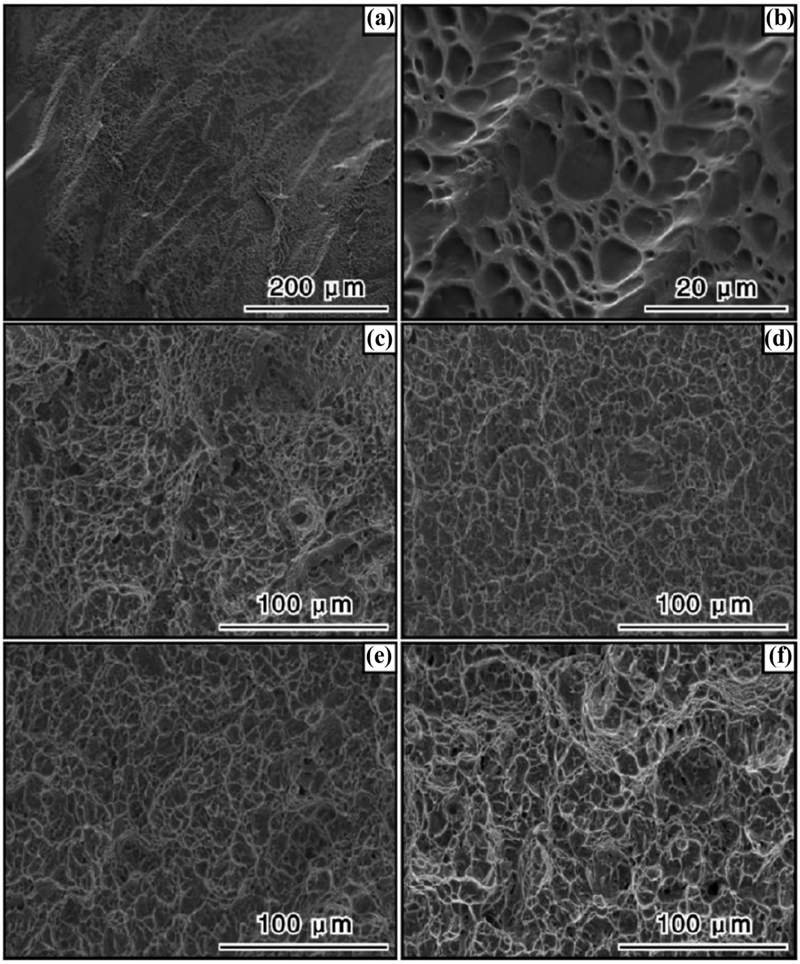
Figure 2. Typical microstructure of SLM formed Ti-6Al-4V

parts, forcing cracks to sprout from deeper places, thereby strengthening the fatigue performance of parts (Xu *et al.*, 2018).

TC4 titanium alloy is a typical $\alpha + \beta$ titanium alloy with good comprehensive mechanical properties and can be strengthened by heat treatment. It is the most widely used titanium alloy in aircraft structures (Cai *et al.*, 2020). In Figure 3, during the SLM forming process, the alloy sample undergoes martensite transformation, and the structure is acicular α' phase. After the TC4 alloy sample is annealed, the α phase decomposes, and the microstructure is mainly composed of (α, β) phases. After solid solution aging treatment, the TC4 alloy sample is composed of α phase and β phase (Zhang *et al.*, 2022b). Comparing several different heat treatment processes, research shows that the strength and hardness of SLM formed TC4 alloy samples have been improved to a certain extent after heat treatment. After 800°C/2h annealing treatment, the TC4 alloy sample has the lowest residual stress value of 43 MPa, which best matches the strong plasticity properties (Huang, 2018).

Ti17 titanium alloy not only has the characteristics of $\alpha + \beta$ type alloy, but is also a transition type alloy rich in β stabilizing elements. Its composition is shown in Table 2. Among them, Al, Sn and Zr metal elements are mainly used for solid solution strengthening of the α phase. Mo can both strengthen the β phase and improve the hardenability of the alloy. Compared with other isomorphous forms, Cr stabilizes β. Beta-stabilizing elements have higher ductility and toughness (Yanyan *et al.*, 2017).

The residual compressive stress induced by the laser reduces the actual working stress on the surface of the specimen and increases the critical stress level for fatigue crack initiation; at the same time, the action of the laser shock wave uniformly refines the surface structure of the material, increasing the difficulty of crack initiation. This phenomenon is shown in Figure 4. Residual compressive stress and grain refinement are the main reasons why laser shock strengthening improves the fatigue strength of repaired specimens (He *et al.*, 2015).



Source(s): Figure courtesy of Huang (2018)

Figure 3.
Fracture morphology of TC4 titanium alloy specimens formed by SLM in different states

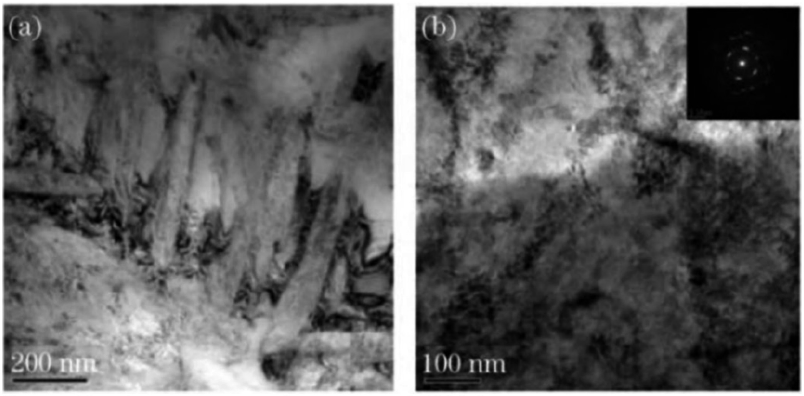
Table 2.
Main chemical composition of Ti17 titanium alloy

Al	Sn	Zr	Mo	Cr	Fe	C	N	H	O	Ti
4.5–5.5	1.6–2.4	1.6–2.4	3.5–4.5	3.5–4.5	0.3	0.05	0.05	0.0125	0.08–0.13	Bal

Source(s): Table courtesy of Yanyan *et al.* (2017)

2.2 Surface integrity of nickel-based alloy parts

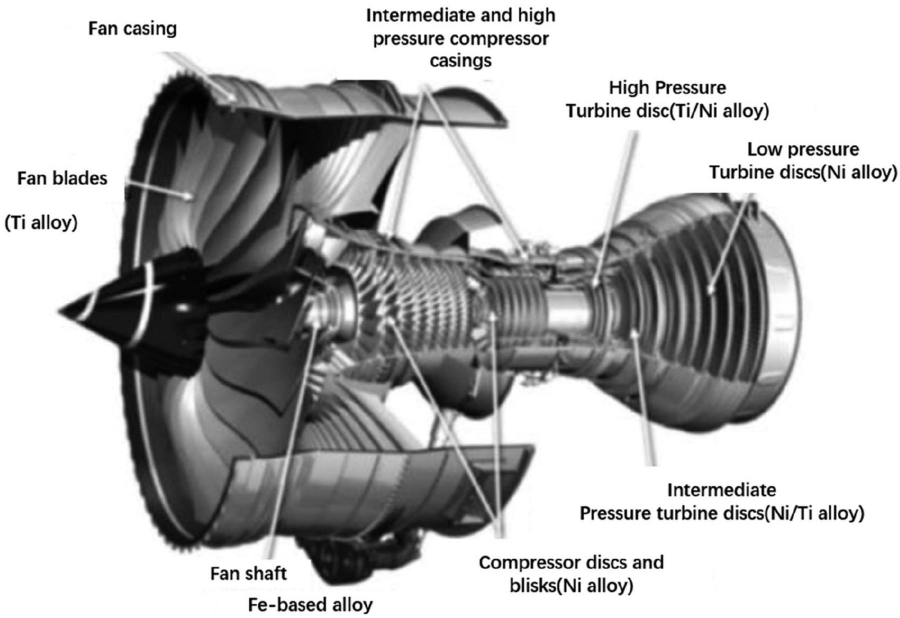
2.2.1 Overview of nickel-based alloy additive manufacturing. In recent years, nickel has been widely used due to its excellent high-temperature mechanical and chemical properties, high toughness and ductility, high melting point, excellent corrosion resistance, thermal shock resistance, thermal fatigue resistance and erosion resistance (Thakur and Gangopadhyay, 2016). Base alloys are widely used in aerospace, shipbuilding, nuclear reactors, chemical



Source(s): Figure courtesy of Yanyan *et al*. (2017)

Figure 4.
TEM image of Ti17 titanium alloy matrix area. (a) Specimen without laser shock (b) Specimen with laser shock

industry and other fields. They are mainly used in key components of aerospace engines and gas turbines, usually operating at temperatures exceeding 800° C (Williams and Starke, 2003). The aerospace engine is shown in Figure 5 Approximately 50% of high-temperature alloys in China are composed of nickel-based alloys (M'Saoubi *et al.*, 2015). Therefore, nickel-based alloys have become the most widely studied alloy materials in the field of AM. Its AM technology has attracted widespread attention from academia and industry due to its unique ability to manufacture complex high-performance components required for high-end industrial systems (Guo *et al.*, 2022).



Source(s): Figure courtesy of M'Saoubi *et al*. (2015)

Figure 5.
Rolls-Royce XWB turbofan engine schematic

The machined surface integrity of nickel-based alloy parts is an important aspect that affects their functional performance, including fatigue life. Nickel-based alloy materials have low thermal conductivity, high work hardening tendency and the presence of abrasive carbide particles in their microstructure. These properties will have a negative impact on the processing of nickel-based alloys (Gao and Zhao, 2019). At the same time, the rapid heating and cooling steps in the layer-by-layer superposition process of AM manifest themselves as large temperature gradients in the molten pool, inevitably leading to serious metallurgical defects in nickel-based alloy parts (Guo *et al.*, 2022).

2.2.2 Surface integrity. Surface integrity can be defined as: the combination of mechanical, metallurgical, morphological, thermal and chemical characteristics of the workpiece surface obtained through the manufacturing process (Pervaiz *et al.*, 2014), including the mechanical properties of the workpiece material during processing (residual stress, hardness etc.), metallurgical state (phase transformation, microstructure, grain size and shape, inclusions and related performance changes, etc.) and morphological characteristics (texture, waviness, surface roughness, etc.). The connotation of surface integrity is the general term of surface geometry and surface physical properties of parts after processing. As shown in Figure 6, surface geometric characteristics include surface roughness, waviness, texture, defects, etc. Surface physical property characteristics include microstructure changes, plastic deformation, recrystallization, microhardness, thermal damage area, residual Stress, microscopic cracks, dilution of alloy elements, etc. Surface integrity affects functional performance by controlling tribological phenomena such as friction and wear behavior, lubrication efficiency, stress corrosion and fatigue crack propagation of the contact body (Pervaiz *et al.*, 2014).

