Expert Introduction

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Abstract

Metal additive manufacturing technology has attracted extensive attention and research in the field of structural engineering in recent years because of its advantages, such as a high degree of automation, savings in labor costs, and the ability to manufacture complex geometric entities. This paper summarizes the research progress of metal additive manufacturing technology in the fields of steel structures and composite structures, introduces the printing equipment and commonly used materials for metal additive manufacturing technology, and identifies the metal additive manufacturing technologies currently applicable to the printing of steel structures and composite structures. It reviews the main research progress in the mechanical properties of steel printed by metal additive manufacturing technology, as well as its applications in the fabrication of steel and composite structural members and entire structures. The analysis shows that the manufacturing process affects the mechanical properties of printed steel; the elastic modulus and strength of steel produced by additive manufacturing technology meet the construction requirements of steel structures and composite structures; and this technology has broad application prospects in the fabrication of complex connections in steel structures and composite structures and in research on lightweight structural members. Meanwhile, it is pointed out that, owing to the influence of current metal additive manufacturing processes, printed members may develop relatively large residual stresses and rough surfaces, while methods such as heat treatment and machining can help improve these defects. Finally, trends in the application of metal additive manufacturing to the optimization design of steel structures and composite structures, structural strengthening and repair, and integration with machine learning and digital twins are discussed, with the aim of providing a reference for the subsequent development and research of metal additive manufacturing technology in the field of structural engineering.

Full Text

Expert Introduction

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Research Progress in Metal Additive Manufacturing Technology in Steel Structures and Composite Structures

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Abstract: Owing to its advantages such as a high degree of automation, savings in labor cost, and the ability to fabricate complex geometric entities, metal additive manufacturing technology has received extensive attention and research in the field of structural engineering in recent years. This paper summarizes the research progress of metal additive manufacturing technology in the fields of steel structures and composite structures, introduces the printing equipment and commonly used materials for metal additive manufacturing technology, and distills the metal additive manufacturing technologies currently applicable to printing steel structures and composite structures. It reviews the major research progress regarding the mechanical properties of steels printed by metal additive manufacturing technology, as well as the application of this technology in the manufacture of steel-structure and composite-structure members and entire structures. The analysis shows that the manufacturing process affects the mechanical properties of printed steel; the elastic modulus and strength of steels produced by additive manufacturing technology meet the construction requirements of steel structures and composite structures; and the technology has broad application prospects in the fabrication of complex connections in steel structures and composite structures, as well as in research on lightweight members. At the same time, it is pointed out that, owing to the influence of current metal additive manufacturing processes, printed members may develop relatively large residual stresses and relatively rough surfaces, and methods such as heat treatment and machining can help improve member defects. Finally, trends are discussed regarding the optimized design of steel structures and composite structures using metal additive manufacturing, structural strengthening and repair, and integration with machine learning and digital twins, with the aim of providing a reference for the subsequent development and research of metal additive manufacturing technology in the field of structural engineering.

Keywords: 3D printing; metal additive manufacturing; steel structures; composite structures; mechanical properties; machine learning

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Research progress in metal additive manufacturing technology in steel structures and composite structures

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Abstract: Metal additive manufacturing technology has been widely studied in the field of structural engineering in recent years due to its advantages of a high degree of automation, labor cost savings, and the ability to manufacture complex geometric entities. This paper summarizes the research progress in metal additive manufacturing technology in the field of steel and composite structures in recent years. The paper introduces the printing equipment and commonly used materials of metal additive manufacturing technology, and condenses the techniques that can be utilized to print steel and composite structures. It then reviews the mechanical properties of the printed components and structures, as well as the main research progress in metal additive manufacturing technology in the production of steel and composite structure components and overall structures. Analysis indicates that manufacturing processes significantly affect the mechanical behavior of manufactured steel. The elastic modulus and strength of additively manufactured steel meet the requirements for construction applications. Metal additive manufacturing technology has broad application prospects in the complex connection production of steel structure and composite structure engineering, and lightweight research of components. The paper also notes that current metal additive manufacturing technology can introduce substantial residual stresses and relatively rough surface finishes, which may be alleviated through heat treatment and machining. Finally, the paper discusses future directions, including integration with structural optimization, repair, and reinforcement methods, as well as convergence with machine learning and digital twin technologies. This paper perspective aims to provide guidance for further development of and research on metal additive manufacturing for structural engineering.

Key words: 3D printing; metal additive manufacturing; steel structure; composite structure; mechanical property; machine learning

Additive manufacturing technology (3D printing technology), owing to its advantages such as a high degree of automation, high design freedom, savings in labor costs, and the ability to manufacture complex geometric entities[1−3], is applicable to fields including marine engineering, aerospace, automobiles, and medicine[4−9]. As a branch of additive manufacturing technology, metal additive manufacturing technology has attracted extensive attention and research in recent years[10−12], and it has demonstrated significant potential in the manufacture of components for steel structures and composite structures[1]. At present, research by scholars in the field of structural engineering on the application of metal additive manufacturing technology to steel structures and composite structures mainly focuses on two major aspects: the mechanical properties of additively manufactured steel, and its application in structural components and overall structures.

The mechanical properties of additively manufactured steel—such as elastic modulus, ultimate tensile strength and yield strength, ductility, and residual stress—are crucial to the structural performance of steel structures and composite structures. Because they are affected by manufacturing process parameters, their performance characteristics often differ from those of traditional rolled or cast steel. Investigating whether the elastic modulus, ultimate tensile strength, and yield strength of additively manufactured steel satisfy the service requirements of steel structures and composite structures, and finding methods to address the relatively poor ductility and residual stresses of additively manufactured steel, are hot issues in this research field.