Since the processing characteristics and forming principles of AM and traditional machining are different, the surface integrity of the two parts is also different. At present, there have been relatively detailed and systematic studies on the surface integrity of conventionally machined nickel-based alloy parts, while research on the surface integrity of AM is still being carried out gradually. There are few documents in this field which are not comprehensive and not clearly summarize the surface integrity and characteristics of nickel-based alloy additively manufactured parts. This section will focus on AM from the aspects of

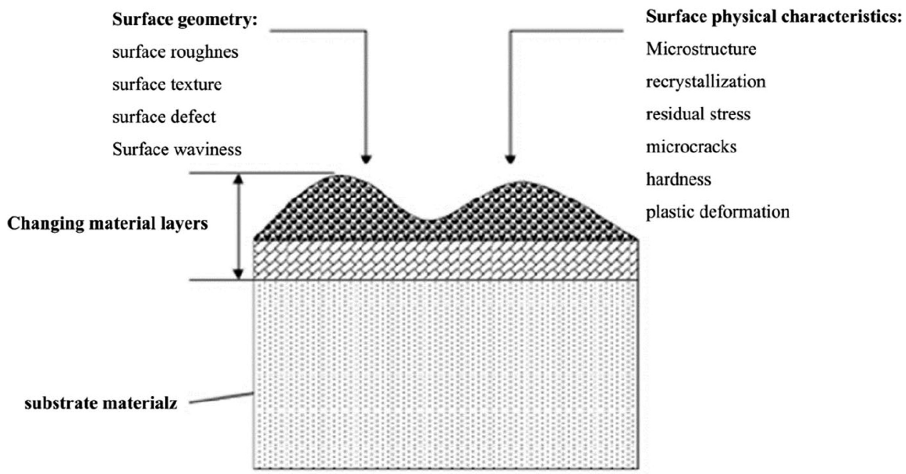


Figure 6.
Schematic diagram of surface integrity

Source(s): Figure courtesy of Pervaiz *et al.* (2014)

microstructure, residual stress and cracks and provide a certain explanation of the surface integrity of nickel-based alloy parts, laying the foundation for subsequent research.

(1) Microstructure

When processing nickel-based alloys using powder bed fusion (PBF) technology, it is easy to form a directional columnar grain structure. This is because the previously formed grains will be partially remelted each time the laser passes. This heat sinking effect creates a highly directional thermal gradient, with heat flowing along the axis of the cast slab, whereby grain elongation is observed (Williams and Starke, 2003).

When using selective laser melting (SLM) technology to process nickel-based alloys, the grain structure is closely related to the texture. In this case, nickel solidifies better in the {0 0 1} direction. When it solidifies directionally or is in single crystal casting, the resulting material shows an obvious {0 0 1} texture along the heat flow axis (M'Saoubi *et al.*, 2015). Furthermore, this directional heat flow is responsible for the formation of elongated grains associated with SLM fabricated materials, often resulting in highly textured microstructures. Some IN 625 samples processed by SLM technology experienced rapid solidification of the material because insufficient time was left for carbide precipitation or diffusion of carbide-forming elements in the material (Guo *et al.*, 2022). These newly formed carbides can precipitate at grain boundaries to form particles, which allows the microstructure to be "tailored" to improve mechanical properties.

(2) Residual stress

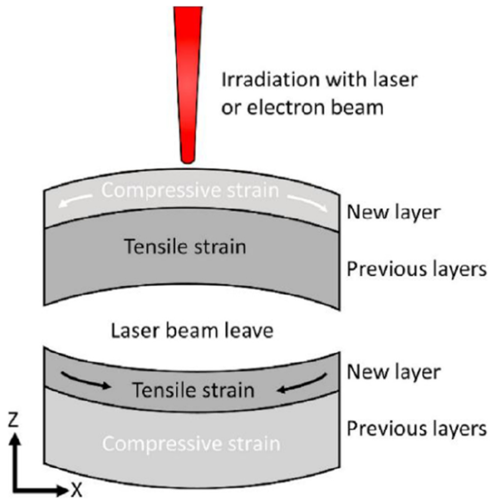
Residual stress, also known as internal stress, is usually defined as the residual stress in mechanical materials in the absence of external loads. It is usually caused by the phase change and temperature gradient produced during the solidification process and the hardening of the material. Formed by accumulation (Gao and Zhao, 2019), all thermomechanical manufacturing processes will produce residual stress. In the process of AM, the rich physical and chemical reactions and the unique thermal changes of the layer-by-layer additive process usually lead to thermal expansion and contraction of the solidified tissue, thus generating high levels of residual stress (Pervaiz *et al.*, 2014).

Similar to traditional machining, the residual stress in AM of nickel-based alloys is mainly mechanical stress, thermal stress and structural stress. The mechanical stress results from the severe shrinkage of the area near the molten pool that occurs during the manufacturing process. Thermal stress is largely caused by the strong temperature gradients generated by uneven and rapid heating and cooling processes during the manufacturing process. Structural stress is caused by microstructure changes (such as heat-affected zones) or volume expansion and contraction during rapid solidification, which are caused by certain volume phase changes. When any stress exceeds the yield strength of the nickel-based alloy material, the material will release the stress through plastic deformation, causing the shape of the component to be distorted or cracked, leading to component failure. These are unacceptable in practical applications, so they must be included in the design. When additively manufacturing part structures, it is important to consider that the residual stress field should be accurately measured to ensure that the residual stress is within a tolerable range, as shown in Figure 7.

(3) Cracks

- Solidification cracking

Solidification cracking, also known as thermal cracking, often occurs in traditional nickel-based alloy processing (Amato *et al.*, 2012). During the AM process of nickel-based alloys, solidification cracking is prone to occur in the fusion zone of the molten pool, resulting in long



Source(s): Figure courtesy of Field *et al*. (1989)

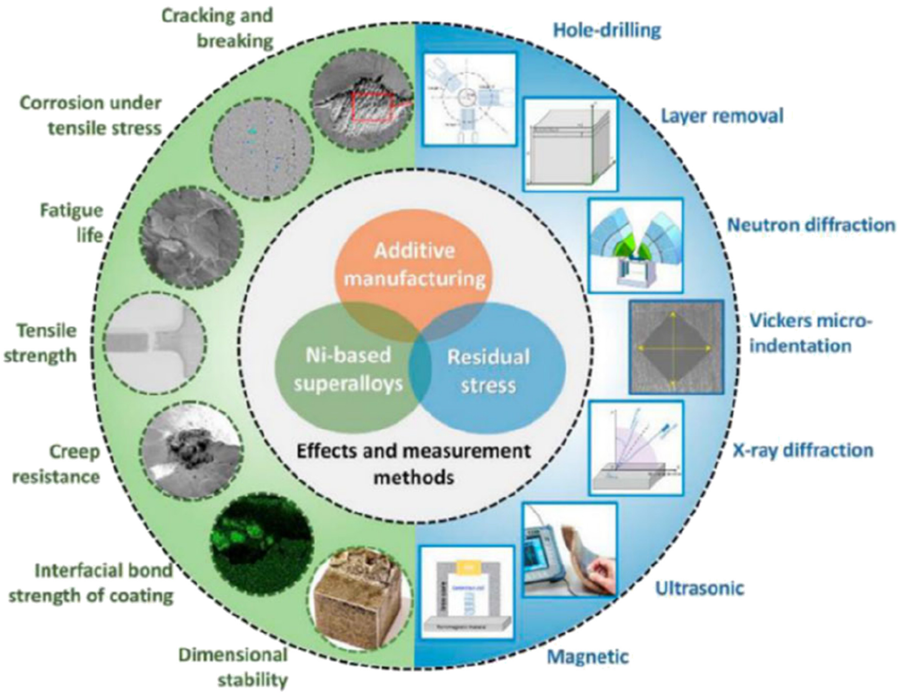
Figure 7.
Temperature gradient mechanism of thermal stress

and straight cracks at the grain boundaries. The typical mechanism of solidification crack formation is depicted in Figure 8. During the metal AM process, dendrites are formed in front of the interface between molten metal and solid metal. Since the metal powder experiences rapid heating and cooling during these processes, the molten metal is in a non-equilibrium solidification state, causing solute distribution and segregation at the solidification interface front. The segregation of elements at grain boundaries lowers the solidus of the molten metal, thus forming a liquid film rich in solute elements in these regions. As the solidification process continues, the solidified dendrites increase in size and the dendrite arms connect, thereby isolating regions of molten metal. These regions are called "islands." Subsequent solidification of these "islands" creates voids that are not filled by molten metal, causing cracks. Specifically, since the residual stress generated during the solidification process can be transferred through the solid but not through the liquid, this residual stress accumulates in the liquid film and is greater than its yield strength, resulting in the formation of crack paths in the liquid film. The final stage of solidification propagates along these paths, eventually forming cracks (Qibiao and Yin, 2016).

Heydari *et al.* (2014) found that the IN718 superalloy formed by direct electron detectors (DED)-laser beam (LB) formed solidification cracks only in the top region. Since solidification starts at the bottom of the molten pool and ends at the top, solidification cracks can be eliminated by remelting and depositing subsequent layers. Therefore, the impact of solidification cracks on the mechanical properties of additively manufactured parts from nickel-based alloys is negligible and the final layer of the part can usually be removed in a post-processing step before industrial application.

- Liquation cracking

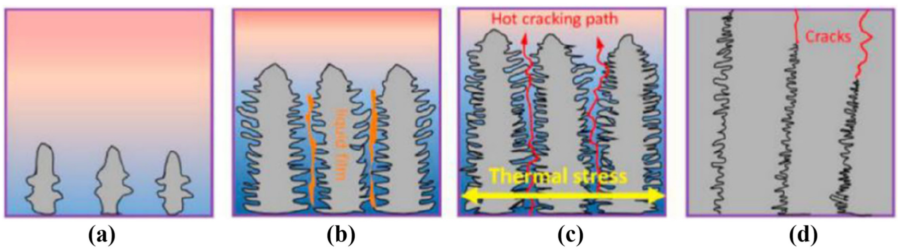
Liquation cracking usually occurs during the laser welding forming process of nickel-based alloys. It appears in the form of micro cracks in the heat-affected zone of the weld bead and molten pool. It is caused by the liquefaction of components and the secondary precipitation of low melting points.



Source(s): Figure courtesy of Guo *et al*. (2022b)

Figure 8. Potential adverse effects and measurement methods of residual stress in additive manufacturing of nickel-based alloys

Component liquefaction is shown in Figure 9(a): First, rapid heating in AM and welding concentrates solutes in a solid-state solution at the precipitate/matrix interface in the heat-affected zone. Then, when the local temperature and solute concentration reach the precipitate-matrix eutectic equilibrium, a metastable liquid film is generated at the precipitate-matrix interface, causing the components to liquefy. When these liquid films reach a certain surface density, they combine to form a larger single-zone film, leading to liquefaction cracking (Li *et al.*, 2015). Secondary precipitates with low melting points, such as $\gamma'-\gamma$ eutectic precipitates, γ-Laves eutectic precipitates and carbides, can also cause liquefaction cracking because these precipitates can melt at the corresponding melting point and cocrystal during subsequent heating cycles. The crystal points melt, thereby forming cracks, as shown in Figure 9(b).



Source(s): Figure courtesy of Guo *et al*. (2022b)

Figure 9. Schematic diagram of the formation mechanism of solidification cracking

Collins *et al.* (2004) observed that liquefaction cracks that occurred during laser deposition of IN718 superalloy started from weak links near the fusion line of the newly deposited layer and propagated along the inter dendritic region of the heat-affected zone of the previously prepared layer. They believe that this cracking is caused by direct melting of the γ-Laves eutectic phase. Due to the effects of residual stress, welding instability and segregation between dendrites, the sensitivity of melting cracking is proportional to the laser scanning speed and energy input. In addition, they experimented with substrate cooling methods and reduced liquefaction cracking.

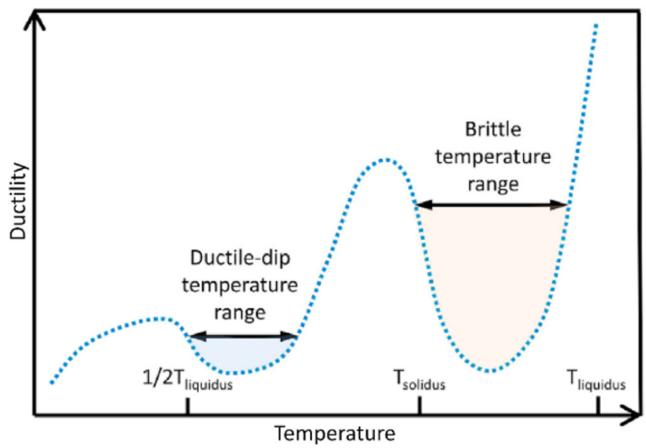
- High-temperature loss of plastic cracks

Ductility dip cracking (DDC) is a solid-phase phenomenon that occurs at high temperatures, commonly found in austenitic stainless steels and nickel-based alloys formed by multipass welding and laser AM (Chen *et al.*, 2016). As shown in Figure 10, during the rapid cooling process of metal AM, the plasticity of the material does not decline monotonically, but fluctuate. The first trough of plasticity occurs at the heating peak temperature ($\approx T_{liquidus}$) and plastic recovery temperature ($DRT \approx T_{solidus}$), i.e. the brittle temperature range (BTR) (Ramirez and Lippold, 2004). In BTR, the material contains a large amount of molten metal in a “paste” state, which leads to solidification cracking, as described in 2.3.1. As the local temperature continues to decrease, in $T_{solidus}$ and $\frac{1}{2}T_{liquidus}$, The plasticity of the material is further reduced. In this temperature range, DDCs are thought to be formed through a creep-like mechanism along grain boundaries due to “plastic depletion” (Chittewar and Patil, 2021).

Figure 11 is a typical example of DDC in nickel-based alloys (Ramirez and Lippold, 2004). Zhang *et al.* (2019) found severe DDC in IN738 superalloy prepared with DED-LB. They believe this is due to the interaction of DDC and liquefaction cracks, i.e. cracks are induced by microscopic liquefaction cracks and then formed by coupling to DDC propagation.

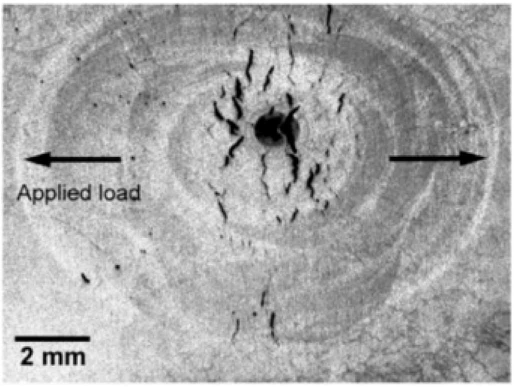
- Oxide cracking

The metal AM process is typically carried out in an inert gas shielded environment or under a vacuum. However, during gas atomization, reactive gases (especially oxygen) cannot



Source(s): Figure courtesy of Guo *et al.* (2022b)

Figure 10.
Plasticity curve with temperature

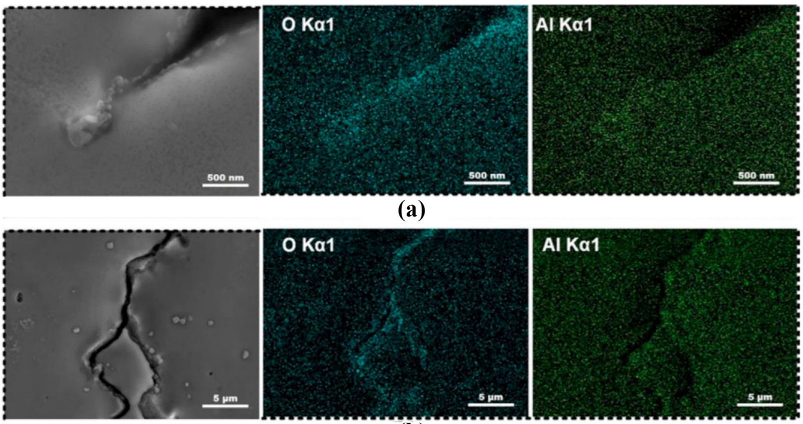


Source(s): Figure courtesy of Ramirez and Lippold (2004)

Figure11. DDC in nickel-based alloy

be completely eliminated from the operating chamber and may also be trapped in the hollow powder. During the interaction of the laser or electron beam with the powder bed, residual oxygen can react with the molten metal, which can lead to instabilities such as Marangoni convection, recoil pressure, Plateau-Rayleigh instability and spheroidization (Guo *et al.*, 2020b, 2021), which can reduce the quality of the additively manufactured part.

Nowadays, the effect of oxygen on the microstructure and defects of additively manufactured parts has received increasing attention, with a focus on cracks caused by oxide formation. Zhang *et al.* (2019) found that in the IN738 alloy formed from DED-LB, O and Al were enriched around the crack and analyzed by energy spectroscopy (EDS) imaging, Al2O3 was found in the front of the crack zone, as shown in Figure 12. They propose that oxides induce crack formation in two ways. First, oxygen diffuses to the front of the crack, which reduces the bond strength of the grain boundaries at the crack tip, thereby accelerating the crack propagation. Secondly, these brittle oxides, or fractures at the interface between the oxide and the matrix, lead to crack propagation. Similarly, Qiu *et al.* (2019) also detected



Source(s): Figure courtesy of Zhang *et al*. (2019)

Figure 12. Imaging analysis of IN738 spectroscopy

the presence of Al2O3 in IN738LC superalloy cracks formed by PBF-LB, while also detecting the presence of Si and W oxides. Nanoindentation tests have shown that these oxides are significantly much harder than matrix γ, and they cause embrittlement at the grain boundaries, which promotes crack propagation.

3. Integrated processing and application of metal additive and subtractive materials

3.1 The current situation and demand for the integration of metal additive and subtractive materials

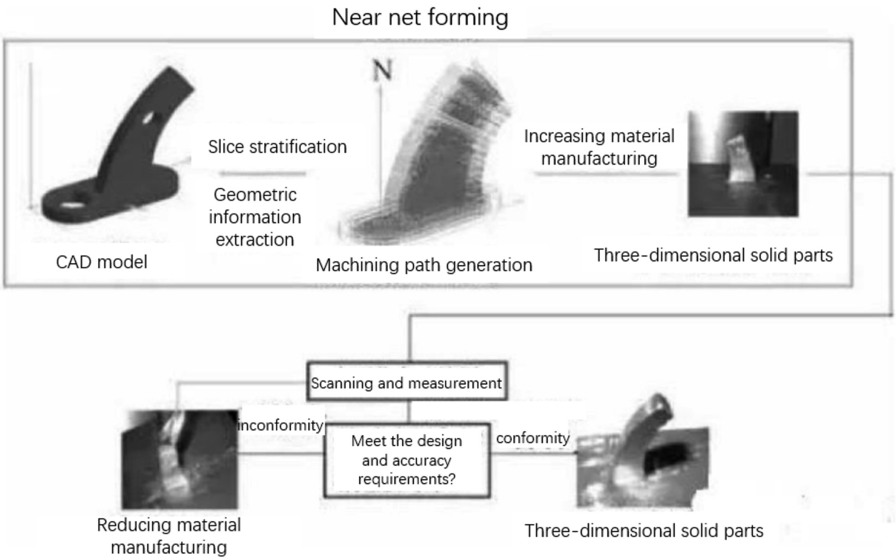
3.1.1 The principle of additive and subtractive integrated processing technology. Additive and subtractive composite processing technology is a new technology that combines product design, software control and additive/subtractive manufacturing. The 3D model generated by the design software is layered in thickness, and then the 3D data information of the part is converted into a series of 2D or 3D contour geometric information, which is fused into the deposition parameters and machining parameters to generate the numerical control code of the AM processing path and finally form the 3D solid part (Ma, 2014). Then, by measuring the formed 3D solid parts, the feature comparison is carried out, and after finding the error area, the parts are further processed and corrected by subtractive manufacturing until they meet the product design requirements. This enables "addition and subtraction" machining on the same machine, which is a hybrid solution of the existing combination of 3D printing and computer numerical control (CNC) machining (Wang, 2012). It not only avoids the accumulation of errors caused by the clamping and pick-and-place of the workpiece during multi-platform processing, improves the manufacturing accuracy and production efficiency, but also saves the workshop space and reduces the manufacturing cost.

It can be seen from the principle of additive and subtractive integrated processing technology that the essence of this technology is the three-dimensional accumulation and machining process driven by CAD software. Therefore, a basic multi-tasking system consists of the following components: a CNC machining center, deposition manufacturing, a feeding system, a software control system and an auxiliary system (Huang and Xiao, 2000). Figure 13 shows the principle of integrated processing of additive and subtractive materials.

3.1.2 The current situation and demand of additive and subtractive integrated processing technology. In the product design stage, the problems that may arise in AM should be considered as a whole. First of all, from the perspective of manufacturing maturity, subtractive manufacturing has accumulated very mature experience in mechanism design, automatic control, intelligent detection and equipment after hundreds of years of development since the industrial revolution (Li and Zhang, 2022). However, looking at AM technology, its development history is only a few decades, and it is still difficult to surpass the traditional subtractive manufacturing process in terms of cost, efficiency, accuracy, material, mechanical properties, etc., so most of the current 3D printing processes are still in a state of "looking beautiful". Material shrinkage, deformation in all directions, surface topography, etc., as well as the shape characteristics of parts, such as complex cavities, internal holes, thin walls and curved pipes, are all problems that are often faced and solved in AM (Wang, 2022).

In addition, in AM, molding efficiency and molding accuracy are contradictory and improving molding accuracy often means using a smaller focusing spot or nozzle and a thinner layer thickness, resulting in a significant increase in molding time; However, improving the molding efficiency will lead to worse molding accuracy (Quan *et al.*, 2021).

In addition, various constraints on the process need to be considered in subtractive manufacturing, such as the geometry of the tool, the trajectory and range of the tool and the number of tool turns.



Source(s): Figure courtesy of Huang and Xiao (2000)

Figure 13. Integrated machining principle

However, in the process of sintering functionally graded materials, it is necessary to convey a variety of different powders at the right time and in the right amount to obtain a gradient material ratio (Wang, 2019). The powder feeding system must control the flow and flow rate of each (up to four) powder separately. At the same time, in the laser AM process, the amount of powder fed needs to be precisely controlled. The powder flow must be uniform and consistent and the amount of powder fed can be adjusted in real time according to the control instructions. The minimum amount of powder should be one gram per minute. The flow rate of the existing powder feeding system is too large, not uniform and consistent, and the flow rate is unstable, and it is not possible to accurately feed the powder (Xiong *et al.*, 2022) Therefore, a new powder feeding system needs to be designed to precisely control the powder flow rate and achieve uniform consistency and repeatability of powder feeding at very small flow rates.

Because of its combination of the advantages of AM and traditional subtractive processing, the promotion and application of additive and subtractive composite processing technology will promote the related industries to usher in a further leap forward for the civil aviation industry and the national defense industry, which often use high-hardness composite metal materials and confidential processing (Gao and Zhao, 2019).