In the application of additively manufactured steel-structure and composite-structure components and overall structures, scholars have carried out extensive research on additively manufactured steel-structure joints, additively manufactured steel tubular columns, additively manufactured steel beams, additively manufactured integral bridges, and related topics. As a new technology in structural engineering, additive manufacturing, when combined with topology optimization, has achieved important applications in the manufacture of complex geometric components and has the advantages of saving materials and reducing self-weight while ensuring load-bearing capacity. Metal additive manufacturing technology has broad prospects in the future field of component fabrication for steel structures and composite structures. However, because of the influence of metal additive manufacturing technology itself, the manufactured metal components and overall structures have relatively large residual stresses and surface defects; how to

Reducing the influence of the inherent shortcomings of the relevant technologies is of great research significance for the further application of metal additive manufacturing technologies in steel structures and composite structures.

To clarify the current research progress of metal additive manufacturing technologies in steel structures and composite structures, and to provide a reference for researchers in related fields in China, this paper reviews the research progress of metal additive manufacturing technologies in the field of steel structures and composite structures. First, typical metal additive manufacturing technologies are introduced, and the metal additive manufacturing technologies currently commonly used for steel structures and composite structures are distilled. Then, based on the two major research hotspots among scholars in the field of structural engineering, the mechanical-property patterns of steels produced by metal additive manufacturing technologies, as well as measures for optimizing these mechanical properties, are summarized. The current applications of metal additive manufacturing technologies in steel structures and composite structures are reviewed, and the deficiencies in current applications and corresponding improvement measures are identified. Finally, future trends in metal additive manufacturing for the optimized design of steel structures and composite structures, structural strengthening and repair, and integration with machine learning and digital twins are discussed.

1 Typical Technologies for Metal Additive Manufacturing

According to the standard UNE-EN ISO/ASTM 52900:2017, the technologies applicable to metal additive manufacturing mainly include the following four types [13–14]: material extrusion (ME), binder jetting (BJ), powder bed fusion (PBF), and directed energy deposition (DED). Schematic diagrams of the working principles of typical equipment for the four technologies are shown in Fig. 1 [14].

Figure 1. Typical equipment for four types of metal additive manufacturing [14]

(a) Material extrusion technology (ME)

(b) Binder jetting technology (BJ)

(c) Powder bed fusion technology (PBF)

(d) Directed energy deposition technology (DED)

Visible labels in the figure include: metal wire, ceramic wire, print head, printing platform, metal part; powder-spreading hopper, metal powder, powder-spreading roller, build chamber, liquid binder; laser, build chamber, powder spreader, powder reservoir, powder bed, overflow powder; robotic arm, working platform, nozzle, metal part, and turntable.

Fig. 1 Typical equipment for four types of metal additive manufacturing [14]

The working principle of typical ME equipment is shown in Fig. 1(a). Its printing principle is to use a printed polymer to bond metal particles; subsequently, the polymer binder is removed by catalytic or thermal debinding and other methods, while the pores are backfilled. Finally, the polymer is removed by high-temperature sintering, forming dense metal parts [15]. ME technology can currently be used to print metals such as stainless steel, titanium alloys, and high-melting-point iron alloys [16–19].

The typical equipment for BJ technology is shown in Fig. 1(b). Its printing principle is to bond metal particles together with a liquid binder to form a large metal solid. This method can currently realize the printing of metals such as stainless steel, titanium alloys, and copper alloys [20–22].

The typical equipment for PBF technology is shown in Fig. 1(c). Its printing principle is to use a heat source, such as a laser or electron beam, to melt and sinter metal particles together to form the target metal solid. This method can currently realize the printing of metals such as stainless steel, carbon steel, titanium alloys, and aluminum alloys [23–26].

The typical equipment for DED technology is shown in Fig. 1(d). Its printing principle is to use high-energy heat sources such as lasers, electron beams, or electric arcs to locally melt metal materials—metal particles or metal wire—on a metal substrate or on already-printed metal, while synchronously feeding metal materials through a nozzle so that the material gradually accumulates and takes shape. This method can realize the printing of metals such as stainless steel, titanium alloys, and aluminum alloys [27–29].

Table 1 lists the advantages, disadvantages, and applicability of the four printing technologies.

application scenarios.

Steel structures and composite structural components are characterized by large steel volumes. As shown in Table 1, compared with other technologies, WAAM offers the advantages of large-volume printing, high printing speed, and dense finished products, making it more suitable for the construction of large structural components and systems. In steel structures, joints with complex force states can be manufactured using SLM technology.

Table 1. Comparison of major technologies for metal additive manufacturing[14]

Item	ME	BJ	PBF	DED
Typical technologies	Fused deposition modeling (FDM); atomic diffusion additive manufacturing (ADAM); bound metal deposition (BMD)	Single-pass jetting (SPJ); supersonic deposition (SD)	Selective laser melting (SLM); electron beam melting (EBM)	Wire arc additive manufacturing (WAAM)
Advantages	Low printing-equipment cost; high material utilization; relatively high printing speed	High material utilization; high printing speed	High surface quality of formed parts; printed products can be used directly; best mechanical properties	Large-volume deposition printing and high printing speed; enables printing of large parts; dense printed products
Disadvantages	Post-processing is required, with a long post-processing time; rough surface quality; relatively low part density; small formed parts	Post-processing is required, with a relatively long post-processing time; small formed parts	High price of printing equipment; low printing speed; low material utilization	Rough printed surface; relatively low material utilization
Application scenarios	Low-cost, small-batch production of complex parts	Mass production of complex structures	High-performance dense parts	Manufacture of large parts

The above four major technologies accounted for 96% of the metal additive manufacturing market share in 2020[30]. Of the remaining market share, sheet lamination (SL) technology (Fig. 2), as a relatively common metal additive manufacturing technology, accounted for 2%[31]. This technology uses metal sheets as raw materials. At room temperature, localized energy (ultrasound or laser) and mechanical pressure are applied to several stacked metal sheets; the interfaces of the stacked sheets are bonded by diffusion rather than melting, and the metal sheets are bonded layer by layer to ultimately form an object[32].