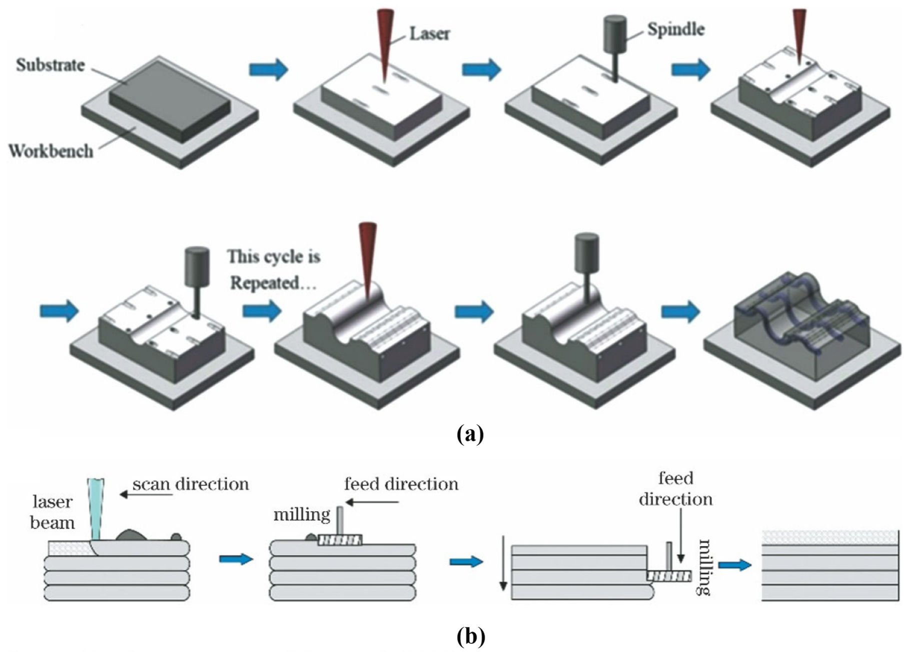
3.2 Combination of additive manufacturing and traditional subtractive manufacturing processes

3.2.1 Overview. AM and CNC machine tool composite processing has attracted great attention at home and abroad. Composite processing technology integrates metal powder selective laser melting additive processing technology and traditional high-speed cutting processing technology and comprehensively integrates material technology, computer software technology, laser technology and CNC machining technology, which is a new type of processing technology and will also be a development trend.

3.2.2 Combination of additive manufacturing and milling. The additive and subtractive composite manufacturing technology based on AM and subtractive manufacturing makes up for the shortcomings of AM, such as low dimensional accuracy and poor surface quality and not only has the advantages of AM for manufacturing complex parts, rapid prototyping and high material utilization, but also takes into account the advantages of high quality and high precision of subtractive processing. As shown in Figure 14, the basic process flow is roughly as follows: relying on AM to achieve material layer forming, using subtractive technology to improve surface quality and stress state and manufacturing the required parts through the combination of the two technologies (Gao and Zhao, 2019).

The following is the specific processing sequence: In the processing device, the laser generator is an important processing source, the laser is concentrated on the workpiece through the reflector and condenser lens and the powder in the powder box of the device is immediately sent to the surface of the workpiece for spreading. The spindle is the power head of processing, which reads out the full frame according to the computer instructions and the charge coupled device (CCD) photoelectric sensor camera, commands the movement of workbench X, Y and Z and finishing milling, in which melting, lamination and milling are repeated repeatedly. (1) Use a laser to melt the metal powder spread on the metal bottom plate; (2) repeatedly spread the metal powder and carry out laser melting and superimpose the shape layer by layer to make the thickness of the stack reach the effective blade length of the cutting tool; (3) cutting is applied to the side of the stack with a small-diameter cutting tool; (4) Repeated laser melting, stack molding and high-speed cutting processing; (5) Finally, a three-dimensional shape with a precision machined surface is made (Tao and Qiu, 2020; Chen, 2021).

A composite manufacturing platform for laser powder feeding, milling and cutting was built and the coordination of additive and subtractive process coordinates was carried out



Source(s): Figure courtesy of Gao *et al*. (2019)

Figure 14.
Basic technology of additive manufacturing and milling

(Xu, 2021). The 316L stainless steel specimen was formed by milling and cutting SLM and three milling process parameters, including milling speed, milling depth and feed, were selected to study the SLM formed specimen from the perspective of subtractive material (Zhu, 2022). 316L stainless steel powder was used as the test material to carry out the test of laser additive and subtractive composite processing of thin-walled parts and the thermal stress deformation of thin-walled parts after the additive and the secondary deformation of the added thin-walled parts after milling were detected (Li and Lin, 2022). In order to solve the problem of poor surface roughness of electron beam selective melting molded parts, an electron beam additive and subtractive technology was proposed, based on electron beam selective melting and electron beam cutting composite. And two electron beam cutting methods, jump point scan and jump line scan, for 316L stainless steel were developed by using the existing electron beam selective melting equipment, and the cutting groove with a depth greater than 1 mm was obtained (Zhao and Mao, 2022).

A collaborative method for additive and subtractive manufacturing was proposed, and the results showed that after adopting this method, the contour accuracy of additive and subtractive composite manufacturing parts was increased by 3–6% on average, and the low-loss, high-precision additive and subtractive controllable manufacturing of complex parts was realized (Zou *et al.*, 2022). The basic principles, typical processes and characteristics of rapid tooling based on additive and subtractive composite manufacturing, as well as the new materials used in rapid tooling, are reviewed (Cao, 2019). Combining the respective technical advantages of addition and subtraction, iron-based alloy metal powder was used to form the brake disc of high-speed trains on the base of cast steel brake discs (Shu *et al.*, 2007). The construction of a machine tool for the combined processing of melt additive and milling, and the printing and milling of engineering plastics were studied.

3.2.3 Combination of additive manufacturing and special processing technology. There is no clear regulation on the classification of special processing, generally according to the energy source, action form and processing principle, it can be divided into electrical discharge machining (EDM), electrochemical processing, laser processing, electron beam processing, ion beam processing, plasma arc processing, ultrasonic processing, chemical processing, rapid prototyping, etc. (Zeng, 2022)

AM technology has received great attention from all over the world in the past 30 years and has been hailed as the "third industrial technology revolution" in human history. Metal AM technology is divided into two main categories: laser and electron beam printing technology according to the energy source. Metal AM technologies include selective laser sintering (SLS), direct metal powder laser sintering (DMLS), selective laser melting (SLM), laser forming (LENSS), electron beam selective melting (EBSM), etc.

When AM is combined with special processing technologies, different kinds of new technologies are created that can solve different specialized problems in a variety of fields.

In recent years, metal AM have shown explosive growth, with Imperial College London developing the electrochemical additive manufacturing (ECAM) metal 3D printing process and ExOne developing binder jetting (BJ) technology. Fabricson developed ultrasonic 3D printing (UAM) in 2017 and XJet developed inkjet metal printing technology. All metal 3D printing technologies show unique technological solutions (Yang, 2019b).

3.2.4 Electrochemical additive manufacturing. The electroplating solution flows to the surface of the cathode in the form of a jet, then the cathode, anode and jet electroplating solution form an electrodeposition system. The fluid interface formed by the jet is divided into the outer zone and the middle retention zone from the outside to the inside, and the relative flow velocity of the central part of the retention zone is theoretically zero and the reaction is relatively stable because the electroplating solution is sprayed in a continuous and uniform manner. In the jet coverage area, the anode and the cathode substrate form a loop through the electroplating solution, and the electroplating solution flows continuously to the surface of the cathode substrate, because the electric field line in the current beam produces a large current density in the micro-area where the cathode substrate and the anode tip are opposite, and the processing current undergoes an electrochemical reaction through this area to reduce the metal cation (Ni2+) in the electroplating solution to the elemental deposition of metal Ni through migration, diffusion and convection, while the current density is low due to the absence of a current beam passing through other parts, no deposition or a small amount of deposition occurs. The triaxial linkage working platform is used to connect the anode for deposition, and the deposition of the helical structure is formed by the precise point-to-point matching of the anode path and the microhelix structure. Therefore, localized ECAM not only has a fast liquid phase mass transfer process, but also has the advantages of selective deposition, which makes it possible to fabricate three-dimensional microstructures by ECAM.

Figure 15 shows that the electrodeposition of localized ECAM has a certain relationship with the overpotential value, and the overpotential value is affected by the combined effect of the voltage between the poles, the pulse duty cycle and the initial pole gap, so the selection of appropriate electrodeposition process parameters can be used for additive fabrication of micro helical structures (Wang *et al.*, 2018b; Hu *et al.*, 2021).

Pulse electrochemical machining (PECM) can be used to process high-strength and hardened metals. Meichsner *et al.* from Otto von Glick Magdeburg University proposed different effective process chains for processing 1,225 square holes using PEMCenter8000 and studied three different process flows: full cathode, segmented cathode, multi-cathode to design suitable ECM process chains, The results show that: the PECM process time is more efficient with the use of an intact cathode (Wei and Heng, 2021). The processed structure and surface are shown in Figure 16.

3.2.5 Binder jetting additive manufacturing. In 2018, metal binder jetting additive manufacturing (BJAM) was named one of the top 10 breakthrough technologies in the world by MIT Technology Review. Figure 17 shows that in recent years, BJAM's printing materials have expanded from iron-based materials to reactive metals such as titanium alloys, superalloys and even aluminum and magnesium. In 2021, DesktopMetal and UniformityLabs jointly launched a BJAM printer that can print fully dense 6,061 aluminum alloy, opening up a new space for the application of BJAM technology. Since 2012, the team has been researching and developing BJAM technology, early printing gypsum, polymer and foundry sand and now focusing on metal BJAM technology. In 2017, Wuhan Yifang Co., Ltd. launched a metal BJAM printer (Mostafaeietal *et al.*, 2020).