Fig. 2. Sheet lamination manufacturing technology[32]

2 Mechanical Properties of Steels Manufactured by Metal Additive Manufacturing

As noted above, WAAM is currently a commonly used technology for manufacturing large components of steel structures and composite structures by metal additive manufacturing, while SLM is currently a commonly used technology for joint fabrication. The review in this section of the mechanical properties of steels manufactured by metal additive manufacturing therefore focuses mainly on these two technologies.

2.1 Process Parameters and Microstructure

During SLM fabrication, laser power, build space, and fabrication speed have important effects on the mechanical properties of steel[33–34]. Laser power and speed cause the fabricated steel to take on different morphologies[35] (Fig. 3). When the laser power is too low or the fabrication speed is too high, because sufficient energy is lacking during the fabrication process, large particles and the underlying substrate are not completely melted, which may lead to incomplete wetting and spreading of the melt pool or liquid metal. Incompletely melted powder cannot provide sufficient constraint on the liquid metal; this produces thermocapillary action and causes the melt pool to spheroidize as it flows[36–37]. As the power increases, the fabricated steel becomes continuous and develops a humping phenomenon; this state is a transition between a stable melt pool and an unstable melt pool. The liquid metal flows toward the rear of the melt pool, which is driven by high vapor recoil pressure. Large variations in capillary pressure along the liquid-metal track cause periodic contraction of the liquid, thereby forming humps[38–39]. The presence of spheroidized steel and humps has a negative effect on the mechanical properties of the steel. When both the scanning power and the fabrication speed are too high, the melt pool enters a keyhole mode; this mode leads to lower density and cracking in the produced steel, thereby adversely affecting its mechanical properties[40]. In addition, build space affects the microcracks in SLM-fabricated steel. When the build space decreases, the melt-pool temperature decreases and the residual stress in the fabricated steel increases, which leads to more microcracks in the steel and thus reduces its strength and ductility[41].

Fig. 3. Influence of laser power and scanning speed on the formation quality of steel[33]

In the WAAM manufacturing process, fabrication speed, deposition path, and interlayer temperature are important process parameters affecting the mechanical properties of steel[42]. Owing to the manufacturing principle of WAAM, fabrication speed and power will affect manufacturing

⋯affect the steel produced[43]. A higher manufacturing speed reduces the height of the deposited steel[44]. In gas-shielded metal arc manufacturing, an increase in manufacturing speed can lead to discontinuities in the geometry of the steel and insufficient material deposition[45]; the manufactured steel may also form humps[46]. All of these negatively affect the mechanical properties of the manufactured steel. The deposition path affects the surface condition of additively manufactured steel. During WAAM fabrication of duplex stainless-steel plates, an alternating-direction path produces uniform layer heights, whereas a unidirectional deposition path produces nonuniform side surfaces because heat accumulates at the stopping point during deposition of each layer[47]. This leads to initial defects in the manufactured steel and adversely affects its mechanical properties. During WAAM fabrication of steel, the interlayer temperature affects the initial defects in the manufactured steel. When the interlayer temperature is too high, defects such as deformation and residual stress are generated; these produce stress concentrations and adversely affect the mechanical properties of the steel[48]. Meanwhile, during production, the processing interval affects the interlayer temperature, thereby indirectly influencing the mechanical properties of the steel[49].

Steel manufactured by WAAM technology usually has a columnar microstructure and rarely exhibits an equiaxed microstructure, because a certain high-temperature gradient exists during WAAM fabrication. The wrought substrate of the manufactured steel contains randomly oriented equiaxed grains, onto which the first layer of the additively manufactured steel component is melted. Since the current manufactured layer has the same chemical composition as the previous layer—or, for the first layer, the substrate—nucleation of a new phase is not required[50], and therefore the grains grow epitaxially. When the second layer is deposited, the temperature gradient is largely downward because the substrate and the previous layer serve as heat sinks, and the grains grow vertically along the build direction, resulting in an anisotropic microstructure[51]. This produces anisotropic mechanical properties[52], which is detrimental for applications involving multiaxial stresses; therefore, under such conditions, an aligned columnar-grain structure is not suitable[53]. Equiaxed-grain materials generally exhibit higher strength and a constant strain-hardening rate, whereas columnar-grain materials exhibit a strain-hardening rate that gradually increases with increasing true strain[54]. Compared with WAAM, steel manufactured by SLM technology exhibits more favorable anisotropic characteristics and is more suitable for load-bearing environments with multiaxial stresses.

2.2 Elastic Modulus

The elastic modulus of steel is a crucial mechanical-property index in steel-structure design. When the angles of tensile specimens produced by additive manufacturing differ, their elastic moduli are also affected. Therefore, in studies of the elastic modulus of steel, scholars mostly take different cutting angles of tensile specimens (Fig. 4) and different thicknesses as research variables[55]. The summarized average elastic moduli of additively manufactured steel are shown in Fig. 5.

Fig. 4 Cutting angle for tensile coupons[55]
Visible annotations in the figure: "As-built plate (8 mm)"; $\theta = 0°, 30°, 45°, 60°, 90°$; "Print layer direction"; "100 mm".

Fig. 5 Effect of thickness and angle on elastic modulus

Visible plot labels:
- Vertical axis: Elastic modulus/GPa
- Horizontal axis: Cutting angle/(°)
- Legend: Ref. [56]—3 mm; Ref. [56]—8 mm; Ref. [57]—4 mm; Ref. [58]—4 mm; Ref. [59-60]—3.5 mm; Ref. [59-60]—8 mm; Ref. [61]—8 mm; Ref. [62]—4 mm; Ref. [63]—7 mm; Ref. [64]—4 mm; Ref. [65]—1 mm.

It can be seen from Fig. 5 that the elastic modulus of additively manufactured steel is mostly 170-220 GPa, close to that of conventionally manufactured steel, and meets the specification requirements for conventional steel manufacturing. When the cutting angle of steel tensile specimens differs, the elastic modulus varies. When the angle is 45°, the elastic modulus of the steel is greater than those along the printing direction and in the perpendicular direction. Comparing the elastic moduli of steels of different thicknesses reported in the same literature shows that the elastic modulus of steel with a thickness of 8 mm is greater than those of steels with thicknesses of 3 mm and 3.5 mm.

After machining, the elastic modulus of additively manufactured steel is greater than that of the as-built, directly manufactured steel[60]. This is because steel produced by additive manufacturing has certain geometric defects, which generate stress concentrations during tensile-performance tests and reduce the elastic modulus of the steel. After machining, the surface of the additively manufactured steel becomes flatter, initial defects are reduced, and the elastic modulus of the steel increases. After heat treatment, the elastic modulus of additively manufactured steel also increases[62]. This is because heat treatment reduces the ferrite percentage in additively manufactured steel and changes the internal microstructure of the steel; this

The transformation may help enhance the mechanical properties. In the design of steel structures and composite structures, the construction direction may be arranged at a 45° angle to the component direction, and machining and heat treatment may also be adopted to optimize the as-built additively manufactured steel.

2.3 Ultimate Tensile Strength and Yield Strength

For studies on steel strength, the average ultimate tensile strengths and yield strengths of steels manufactured by WAAM and SLM are shown in Figs. 6 and 7, respectively.

Fig. 6 Average ultimate tensile and yield strength of steel manufactured by WAAM technology

Fig. 7 Average ultimate tensile and yield strength of steel manufactured by SLM technology

It can be seen from Fig. 6 that, for steels manufactured by WAAM, most of the ultimate-strength-to-yield-strength ratios lie on one side of the line corresponding to a ratio of 1.2, indicating that steels manufactured by WAAM can satisfy the requirement in steel-structure specifications that the yield ratio be less than 0.85 [80]. The strengths marked by the purple lines in the figure are the ultimate tensile strength (520 MPa) and yield strength (378 MPa) of the ER70S-6 welding wire used in WAAM [69]. It can therefore be seen that, because WAAM uses welding wire as the feedstock, the ultimate tensile strength and yield strength of the steel it produces are close to those of the original welding wire.

Fig. 7 summarizes the strengths of 316L stainless steel manufactured by SLM. It can be seen from Fig. 7 that, in most studies, the ultimate-strength-to-yield-strength ratios of stainless steels manufactured by SLM are between 1.0 and 1.4, distributed on both sides of the line corresponding to a ratio of 1.2. The strengths marked by the purple lines in the figure are the yield strength (220 MPa) and ultimate tensile strength (530 MPa) of 316L stainless steel manufactured by conventional methods [79]. The strengths of 316L stainless steel manufactured by SLM mostly fall in Region I, that is, both the yield strength and the ultimate strength are greater than those of conventionally manufactured steel; among all the studies listed, the yield strengths are all greater than those of conventionally manufactured steel.

Meanwhile, owing to the characteristics of additive manufacturing technology, the strength of steel is related to the sampling angle [55, 81–83], as shown in Fig. 8. The strength of steel along the printing direction is higher than that perpendicular to the printing direction, and this influence is more pronounced for the ultimate tensile strength of steel.

Fig. 8 Stress-strain curves of tensile coupons at different picking angles [81]

Because the microstructure of metals manufactured by SLM is denser than that of metals produced by conventional processes such as casting and forging [84–88], under the same material composition, the ultimate strength and yield strength of steel printed using this technology are higher than those produced by conventional processes.

Similar to the elastic modulus, after machining and heat treatment, the ultimate tensile strength and yield strength of steels manufactured by the above additive manufacturing technologies are higher. This is because machining reduces the surface defects of steels manufactured by additive manufacturing, thereby reducing the influence of stress concentration caused by surface roughness during tensile loading and improving the ultimate tensile strength and yield strength of the steel. Heat treatment changes the internal structure of additively manufactured steel and improves its mechanical properties.

Vertical load-bearing components such as columns are subjected to horizontal actions during service. Such transverse actions are parallel to the interlayer bonding regions during printing and may cause shear failure of the component. During the fabrication of steel structural members, the angle between the construction direction of the member and the principal force direction may be set to 45° to effectively improve the bearing capacity of the member.

2.4 Ductility

In structural engineering, the important mechanical performance requirements for materials not only···

there are strength requirements and also requirements for elongation performance. Compared with hot-rolled steel, the plasticity of additively manufactured steel is somewhat reduced[89], and its tensile elongation also exhibits anisotropy: the ductility along the printing direction is greater than that perpendicular to the printing direction[90].

To improve the ductility of additively manufactured steel, many scholars have adopted various methods. WATANABE et al.[91] used a multi-material WAAM printing method to prepare steels with special properties, some of which showed better ductility than steels fabricated by single-material printing. CHEN et al.[92] used WAAM technology to alternately deposit 304 stainless steel (304 SS) and low-carbon steel (LCS) on a Q345 substrate, preparing a bimetallic layered steel structure (BLSS) with a synergistic strengthening–plasticizing effect.

Changing the internal microstructure of additively manufactured metals can effectively improve their ductility. LI et al.[93] used additive manufacturing technology to embed fine grains in stainless steel, producing a complex cellular dislocation structure that effectively improved the elongation performance of the steel. Its mechanism of action and stress–strain curves are shown in Fig. 9.

Stainless steel fabricated by this method exhibited a tensile elongation 45% higher than that of conventionally cast and forged 316L steel. KARTHIK et al.[94] showed that cellular dislocation structures significantly improve the mechanical stability of austenite and delay deformation-induced martensitic transformation (DIMT) in austenite at low temperature (77 K). The delayed and slower rate of DIMT leads to synergistic strengthening of strength and plasticity in steel, and demonstrates the capability of MAM technology to control DIMT behavior and achieve combinations of high strength and high ductility. CHEN et al.[95] enhanced additively manufactured 15-5PH martensitic stainless steel by adding micron-scale titanium carbide (TiC), giving it an optimized combination of high strength and high ductility. LI et al.[96] proposed a biomimetic mechanical interlocking-structure strategy. By laser additive manufacturing, they processed stainless steel 316L and Inconel 625 DMMs with an enhanced strength–electrical-conductivity trade-off; the newly fabricated metal exhibited an elongation of 33.6%, superior to SS316L steel fabricated under the same processing parameters.