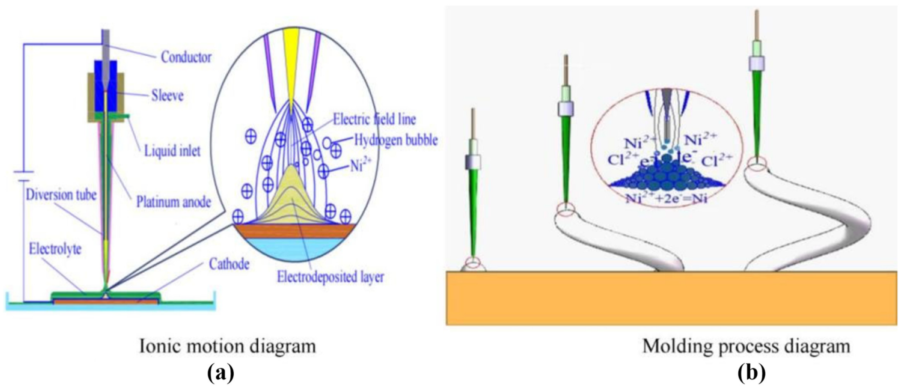
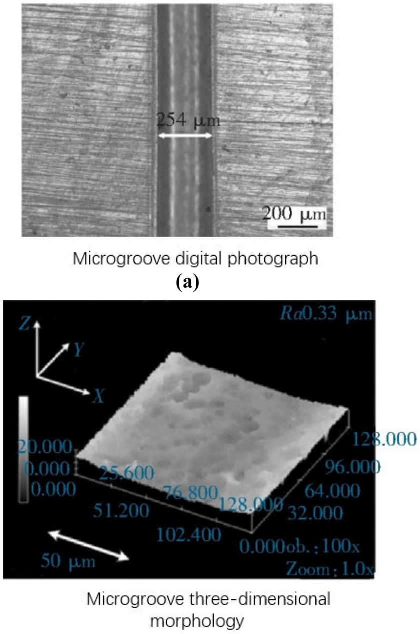


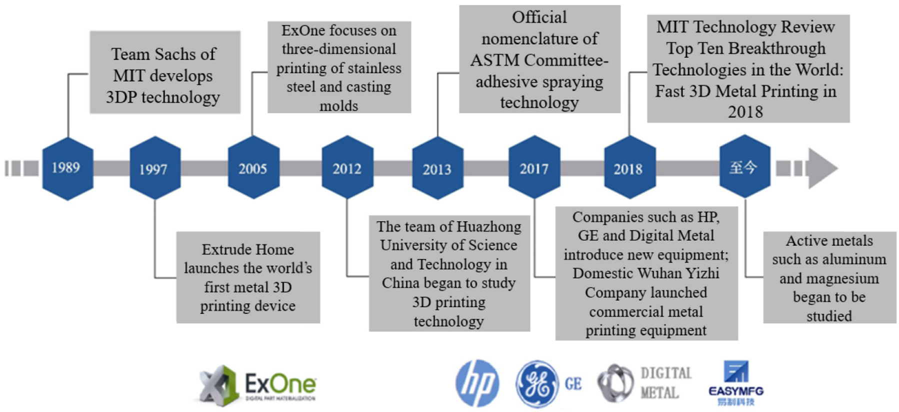
Figure 15.
Schematic diagram of electrochemical additive manufacturing

Source(s): Figure courtesy of Wang *et al*. (2018b), Hu *et al*. (2021)



Source(s): Figure courtesy of Wei *et al*. (2021)

Figure 16.
Machining micro-groove structure and surface morphology



Source(s): Figure courtesy of Mostafaeietal *et al*. (2020)

Figure 17.
Development course of binder injection additive manufacturing

The production process is as follows:

Printing: (1) Obtain a 3D model of the part according to modeling or scanning and convert the CAD model into an STL file that can be used for printing; (2) Spread a certain thickness of powder on the substrate; (2) spread a certain thickness of powder on the substrate; (3) Spray the liquid binder onto the powder layer and calculate the binder saturation according to the density of the powder bed; (4) After the spraying of one layer, the printing platform lowers the height of one layer, usually in the range of 50~200 μm. The powder rollers distribute the powder from the powder supply source to the powder bed.

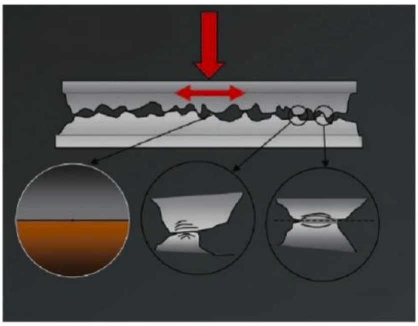
Curing and depowdering: After all the printing is complete, post-curing is required to dry the binder to give the billet sufficient strength. Heat until the binder is sufficiently dry and then remove the blank, which can usually be heated to 180℃–200℃ in an oven for a certain period of time for thermosetting resins such as phenolic resin or epoxy resin (Gilmer, 2020).

Sintering or impregnation: In order to obtain the best density and mechanical properties, further densification can be achieved by a variety of methods, such as sintering or impregnation. Before sintering, it is also necessary to remove the binder from the primary billet, i.e. degreasing. The sintering process is usually done in a single heat treatment process with debinding. For *in situ* crosslinkable binders (75% triethylene glycol dimethacrylate and 25% isopropanol), the binder can be completely burned out by heating at low temperatures (typically 250–630° C) for several hours (Yang and Tang, 2005).

3.2.6 Ultrasonic 3D printing. The ultrasonic metal welding technique was discovered by chance in the 30s of the 19th century. At that time, when doing the current spot welding electrode plus ultrasonic vibration test, it was found that welding could be carried out without current, so the ultrasonic metal cold welding technology was developed.

Although the discovery of ultrasonic metal welding technology is earlier than ultrasonic plastic welding, ultrasonic plastic welding is still widely used at present, because ultrasonic plastic welding has much lower requirements for the quality of the sonotrode and transducer power than metal welding. Therefore, due to the limitation of ultrasonic transducer power, ultrasonic welding technology has not been well applied and developed in the field of metal welding for many years and is mainly limited to four aspects: metal spot welding, roll welding, wire harness and pipe sealing (Liu *et al.*, 2003; Peng and Jiao, 2016).

Ultrasonic consolidation forming technology is to use high-power ultrasonic energy, using metal foil as raw material, using the heat generated by vibration friction between metal layers and layers, promoting the mutual diffusion of metal atoms between interfaces and forming solid-state metallurgical bonding, so as to realize the AM molding of layer by layer. Figure 18 shows a schematic diagram of the principle of ultrasonic consolidation. When the metal foil of the upper layer vibrates at high frequency relative to the lower layer of foil under the drive of ultrasonic indenter, the temperature of the convex part between the foils rises due to the heat of friction and plastic deformation occurs under the action of static pressure and the metal atoms in the ultrasonic energy field will diffuse to form an interface bond, so as to realize the metal layer by layer additive consolidation molding manufacturing. Combining additive



Source(s): Figure courtesy of Liu *et al*. (2018)

Figure 18.
Schematic diagram of ultrasonic consolidation principle

rapid prototyping with CNC milling and other processes, the 3D printing technology is formed that integrates ultrasonic consolidation forming and manufacturing (Liu *et al.*, 2018).

3.2.7 Electrical discharge machining (EDM). EDM is one of the most popular processing methods today. The tool electrode is constantly close to the workpiece to be processed, when the distance between the two poles reaches a critical value, the voltage between the poles breaks down the working liquid medium, thereby generating a spark discharge to remove the surface material of the workpiece and realizes complex three-dimensional parts processing (Yang, 2020).

As a processing tool for EDM, the discharge electrode is easy to form and has low wear rate requirements, which requires the electrode material to have the characteristics of high melting point, high thermal conductivity and high electrical conductivity. Corrosion-resistant materials such as copper and its alloys (such as copper alloys) and graphite are usually used as tool electrode materials with good conductivity, slightly higher melting point and easy processing (Dong, 2011).

EDM can be divided into three stages: (1) Ionization and breakdown of the interpolar medium and the formation of discharge channels; (2) melting, gasification and throwing of electrode materials; (3) deionization of interpolar media (Guo and Xiong, 2020). Among them, the melting and ejection removal mechanism of electrode materials is the focus of many scholars' research and all kinds of studies believe that the material is melted in EDM, and the final removal part is the melted part of the material, but there is no unified conclusion on the material removal method. Some theories suggest that material removal is mainly electrodynamic, i.e. high-density, high-speed electron impact on the anode to remove the anode material. The thermodynamic theory insists that the removal of materials is due to the action of thermal stress and the instantaneous high temperature and rapid drop caused by the pulse power supply cause the change of thermal stress and then remove the material. The theory of electric field mechanics holds that the key to material removal is that the high electric field gradient during discharge produces an electric field force far greater than the tensile strength of the metal material, which causes the metal material to peel off.

4. Surface integrity of integrated processing of metal additive and subtractive materials

4.1 Comparison of surface quality between the integration of additive and subtractive materials and the surface quality of pure subtractive materials

Additive and subtractive composite processing technology is a technology that combines the advantages of additive and subtractive manufacturing. The process combines AM and subtractive manufacturing, maintaining the advantages of AM in terms of processing speed, structural constructability, degree of automation, etc., while also ensuring high accuracy, precision and good material properties and surface finish through subtractive manufacturing (Wang, 2018), the relationship between them is shown in Figure 19 (Li and Zhang, 2022). Surface quality is a comprehensive description of the macroscopic and microscopic shape errors of the surface layer and the mechanical properties of the surface layer, including surface roughness, surface waviness, mechanical properties of the surface layer, etc. The surface quality has a significant impact on the performance and life of the part (Lv, 2016). In this paper, we will compare the surface quality of the integrated additive and subtractive materials from three aspects: surface properties, subsurface structure and mechanical properties.

First is the surface characteristics, mainly including morphology and roughness, etc., on the whole, the parts obtained by the integrated processing of additive and subtractive materials have better surface characteristics. Although pure subtractive manufacturing can also process to obtain better surface characteristics, it does not have many advantages of AM,

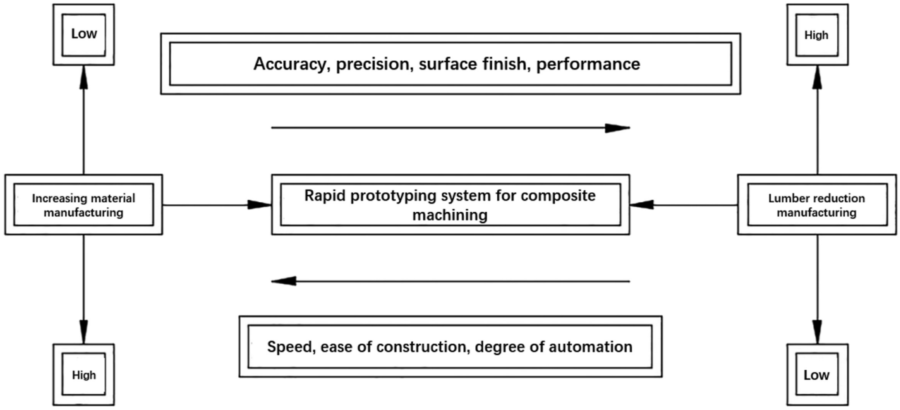
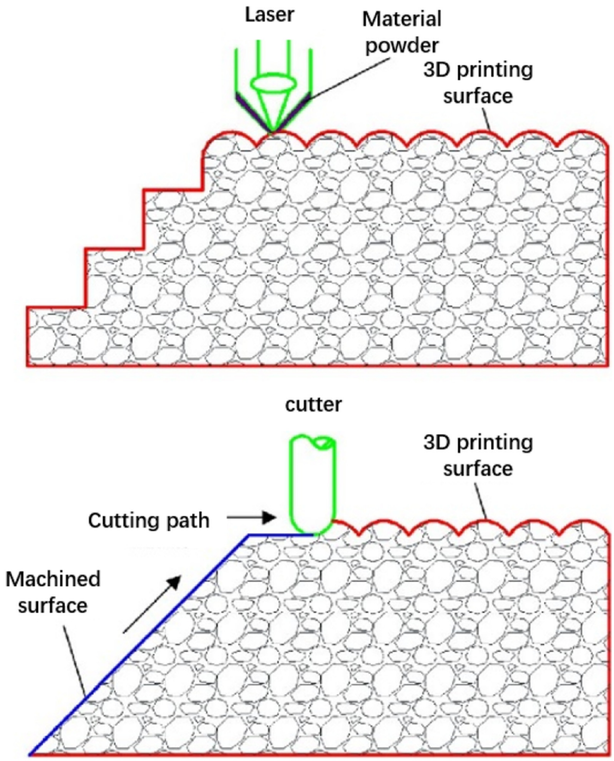


Figure 19. Characteristics of additive-subtractive composite manufacturing

Source(s): Figure courtesy of Li *et al*. (2022)