Visible labels in Fig. 9(a): GB; Grain; GB slipping; Dislocation; Crack; Cell; Elongated cell; Cell cracking.
Visible labels in Fig. 9(b): stress/MPa; strain/%; AMSS 316L[93]; AM 316L SS[97]; Ultrafine-grained[98]; AISI 316L[99]; AS-cast[100].

(a) Mechanism of action of the cellular dislocation structure

(b) Comparison of stress–strain curves for additively manufactured optimized and conventionally manufactured 316L

Fig. 9 Mechanism of action of the cellular dislocation structure and stress-strain curves of tensile coupons

In addition, the additive manufacturing process has a certain influence on the ductility of steel; therefore, additive manufacturing technology can be optimized to improve the ductility of the fabricated metal. RODRIGUES et al.[101] proposed an Ultra-cold-Wire and arc additive manufacturing (UC-WAAM) technique, and HSLA steel fabricated by UC-WAAM retained relatively high ductility. KUMARAN et al.[102] demonstrated that heat treatment can effectively improve the mechanical properties of additively manufactured 316L SS hybrid specimens, with the maximum ductility of the steel reaching 70.1%. The study by ZHAO et al.[63] also verified that the ductility of heat-treated steels produced by metal additive manufacturing is improved compared with untreated steels. BADONIYA et al.[103], through mechanical testing, showed that heat treatment improves average microhardness and mechanical strength by reducing specimen anisotropy and interlayer defects. The average elongation of heat-treated steel increased by 32.72%.

2.5 Residual Stress

In metal additive manufacturing, the large thermal gradients present during processing cause residual stresses in the printed metal products[104–107]. The effects of residual stress on additively manufactured products are as follows: if the residual stress exceeds the local buckling stress of the material, the product may undergo buckling or plastic deformation; if the residual stress exceeds the local ultimate tensile strength of the material, local cracking may occur in the product[105]. In applications of additively manufactured steel structures, the presence of residual stress is the main cause of deformation and loss of geometric accuracy in additively manufactured steel structural components[106–108].

Regarding the reduction of residual stress generated in additive manufacturing, many scholars have carried out studies. As is known from the preceding discussion, because metal additive manufacturing has a relatively high thermal gradient and heat input, the formed metal contains relatively large residual stresses. Therefore, the residual stress in formed steel can be reduced by decreasing heat input[109]. LIU et al.[110] introduced the concept of an external filler wire into WAAM. By feeding an external wire into the arc, part of the arc energy was consumed, thereby reducing the heat input during additive manufacturing and decreasing the residual stress in the fabricated metal. In addition, residual stress in manufactured steel can also be reduced by directly separating part of the wire-melting current from the bypass arc to decrease the heat input into the deposited layer[111-112]. It can also be reduced by lowering the input power to decrease the residual stress in the fabricated component[113], by reducing the temperature difference between the additively manufactured steel and the substrate and lowering the cooling rate of the fabricated steel to reduce residual stress and deformation—therefore, preheating the substrate can be adopted to reduce residual stress[114]—and by increasing the travel speed to reduce residual stress along the scanning direction[115].

The above are measures adopted during steel fabrication to reduce residual stress. After fabrication is completed, residual stress can be reduced through subsequent treatment methods, among which heat treatment is considered one of the most effective methods for improving the mechanical properties of WAAM components and reducing residual stress[116]. Through heat treatment, the mixing of fine and coarse grains in additively manufactured steel, elemental segregation, and the mixing of equiaxed and columnar grain regions can be reduced; the residual stress of the material can be decreased; and the strength and ductility of the material can be improved[117-120].

This paper reviews the research progress on the mechanical properties of steel manufactured by metal additive manufacturing, and summarizes the elastic modulus, ultimate tensile strength and yield strength, ductility, and residual-stress characteristics of steel produced by metal additive manufacturing, as well as the effects of materials and fabrication processes on the relevant mechanical properties. The review shows that the elastic modulus, ultimate tensile strength, and yield strength of additively manufactured steel all satisfy the service requirements of steel structures and composite structures, while its ductility is weaker than that of conventionally manufactured steel. In addition, owing to the influence of additive manufacturing technology, the manufactured steel contains residual stress. For steel treated by heat treatment and machining, its elastic modulus, ultimate tensile strength, and yield strength are all superior to those of steel produced directly by additive manufacturing. This is because machining reduces the surface defects of steel fabricated by additive manufacturing, thereby reducing the influence of stress concentration caused by surface roughness during the tensile process and improving the ultimate tensile strength and yield strength of the steel; meanwhile, heat treatment changes the internal structure of additively manufactured steel, reduces the influence of residual stress, and improves the mechanical properties of the steel.

3 Application of Metal Additive Manufacturing in Steel Structures and Composite Structures

3.1 Joints

When early metal additive manufacturing technology was applied in the field of structural engineering, because of limitations in printing size, hybrid manufacturing methods were mostly adopted: key components such as joints in the structure were fabricated by additive manufacturing, while the remaining components were manufactured using conventional methods. A typical example is that GALJAARD et al.[121] used direct metal laser sintering (DMLS) technology to manufacture an optimized metal joint (Fig. 10). Compared with the original joint, this joint reduced its self-weight by 75%, demonstrating that additively manufactured metal joints have the advantage of effectively reducing self-weight.