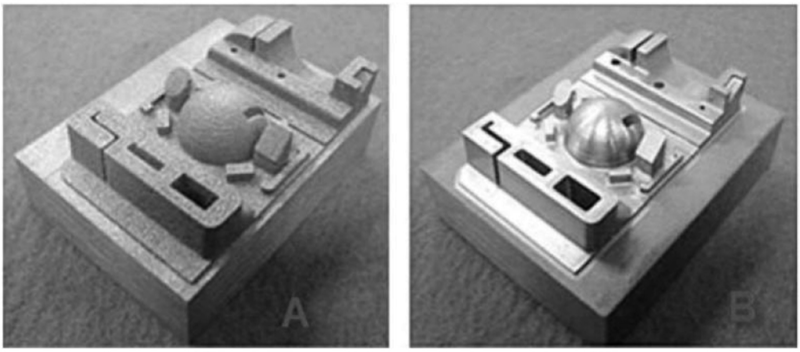
so in this regard, there is no integrated performance of additive and subtractive materials. Additive and subtractive hybrid manufacturing generally adopts the installation of a 3D printing device on a CNC cutting machine to realize the rapid 3D printing of the workpiece. CNC cutting processing is carried out on the same machine tool. Its working principle is shown in Figure 20, and the surface roughness of the workpiece can reach nanometer level (Lin *et al.*, 2020). The general surface roughness of pure subtractive manufacturing is in the micron range (He *et al.*, 2022), the turning accuracy is generally IT8-IT7, and the surface roughness is 1.6–0.8 μm; the machining accuracy of milling can generally reach IT8-IT7, and the surface roughness is 6.3–1.6 μm; the planing accuracy can generally reach IT9-IT7, and the surface roughness is Ra6.3–1.6 μm; grinding is typically used for semi-finishing and finishing with an accuracy of IT8IT5 or even higher, and a surface roughness of 1.25–0.16 μm is generally ground to 1.25–0.16 μm.

There are many examples of the integration of adding and subtracting materials. For example, the composite processing technology of metal powder laser modeling integrates the selective laser melting and adding materials processing technology of metal powder with the traditional high-speed cutting processing technology. During its operation, lamination and milling are repeated continuously. Finally a three-dimensional shape modeling with a precision machined surface is made, as shown in Figure 21. Compared with the previous simple metal powder selective laser melting lamination molding technology, its machining dimensional accuracy can reach below ±0.005 mm, with the hardness of the material after heat treatment reaching 54HRC (She *et al.*, 2021). In pure material reduction, taking milling as an example, the microstructure array processed by micromilling has high dimensional accuracy, and the dimensional deviation is within 5 μm (Tang *et al.*, 2022). In improving the surface quality of parts, the effect of compound machining of curved parts using additive and subtractive materials is more obvious. After using the process arrangement method of alternating increasing and decreasing materials for curved parts, relevant experiments prove that the wear of scraper is about 35% lower than that of the simple SLM processing method. This is because the surface roughness caused by the spheroidization of SLM processing surface and powder bonding increases with the increase of processing layers. This cumulative effect affects the dimensional accuracy of parts in the vertical direction and causes wear to the scraper used for powder spreading. This problem can be effectively solved by adding the upper surface milling process in SLM processing (Li and Lin, 2022). Electron beam powder bed melting and cutting combined material addition and subtraction



Source(s): Figure courtesy of Lin *et al*. (2020)

Figure 20. Working principle of mixed manufacturing of additive and subtractive materials



(a) (b)

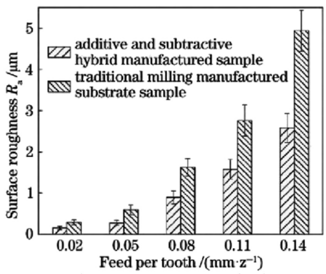
Note(s): A-part processed by SLM technology B-part processed by composite processing technology
Source(s): Figure courtesy of Li and Lin (2022)

Figure 21. Schematic diagram of comparison between SLM technology and composite processing technology

technology tries to improve the surface quality of the formed part by using electron beam to gasify and cut the contour of the formed part. Relevant experiments show that the roughness of the side surface of the sample is reduced from more than Ra25 μm to about Ra12 μm (Bo and Yuhua, 2017) under the condition of compound cutting technology. Similarly, scholars from Dalian University of Technology found that the surface roughness of maraging steel parts can be greatly reduced by using Sodick OPM250 equipment, which can integrate selective laser melting and CNC technology (Zhang and Xiong, 2007). Zhang Haiou of Huazhong University of Science and Technology and Xiong Xinhong of Wuhan University of Science and Technology put forward an effective method to control the step effect in AM process to realize the connection between plasma deposition and CNC technology. This method can control the dimensional error within 0.05% (Chen and Song, 2022).

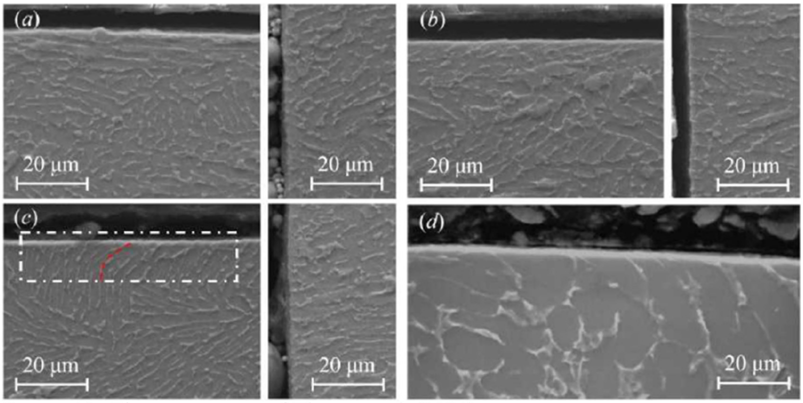
Chen Feng and others of South China University of Technology showed the comparison of surface quality between the composite manufacturing of additive, subtractive materials and the traditional technology with specific experiments. In order to study the surface quality and mechanical properties of the parts made by the composite manufacturing of additive and subtractive materials by powder feeding laser They took 316L stainless steel powder as raw material and manufactured the samples by the alternating cycle of "additive-subtractive-additive-subtractive". The final surface roughness result is shown in Figure 22. It can be seen that the surface roughness of the substrate sample increases with the increase of feed per tooth, while the surface roughness of the substrate sample increases faster than that of the substrate sample. At the same time, the surface roughness of the substrate sample is higher than that of the substrate sample. This is due to the difference of internal microstructure. The microstructure of the samples made by adding and subtracting materials is more uniform and the grain size is smaller, so its hardness and strength are higher while its plasticity is worse. During milling, the plastic deformation degree of the samples made by adding and subtracting materials is small, mainly brittle fracture. The deformation rebound is small, causing it not easy to produce chip accumulation tumor, so the surface roughness is reduced (Liu and Zhang, 2021).

Secondly, in the subsurface structure, mainly including microstructure and composition, the samples made by adding and subtracting materials have finer microstructure and grains than those made by traditional processes such as pure reducing materials. In general, when turning and milling titanium alloy, a layer of white hardened material can be found on the machined surface. This is because in the cutting process, under the strong thermal-mechanical coupling, the microstructure of the machined surface material will undergo complex evolution, which eventually leads to the microstructure of the machined surface material being different from the matrix material. The changed surface material is called "surface metamorphic layer" (Huang, 2017). The team of Dalian University of Technology conducted dry slot milling experiments on titanium alloy additive formed parts and compared them with traditional titanium alloy forgings. The results of related experiments are shown in Figures 23 and 24. Compared with the substrate samples, there is no



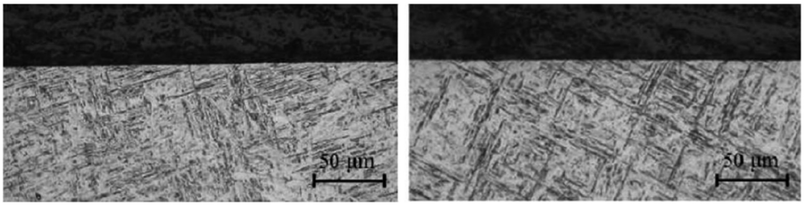
Source(s): Figure courtesy of Liu *et al.* (2021)

Figure 22.
Comparison of the surface roughness after milling between the sample made of additive/subtractive composite and the sample made of substrate by traditional technology



Source(s): Figure courtesy of Zhang *et al*. (2021)

Figure 23.
Surface microstructure of substrate specimens



Source(s): Figure courtesy of Zhang *et al*. (2021)

Figure 24.
Microstructure of the machined surface of an additive specimen under different parameters

metamorphic layer on the processing plane and side of the additive samples under all parameters (Zhang *et al.*, 2021b).

Finally, in terms of mechanical properties, mainly residual stress, hardness, etc., the integration of additive and subtractive materials can better process high-hardness composite metal materials, and this processing method can eliminate residual stress and internal defects in many cases. In AM, due to the uneven heating of materials, residual stress and deformation are generally generated. The synergistic manufacturing technology of additive and subtractive materials can play a positive role in reducing the above problems. For example, an AM experiment for steel that combines arc AM with rolling technology shows that the increased rolling process reduces the stress concentration of the component and reduces crack initiation and deformation, thereby increasing the service life of the component by 66% (Yang and Zhang, 2021). For rolled parts, the thinner and wider or the more brittle and hard the material, the weaker the flow ability of metal deformation, the more likely it is to produce large residual stress or local stress concentration, inducing the relaxation change of metastable defects, randomly forming multi-point or local instability warping or edge crack brittleness (Wu and Wu, 2022). The combination of AM and rolling can reduce stress concentration. In addition, the integrated manufacturing of additive and subtractive materials can also improve the fatigue properties of materials, such as experiments have shown that ultrasonic impact can make the surface of additive metal plastically deformed, achieve the effects of pore closure, grain refinement and residual compressive stress improvement, improve fatigue performance (Xu, 2004). In pure subtractive manufacturing, welding is a processing mode that often occurs. The stress concentration that welding will cause, as well as the inclusions, porosity, cracks, etc. of the welding part will become the stress concentration point, and these stress concentration points will greatly weaken the fatigue strength of the metal in the welding part, so as to produce the crack source point, then the fatigue crack will appear and cause the shaft to break (Song and Fu, 2022), and the use of additive and subtractive integrated manufacturing technology can avoid these situations. In addition, additive and subtractive integration eliminates internal defects. Metal AM technology has been greatly improved over the past few decades, and laser powder bed fusion (LPBF) technology is one of them. LPBF, also known as Selective Laser Melting (SLM), melts and solidifies metal powders at an extremely high rate in LPBF processing, causing drastic changes in the temperature and phase of the melt pool, and the parts are prone to internal defects, which affect the forming quality of the parts. In order to solve this problem, the milling processing composite LPBF came into being, in the additive and subtractive composite processing, the part manufacturing process is often divided into a plurality of machining layers. A machining layer will carry out a plurality of layers of LPBF processing and a milling process, thereby obtaining a part with complex internal structure and high surface quality. Additive and subtractive machining not only provides the flexibility of AM, but also the ability of milling to eliminate internal defects and improve the internal quality of parts. However, it is inevitable that the alternating processing of additive and subtractive materials will greatly reduce the processing efficiency of parts, so more efficient additive and subtractive composite methods need to be explored urgently (Yu, 2017). In terms of hardness, for the civil aviation industry and the national defense industry that often use high-hardness composite metal materials and confidential processing, the promotion and application of additive and subtractive composite processing technology will bring a new journey to the manufacturing industry and will also become the focus and hot spot of the manufacturing industry in the next step (Grzesik, 2018).