Fig. 10 Optimized joints manufactured by DMLS[121]

Fig. 10 Optimized joints manufactured by DMLS[121]

Researchers have used topology optimization to design joints that are lighter and more artistic while effectively realizing joint functions, thereby achieving the objective of lightweight and aesthetically optimized overall structures. For example, SEIFI et al.[122] adopted bidirectional evolutionary structural optimization and additive manufacturing technology, and proposed a rapid and precise fabrication method for customized structural joints optimized for specific loads and boundary conditions. WANG et al.[123] used metal additive manufacturing technology to fabricate scaled models of the connecting joints between tree-like supports and the upper structure. They also demonstrated that representative joints obtained through generative design exhibited more uniform stress distributions and better static performance than other joints. HUANG et al.[124-126] proposed an innovative prefabrication method combining topology optimization based on the solid isotropic material with penalization method and additive manufacturing, and put forward an efficient method for mass-producing repetitive joints, among which the X-shaped joint is shown in Fig. 11. ZUO et al.[127] combined additive manufacturing with topology optimization and proposed a new integrated computer-aided spatial structure design and construction method, providing a complete computer-aided workflow for topology optimization design, numerical analysis, and additive manufacturing of steel joints in lattice-shell structures.

In addition to directly manufacturing connecting joints, metal additive manufacturing technology can also be used to manufacture connectors, facilitating the assembly of components such as beams and columns[128], as shown in Fig. 12.

Figure 11 X-nodes for efficient mass production

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Fig. 11 X-nodes for efficient mass production

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Figure 12 3D-printed beam–column connecting hook

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Fig. 12 3D printed beam-column connecting hook

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Compared with conventional methods for fabricating joints, additively manufactured steel-structure joints can realize complex geometries, reduce thermal residual stresses caused by welding

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, and mitigate local residual-stress problems arising from bolt holes. Because most additively manufactured joints are produced using SLM technology, they have better isotropy and strength. However, joints manufactured by additive manufacturing also have drawbacks introduced by the printing process: their strength perpendicular to the printing direction is relatively low. Therefore, during design, it is necessary to avoid subjecting the joints to tensile forces perpendicular to the printing direction.

3.2 Columns

At present, there are relatively few studies on full-scale steel-structure columns fabricated by metal additive manufacturing; existing research is mostly concentrated on small short columns. The main topics include the influence of printing methods on the surface roughness of columns, the mechanical properties of the printed components, and comparative analyses with the mechanical properties of columns manufactured by conventional methods. As early as 2017, BUCHANAN et al.

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carried out axial compression tests on a series of square hollow-section short columns manufactured by powder bed fusion (PBF), verifying that they exhibited compressive behavior similar to that of conventionally produced stainless-steel short columns. This demonstrated the feasibility of printing structural components using additive manufacturing; the manufacturing process and buckling modes are shown in Figure 13.

The fabrication and testing of square hollow-section columns demonstrated the feasibility of additively manufactured printed columns. Subsequently, more scholars carried out research on this topic. ZHANG et al.

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used PBF to manufacture circular hollow-section short columns, measured their geometric characteristics, and conducted axial compression tests and numerical simulations on five short columns. A comparison between the test results and numerical simulations is shown in Figure 14.

(a) 316L short column during the construction process

(b) Buckling mode of 316L short columns under compression

Figure 13 Manufacturing process and test diagrams of BPF square hollow-section short columns

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Fig. 13 Manufacturing process and test diagrams of BPF square hollow section short columns

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Figure 14 Failure characteristics and finite element analysis of circular hollow-section columns manufactured by PBF

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Fig. 14 Failure characteristics and finite element analysis of circular hollow section columns manufactured by PBF

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Combining the geometric characteristics with the axial compression test results shows that, owing to the influence of the manufacturing technology itself, additively manufactured hollow-section column members have certain local defects, leading to a reduction in local load-bearing capacity. YAN et al.

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investigated the influence of different additive-manufacturing printing paths on the mechanical properties of high-strength steel tubular columns. Compression tests on short steel tubular columns fabricated by SLM using different paths showed that steel tubular columns printed ring by ring along the circumference had higher load-bearing capacity, but relatively poorer ductility.

The discussion in Chapter 1 also shows that, because WAAM can manufacture large components, has high production efficiency, and offers relatively low cost, it is more suitable for the field of structural engineering. In recent years, most scholars have studied the mechanical properties and geometric characteristics of columns manufactured by WAAM. KYVELOU

···et al.[132] used WAAM technology to fabricate 14 square hollow-section short columns with different local slenderness ratios and conducted axial compression tests on them. The results showed that, owing to the inherent initial defects and surface undulations associated with WAAM technology, there were relatively large differences in the load-carrying capacities among nominally identical short columns fabricated in parallel. HUANG et al.[133] carried out axial compression tests, under pinned boundary conditions, on 18 stainless-steel square and circular hollow-section short columns printed by WAAM, and compared the results with EN 1993-1-4 and AISC 370. As shown in Fig. 15(a) and Fig. 15(b), the WAAM-fabricated short columns exhibited relatively low load-carrying capacity because of geometric defects introduced by the technology; therefore, when short columns fabricated by WAAM are used, the reduction in load-carrying capacity caused by geometric defects must be fully considered. KRAUS et al.[134] summarized the causes of geometric defects as the difficulty of controlling the molten metal at the arc, changes in welding parameters during fabrication—including deviations in current, voltage, and wire diameter, as well as fluctuations in shielding gas—and interference from the welding environment. They also investigated the outer diameter, curvature, straightness, thickness, and printing-induced pores of printed columns, exploring the initial geometric defects of the printed columns; the pores in a printed column are shown in Fig. 15(c).

(a) Fabrication process[133]
(b) Strength comparison between WAAM-printed columns and conventionally machined columns[133]
(c) Pores in a WAAM-printed column[134]

Figure 15 Manufacturing process, strength, and geometric defects of WAAM columns

Fig. 15 Manufacturing process, strength and geometric defects of WAAM columns

Additive manufacturing has the advantage of enabling the precise fabrication of complex geometric shapes, and can realize optimized fabrication of column forms. ZHANG et al.[135–136] proposed a fabrication method for optimized corrugated shells, using PBF to fabricate nine optimized corrugated shells with different diameter-to-thickness ratios and one reference cylindrical shell. Through tensile tests, measurements of basic geometric properties, and axial compression tests, they conducted experimental and numerical simulation studies on the structural behavior of AM shells. The experimental and numerical results verified the effectiveness of the optimized corrugated cylindrical shells in improving local buckling capacity and reducing defect sensitivity. LAGHI et al.[137] described the overall design process, from concept to fabrication, of a half-scale three-dimensional diagonal grid column printed using WAAM technology, demonstrating the feasibility of additive manufacturing for optimized construction of column topology. Its overall shape and application scenario are shown in Fig. 16.

Figure 16 Overall shape and application scenarios of 3D diagonal grid columns[137]

Fig. 16 Overall shape and application scenarios of 3D diagonal grid columns[137]

Compared with reinforced-concrete structures, composite structures have superior seismic performance and are widely used in the field of structural engineering[138]. In recent years, metal additive manufacturing technology has also been applied in composite structures, mainly focusing on the fabrication of concrete-filled steel tubular members under axial compression. CHEN et al.[139–141] used WAAM technology to print the outer steel tube of concrete-filled steel tubular columns, then poured concrete inside to form concrete-filled steel tubular specimens. On this basis, they investigated the geometry and axial compression performance of the specimens; their compression failure modes are shown in Fig. 17.

Figure 17 Typical failure modes of concrete-filled 3D-printed steel tubular columns[139]

Fig. 17 Typical failure modes of concrete-filled 3D printed steel tubular columns[139]

Studies show that steel tubes manufactured by additive manufacturing technology, because of their surface

A certain degree of geometric roughness enables better composite action with concrete. However, geometric imperfections in the steel tube weaken the load-bearing performance of the member; therefore, the influence of the geometric imperfections of the printed external steel tube must be considered in the corresponding design.

3.3 Beams

At present, research on steel-structure beams fabricated by metal additive manufacturing is still in its initial stage, and is mainly concentrated in the following areas: topology optimization of beam members, hybrid manufacturing of beams, and integral printing of beams.

Early studies focused on topology optimization of beams, with the aim of saving material consumption during the fabrication of beam members. YE et al.[142] combined topology optimization with metal additive manufacturing technology and established an optimization model for metal frame beams. The optimization process is shown in Fig. 18. This optimization model reduced material consumption, and physical tests verified that the beam had good load-bearing capacity.

Figure 18. Topology optimization process of beam members[142]

KYVELOU et al.[143] carried out optimization studies on metal steel beams fabricated using the above method. Based on the WAAM stainless-steel material properties reported in existing studies, BRUGGI et al.[144] proposed a new numerical simulation technique for WAAM topology optimization. Their study also showed that combining topology optimization with additive manufacturing technology can effectively reduce the self-weight of beams.

Because metal additive manufacturing offers the advantage of manufacturing flexibility, many scholars have also applied it to the hybrid manufacturing of beams; that is, the flanges and web of the beam are fabricated by conventional techniques, after which the stiffeners of the beam are fabricated by additive manufacturing. LAGHI et al.[145] proposed a hybrid manufacturing method in which, on the basis of conventional members, strengthening is performed by combining topology optimization with WAAM technology; this method was applied to an I-shaped stainless-steel beam in a multi-story frame structure. The study demonstrated that hybrid manufacturing technology can be effectively used to optimize structural members. BAQERSHAHI et al.[146] combined WAAM with conventional manufacturing and proposed a new hybrid manufacturing method; after validation, this hybrid manufacturing method was shown to effectively reduce material consumption. KYVELOU et al.[147] conducted a study on strengthening hot-rolled I-sections by adding WAAM stiffeners at the flange ends. By making use of the residual stresses from the thermal processing and by increasing the stiffeners to improve the local buckling resistance and flexural stiffness, the load-bearing capacity of the steel beams was enhanced. YANG et al.[148] carried out four-point and three-point bending tests on 10 hot-rolled I-section steel beams strengthened using WAAM technology (Fig. 19), verifying that the adopted WAAM strengthening method can be used for the reinforcement, repair, and retrofit of in-service steel beams. MENG et al.[149] investigated several uses and related cases of WAAM-strengthened beams, indicating that WAAM has broad application prospects in beam strengthening.

Figure 19. WAAM-reinforced beam fabrication[148]

With regard to the integral fabrication of beams by additive manufacturing, HUANG et al.[150] conducted four-point bending tests on the performance of 14 stainless-steel square, rectangular, and irregular hollow-section beams manufactured by WAAM. The test results are shown in Fig. 20.

Figure 20. Bending deformation of integral beams manufactured by WAAM[150]

Experiments show that the cross-section of a WAAM beam exhibits sectional behavior similar to that of an equivalent conventionally manufactured cross-section, and that more slender cross-sections are more prone to local buckling.

Moreover, because of the inherent geometric characteristics of the WAAM manufacturing method, the load-bearing capacities of parallel specimens differ considerably.

3.4 Integral Bridges

At present, the use of metal additive manufacturing for the integral fabrication of steel structures and composite structures is still at an early stage, and the related research remains relatively limited. Faculty and students at Technische Universität Darmstadt in Germany built a bridge over a stream [82,128,151], as shown in Fig. 21. This bridge demonstrates the potential of WAAM to produce complex, streamlined geometries at the scale required by the construction industry.

GARDNER et al. [152] conducted testing, analysis, and preliminary verification of a printed integral bridge and its components in the United Kingdom. The tests carried out included advanced geometric analysis of the bridge at various stages, material testing, cross-sectional compression tests, and full-scale load tests of the completed bridge and during later stages; ultimately, it was confirmed that the bridge could withstand the design loads for fully normal service [153]. The manufacturing process, pressure test, and finite element simulation of this integral bridge are shown in Fig. 22.