In terms of surface quality, AM has burst out of infinite vitality after the introduction of subtractive manufacturing and it also has a relatively good performance in many experimental studies Compared with pure subtractive materials, the integration of additive and subtractive materials has its own unique advantages, although there are not many related researches now, but I believe that in the near future, the integration of additive and subtractive materials will guide intelligent manufacturing to a new stage.

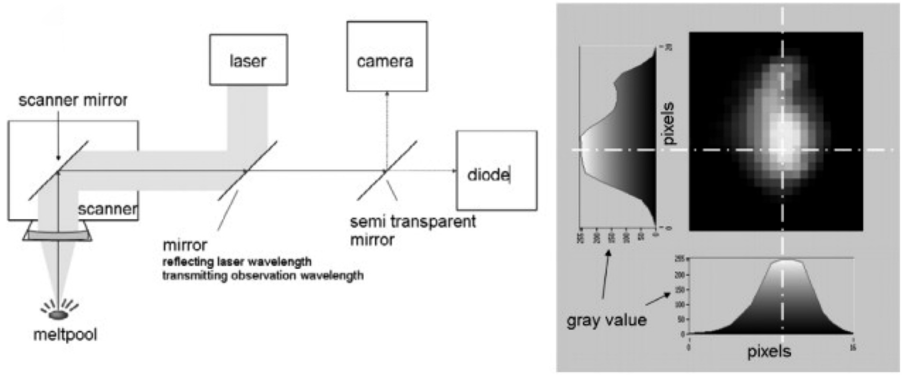
4.2 Methods of detection and analysis (1) surface characteristics

4.2.1 Methods for detecting and analyzing surface characteristics of integrated processing of metal additives and subtractions. At present, the surface characteristics of metal processing generally need to be processed after surface treatment and heat treatment (Waller *et al.*, 2014), but in the integrated processing of metal additives and subtractions, especially in the AM part, internal defects, such as pores, voids, cracks, etc. (Abouel Nour and Gupta, 2022) are prone to occur, which also makes it difficult to repair defects through post-processing (Hossain and Taheri, 2020). Therefore, it is best to perform surface property inspection and analysis during the manufacturing process, using *in situ* inspection methods for non-destructive testing (Mandache, 2019), analyzing the measurement data in real time and finding surface defects to guide the machining process (Kruth *et al.*, 2005). Next, we describe the current *in situ* testing methods for metal additive and subtractive manufacturing and analyze other non-destructive testing processes that may be suitable for *in situ* testing.

The PBF process uses a laser or electron beam as an energy source to melt powdered materials (Murr *et al.*, 2012). Different energy sources require different operating environments, requiring an inert atmosphere, usually nitrogen or argon, under the laser and under an electron beam near vacuum (Berumen *et al.*, 2010).

Early work on *in situ* detection of laser PBF focused on the use of line scan cameras (Craeghs *et al.*, 2012), with some closed-loop control in combination with photodiodes and melt pool temperature (Clijsters *et al.*, 2014). Its principle is shown in Figure 25. High-speed image processing from 10–20 kHz enables the identification of areas of molten powder and pores and detection of nodularization, local overheating and porosity (Furumoto *et al.*, 2013). High-temperature surface detection techniques have been applied to solidification studies of molten powders (Pavlov and Doubenskaia, 2010; Chivel and Smurov, 2010), but their application is limited by limited field of view and data acquisition rate (Krauss, 2012). Infrared thermography has shown great potential for *in situ* detection of laser PBF processing, with higher capture rates and higher accuracy. It also has been used to detect defects such as porosity caused by insufficient heat dissipation (Schwerdtfeger *et al.*, 2012).

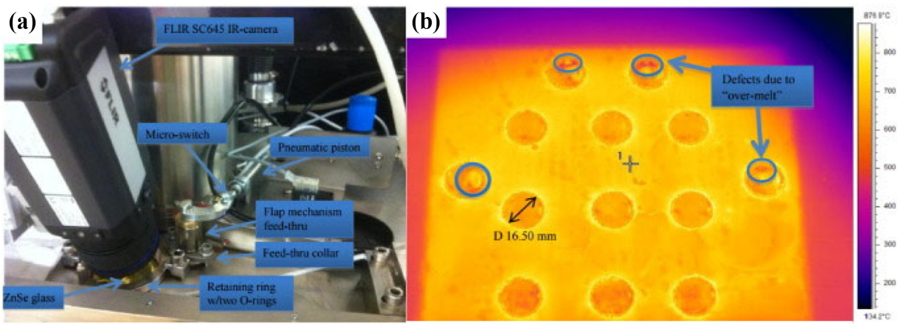
The different operating environments in the EBB pose additional challenges for *in situ* inspection. Processing takes place in a vacuum, limiting the integration of inspection equipment inside the machine (Dinwiddie *et al.*, 2013; Rodriguez, 2012). Due to the fast transient nature of the electron beam energy source, surface-based high-temperature detection technology is no longer applicable, while infrared detection technology is widely used, as shown in Figure 26. Although the resolution of the infrared image is limited, there is a high correlation with the void and the experimental evidence shows that the area with high



(a) (b)

Source(s): Figure courtesy of Rabinarayan and Goutam Kumar (2021)

Figure 25.
(a) Schematic diagram of a photodiode and a line scan camera and (b) camera output grayscale plot



Source(s): Figure courtesy of Dinwiddie *et al.* (2013)

Figure 26.
(a) Structural design and infrared camera and (b) images taken with an infrared camera

thermal radiation corresponds to the presence of surface defects (Dinwiddie *et al.*, 2013). The material discontinuity caused by excessive melting during processing can be identified from the generated infrared image (Costa and Vilar, 2009).

Directed energy deposition (DED) is similar to PBF, but instead of directly melting the powder, the DED-focused energy beam transports the powder (Turner *et al.*, 2014) or wire into a molten pool on the surface of the substrate (Hu and Kovacevic, 2003).

In the case of powder DED, *in situ* inspection with pyrometers and thermal imaging cameras has been shown to improve the geometric accuracy of the part compared to image processing with high-speed cameras (Wang *et al.*, 2008). In addition, progress has been made in the use of acoustic emission detection technology to identify crack formation in powder DEDs, but it is still not possible to monitor cracks in real time, and their location and generation time are obtained through post-processing of data. There is still room for further improvement (Zalameda, 2013). Although wire DEDs differ from powder DEDs in material transport, many discontinuities of the same material have been found and the same method can be used for *in situ* detection (Liu *et al.*, 2014). Besides, the correlation between spectroscopy and surface properties has been verified by spectroscopy (Nassar, 2014), but some scholars have found that this method still has some shortcomings (Klein and Sears, 2004).

In addition to some of the above-mentioned applied *in situ* testing technologies, there are also some potential non-destructive testing technologies that may be helpful for the development of integrated metal additive and subtractive processing in the future.

Laser ultrasound (LU) is a technology under development, LU uses pulsed lasers to generate ultrasound waves and continuous-wave laser interferometers can detect small surface displacements when the wave reaches the detection point, which can be used to detect material discontinuities such as defects, density, porosity and mechanical properties of materials. At the same time, because the LU is non-contact, it can be used in curved or areas that are difficult to access by conventional methods, especially for additive and subtractive integrated processing (Kolkoori *et al.*, 2015).

X-ray backscatter (XBT) technology will also play a unique role in the integrated processing of additive and subtractive materials. Since the X-ray source and detector are on the same side of the object, large components can be more easily inspected and real-time imaging allows for recursive scanning. Some scholars believe that it has broad application prospects in corrosion detection, foreign body damage detection and finding cracks and voids (Vandone *et al.*, 2018).

As traditional analytical methods for surface inspection are increasingly limited by the basic principles of surface properties, such as the compromise between spatial resolution and field of view; loss of effective spatial resolution due to motion blur, etc. The development of sensors is important, but it is difficult to solve the bottleneck faced by the current detection and analysis technology by relying on development alone. Based on prior knowledge, through the way of multi-sensor fusion, it will be the development trend of the surface characteristics detection method of integrated processing of metal addition and subtraction materials in the future, for example, the detection area can be detected by low-resolution sensors and high-precision detection is carried out by using local high-resolution sensors (Liao *et al.*, 2021). The accuracy of detection and analysis will be greatly improved by using the advantages of multiple detection and analysis methods at the same time. However, there is still a long way to go from concept to application and more progress is needed in various areas.

4.2.2 Subsurface detection technology. 4.2.2.1 Overview of detection techniques. Subsurface structures can be studied using a variety of methods, including scanning electron microscopy (SEM) (Zhang and Li, 2021), transmission electron microscopy (TEM) (Liu *et al.*, 2002), electron backscatter diffraction (EBSD) (Ren and Tian, 2004), atomic force microscopy

(AFM) (Neauport *et al.*, 2009), surface-enhanced Raman spectroscopy (SERS) (Kevin *et al.*, 2005), tomography (Chen and Zhang, 2005; Xu *et al.*, 2008) and chemical corrosion treatment (Xiang and Nie, 2007; Hu and Xu, 2001). These techniques can be used to study the structure, morphology and dynamic processes of the surface of matter.

4.2.2.2 Application of detection technology.

(1) Confocal scattering scanning technology

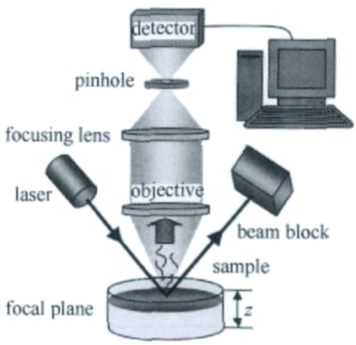
Confocal microscopy combined with light scattering tomography (Luo and Fang, 2006) uses the intense scattering of incident light by subsurface defect structures to reflect the defect information by the intensity distribution of the scattered light signal.

As shown in Figure 27, the detection beam is incident on the surface of the sample at a certain angle and the scattered light that deviates from the position of the reflected light produced by the internal defect enters the objective lens. Only the scattered light at the focal plane position passes through the small hole after focusing and is finally received, imaged and analyzed by the CCD detector directly above. The scattered light at the rest of the position will be blocked, so that the defect distribution of each position inside the sample under the current focal plane is obtained, and the tomography analysis is realized.

(2) Raman spectroscopy

Raman spectroscopy (RS) is a molecular structure characterization technique based on the Raman effect (Zhu *et al.*, 2003) that uses photons as probes and has the characteristics of real-time detection, while surface-enhanced Raman scattering (SERS) is widely used in surface research, adsorbate interface surface state study, interface orientation and configuration, conformation study and structural analysis of biological macromolecules due to its high detection sensitivity, high resolution, low water interference, quenching fluorescence, good stability and suitable interface study (Gao and Huang, 2021).

SERS studies the change of adsorption state, that is, using the high detection sensitivity of SERS to detect the monolayer molecules adsorbed on the surface of a specific metal, because the orientation and state of the adsorbed molecule have different enhancements to different molecular vibration modes, this characteristic is used to detect the adsorption state of the adsorbed molecule and realize the resolution of the adsorbed state. Near-infrared studies in Ag and Au colloids have yielded good results (Zaefferer, 2006).



Source(s): Figure courtesy of Luo and Fang (2006)

Figure 27. Schematic diagram of the structure of a confocal scattering scanning microscope

(3) EBSD testing technology

EBSD is an important complement to SEM due to its ability to obtain information on crystal structure and orientation and is playing an increasingly important role in the fields of metals, semiconductors, minerals and ceramic materials (Li and Mo, 2021).

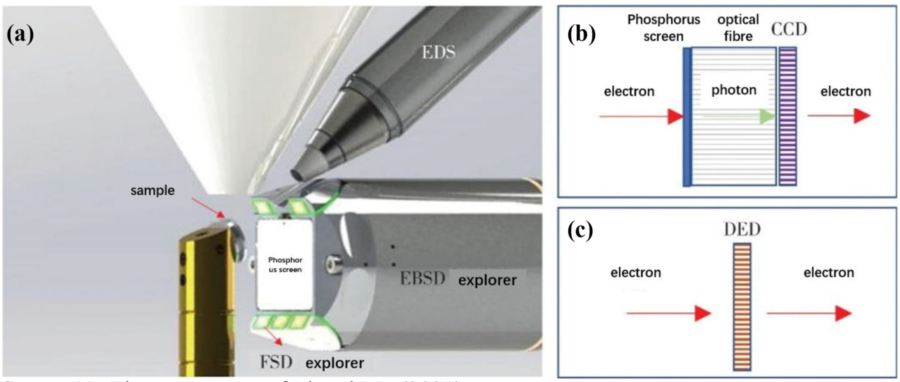
EBSD uses Kikuchi diffraction in SEM. The formation of the band-like region in Kikuchi undergoes the following process: the incident electrons interact with the crystal to produce incoherent quasi-elastic backscattered electrons and the quasi-elastic backscattered electrons undergo coherent diffraction, that is, quasi-elastic backscattered electrons from all directions are incident on a family of parallel crystal planes. The direction of diffraction is the direction of backscattering relative to the direction of the incident beam, so it is called EBSD.

The EBSD detector image is shown in Figure 28. This is shown in Figure 28(a). The detector is mainly composed of a phosphor screen and a CCD camera (CMOS cameras have emerged). The phosphor screen converts the diffracted electrons into photons, then the optical signal is transmitted to the camera through a lens or optical fiber and the camera converts the optical signal into an electrical signal, after that the subsequent image and data analysis system analyzes the collected Kikuchi pattern, as shown in Figure 28(b). Components such as the latest DED non-phosphor screens, as shown in Figure 28(c), can directly detect electrons and convert them into electrical signals.

4.3 Future developments and needs

With the continuous pursuit of cost and sustainable production of parts, as well as manufacturers' pursuit of simplifying production processes and improving efficiency, the demand for integrated additive and subtractive machining will further increase in the future (Wang, 2008). However, the integrated processing method of metal addition and subtraction still has a large space for development. When AM and subtractive manufacturing (SM) processes are combined, it is necessary to consider comprehensive machining challenges that are different from individual machining processes, such as transferring manufacturing information, increasing machining allowances, designing AM/SM fixtures, positioning AM-to-SM transition parts, process planning and design of mixed, additive and subtractive machining (Cui and Chen, 2009).

4.3.1 Machined surface integrity. For the manufacture of metal parts with higher surface quality requirements, the integrated processing of metal additive and subtractive materials has shown great potential for processing. AM makes efficient use of difficult-to-machine materials to produce parts with complex geometries. However, the resulting surface quality



Source(s): Figure courtesy of Li and Mo (2021)

Figure 28.
(a) Position of EBSD detector and signal (b) conversion by conventional method and (c) direct electron detection method

and dimensional accuracy are significantly worse when compared to the machined counterpart minus (Huang and Guan, 2021; Gao and Zhang, 2001). By combining AM technology with CNC milling, both the inner and outer surfaces of the parts can meet the surface integrity requirements that are superior to the traditional CNC surface finish (Yang, 2000; Zhang, 1998). At the same time, the metal additive and subtractive integration allows the surface of each part to be printed and milled in the same reference coordinate system, with higher tolerance requirements (Wei, 2007).

Integrated metal additive and subtractive machining uses AM to produce complex geometries and process areas with high requirements for dimensional accuracy and surface integrity (Li, 1997; Yang and Chen, 2007). At the same time, it can also be used for the processing and production of polymer parts and multi-material composition parts (Shen, 2008). The integrated processing of metal additives and subtractions can compensate for the shortcomings of the AM or SM processing process alone and use their respective processing advantages to achieve better processing results (Yang and Chen, 2007; Zhang, 1989; Chen, 2004).

4.3.2 Processing efficiency and sustainable manufacturing. CNC machining has an advantage over AM in a high-volume production environment. However, because this SM processing method produces by removing the material, it has a higher "flight ratio" (i.e. the ratio of material input to final part output), resulting in more material wasted in the SM production process compared to AM (Chang and Zeng, 2022).

AM outperforms traditional manufacturing processes in terms of manufacturing flexibility, but limits the ability to manufacture complex, high-precision parts. The nature of the layered construction geometry gives AM the advantage of automating process planning, but it also limits its machining accuracy. AM often has support structures that are difficult to remove, especially for metal AM parts. As a result, in actual production, AM parts require tedious post-processing to remove support structures and allowances, which makes the AM process less efficient than expected (Cui and Chen, 2009).

In traditional manufacturing, multiple parts are usually bolted, welded and brazed into the final product. The integrated metal additive and subtractive machining design reduces machining time, labor and production costs by simplifying a complex multi-part body into a single part and adding complex features to the outside (Cui and Chen, 2009; Shen, 2008).

4.3.3 Diversity of processing design. Traditional manufacturing processes do not balance design diversity and cost well. AM offers a new flexible material addition process that allows materials to be selectively added in three-dimensional space. In machining, milling provides a more flexible material removal process in three-dimensional space compared to turning and drilling.

At the same time, the integrated metal additive and subtractive processing equipment can use the AM or SM process to repair parts with quality problems. Even with processing methods such as AM, it is extremely difficult to machine parts composed of multiple metals. The use of metal additive and subtractive integrated processing can effectively solve the problem of multi-metal 3D printing by starting from the prefabricated part of material A, adding material B through AM and then switching to material C for AM (Chen and Yao, 2004).

Therefore, the integrated processing of metal additive and subtractive materials not only shows unique advantages in terms of surface integrity, but also has great development potential and application prospects from the perspective of actual processing production and personalized production trends.

4.3.4 Process planning. Currently, AM and SM processes in additive and subtractive systems are usually carried out on the same machine. Therefore, interference and gouge inspection is crucial, resulting in complex machining planning and operation sequences that require extensive process planning. Among them, tool change operations between deposition and processing take a long time.

In addition, there is still a lot of room for development in how to more effectively plan the two processes to meet the processing needs of a specific product in an optimal way. In the actual machining process, such activities often require operators with specialized knowledge who can manually adjust them to the specific processing equipment and part requirements, combined with empirical knowledge. However, when part geometry, size and materials begin to change, a lot of effort is still required.

As a result, there is an urgent need to develop an additive-subtractive integrated processing method that can be integrated with any manufacturing system, requiring significant modifications to existing equipment and automating the search for an optimal process planning process.

4.3.5 Build direction. The integrated processing technology of metal augmentation and subtraction mainly realizes the integrated processing of additive and subtractive materials through the directed energy metal deposition process and the laser-assisted deposition process. For example: metal inert gas welding wire welding; easy integrated laser melting; Methods such as depositing material from multiple directions and then machining it. Wherein, the ability to withstand the machining force often depends on the surface area of the part attached to the deposited plate and in order to ensure that the maximum cross-section of the part is always formed in the first layer, it directly determines the machining construction direction.

Cutting fluids are limited in the integrated processing of some additives and subtractions, which leads to an increase in the processing cost of some difficult-to-machine materials (such as nickel superalloys). Even though AM produces multiple parts, which reduces the cost of additive and subtractive machining, due to the limitation of the construction direction, it is found that AM processing time (electron beam melting (EBM) cooling time, heat treatment of other powder bed AM processes) and AM manufacturing cost have a great impact on the total cost of additive and subtractive processing and greatly increase the processing difficulty of some parts.

4.3.6 Supporting structures. AM requires additional post-processing to remove support structures. However, the demolition process was not formally considered when designing the support structure. As a result, when manual or CNC milling is required, some support structures may not be easily removed due to the accessibility of the tool. A related study proposes to use the STL model as an input, calculate the accessibility of the tool and map it to the facet to grow supports that are easier to mechanically remove.

Therefore, it is possible to try to consider the critical angle at which support is needed, to combine the previous analysis of the bracket layout with other information, etc., to achieve a better support design, thereby increasing the production of metal AM by reducing the effort and expense of post-processing processing.

4.3.7 AM/SM fixture design. Designing fixtures for AM/SM is a complex task that requires careful consideration of various factors. A well-designed fixture can significantly improve the efficiency and quality of the manufacturing process, while a poorly designed fixture can lead to costly delays and defects.

It is often necessary to consider the geometry of the part, so that the fixture can be designed to hold the part firmly in place during the integrated machining process. This may require special designs, such as clamping points or support structures for specific part geometries.

At the same time, it is important to choose materials that can withstand the high temperatures and stresses of AM as well as the SM cutting forces, e.g. consider using materials such as tool steels or heat-resistant alloys. Special features such as movable parts or adjustable clamping points are implemented via planning tool access. For specific manufacturing processes, processing time should be minimized, and the need for multiple fixture replacements should be reduced to improve processing efficiency.

5. Conclusion

In the process of reducing materials for AM materials, by combining the process of reducing materials with AM, we successfully removed the redundant materials in AM and got more accurate and lightweight parts. The surface integrity of materials is a key consideration in subtractive processing and the surface defects, residual stress and deformation caused by processing may have a negative impact on the performance of the final parts, so this paper focuses on the subtractive processing and surface integrity of AM. Consider the above machining challenges and potential lifting directions and consider combining the integrated machining of metal addition and subtraction materials with other manufacturing techniques to produce parts with complex geometries or high-quality surfaces in a single process, reducing the need for multiple setup and handling operations. At the same time, the author briefly summarizes the actual situation of the integrated processing of metal addition and subtraction materials from many aspects.

For the problem limited by the construction direction, can try to use the multi-axis robot to change the construction direction, thereby improve the processing ability of the part. For materials that are difficult to process, other additive and subtractive integrated processing technologies, such as electron beam manufacturing or EDM, can be tried to reduce processing costs. In order to reduce the impact of AM processing time and AM manufacturing cost on the total cost of additive and subtractive processing, it is possible to consider exploring the use of more efficient AM technologies, such as oxide laser rapid firing technology. When processing difficult parts, you can try to combine a variety of additive and subtractive integrated processing technology to improve processing efficiency. In order to reduce the cost of integrated additive and subtractive processing, production process optimization measures such as the use of automated equipment and robots to reduce labor costs can be considered. The surface characteristics and subsurface structure of the processed parts are detected, and the surface performance under the corresponding processing modes is analyzed. As a reference, the combination of processing modes and processing parameters can be continuously optimized to produce parts with higher performance.

Overall, with the gradual improvement of the requirements for the surface quality of parts in the production process and the in-depth implementation of sustainable manufacturing, the demand for integrated processing of metal addition and subtraction materials is likely to continue to grow in the future. By deeply understanding and studying the problems of material reduction and surface integrity of AM materials, we can better meet the challenges in the manufacturing process and improve the quality and performance of parts. This research is very important for promoting the development of manufacturing technology and achieving success in practical application.

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