Fig. 21 Bridge printed by Technische Universität Darmstadt, Germany [128]

(a) Manufacturing process of a 3D-printed integral bridge
(b) Pressure test and finite element simulation of a 3D-printed integral bridge

Fig. 22 Manufacturing process, pressure test, and finite element simulation of a 3D-printed integral bridge [153]

3.5 Component Optimization Technologies

From the above summary of progress in additively manufactured steel structures and metal structural column components, it can be seen that, owing to the influence of the manufacturing technology itself, the formed integral structural components of additively manufactured columns currently contain certain local defects, and such defects reduce the load-bearing capacity of the components. In the field of structural engineering, relatively little research has been conducted on optimizing the initial defects of components. Based on the preceding analysis of the mechanical properties of additively manufactured steel, it is known that heat treatment and machining can improve the mechanical properties of steel; therefore, these methods can also be used to improve defects in components. Subsequent heat treatment can homogenize the microstructure of additively manufactured components and improve their mechanical properties [154–155]. Machining methods such as milling, grinding, and turning can improve the external geometric defects of additively manufactured components and enhance their mechanical properties [154,156].

Innovations in additive manufacturing technology can effectively mitigate component defects. POONGUZHALI et al. [157] investigated a novel self-rotating arc (SA) GMAW welding torch for producing deposited weld beads with filler wire. Figure 23 shows the SA-GMAW process. This method provides a more efficient and defect-free arc-welding additive manufacturing process, offering metallurgical advantages such as control of microsegregation, reduced porosity, and lower susceptibility to hot cracking. NIU et al. [158] proposed a process combining mixed-gas wire-arc additive manufacturing with high-performance laser directed energy deposition (WAAM-LDED). Application of this process can produce fine structures and improve the surface flatness of WAAM structures.

This chapter reviews the application of metal additive manufacturing in steel structures and composite structures. It provides a detailed summary of additive manufacturing technology in

nodes, columns, beams, and entire bridge structures. From the analysis of progress, it can be seen that additively manufactured steel-structure joints can realize the fabrication of complex shapes, reduce thermal residual stresses generated by welding, and mitigate local residual-stress problems caused by bolt-hole openings. Because additively manufactured joints are mostly fabricated by SLM technology, they exhibit better isotropy and strength, and the fabricated joints are also smoother. Owing to its advantages of flexible printing size, relatively low printing cost, and high printing efficiency, WAAM technology is more suitable than other additive manufacturing technologies for printing large components of steel structures and composite structures. For additively manufactured columns, the influence of the printing technology may cause certain geometric imperfections; on the one hand, this leads to uneven column surfaces, and on the other hand, the initial imperfections reduce the load-bearing capacity of the columns. At present, the advantage of flexible forming in additive manufacturing can be used to fabricate complex columns so as to improve their load-bearing capacity. The applications of additive manufacturing in beam members mainly include the following aspects: combining it with topology optimization technology to help reduce the self-weight of beams; carrying out hybrid manufacturing by combining additive manufacturing with traditional technologies to reinforce beams; and printing complete beam members. At present, there are relatively few structural members produced by integral additive manufacturing; however, the printing of full-scale steel-structure bridges has demonstrated that integral printing of steel structures has certain potential. At present, defects in the manufacturing process of components can be improved through heat treatment, machining, and other methods; moreover, innovations in additive manufacturing technology can effectively improve component defects and have broad prospects in the future.

Fig. 23 SA-GMAW additive manufacturing technology[157]

4 Conclusions and Prospects

Because metal additive manufacturing technology has the advantages of a high degree of automation, savings in labor cost, and the ability to fabricate complex geometric solids, it has received extensive attention and research in the field of structural engineering in recent years. This paper summarizes the research progress of metal additive manufacturing technology in the fields of steel structures and composite structures. The main conclusions are as follows.

1) Owing to its advantages of flexible printing size, relatively low printing cost, and high printing efficiency, WAAM technology is more suitable than other additive manufacturing technologies for printing large components of steel structures and composite structures. SLM technology produces better isotropy and strength, and is currently a commonly used technology for fabricating joints in structural systems.

2) The elastic modulus and strength of 316L steel fabricated by WAAM and SLM meet the application requirements of steel structures and composite structures. When the sampling angle of steel tensile specimens differs, the elastic modulus and strength also differ; when the angle is 45°, the elastic modulus and strength of the steel are greater than those along the printing direction and in the perpendicular direction. After mechanical processing and heat treatment of additively manufactured steel, its elastic modulus and strength are also improved.

3) Due to technological reasons, steel produced by metal additive manufacturing has lower ductility than rolled steel and has a certain amount of residual stress. The ductility of steel can be improved by changing the internal microstructure of the additively manufactured metal, mechanical processing, heat treatment, and other methods, thereby reducing the residual stresses generated during the manufacturing process.

4) The integration of metal additive manufacturing technology with topology optimization technology has broad application prospects in the production of complex connections for steel-structure and composite-structure engineering, as well as in research on lightweight components. The printed full-scale steel-structure bridge demonstrates that integrally printed steel structures have certain potential.

5) Components fabricated by metal additive manufacturing technology have certain local defects due to the influence of the manufacturing process, resulting in a decrease in local load-bearing capacity. At present, defects in the component manufacturing process can be improved through heat treatment, machining, and other methods; moreover, innovations in additive manufacturing technology can effectively improve component defects and have broad prospects in the future.

In summary, metal additive manufacturing technology has the advantages of a high degree of automation, savings in labor cost, and the ability to fabricate complex geometric solids. In recent years, it has been extensively studied by researchers in the field of structural engineering and has broad research prospects.

Reinforcement and maintenance of steel structures and composite structures: additive manufacturing technology can be used for metal cladding[159] to repair damaged external steel in steel structures and composite-structure components. At present, KANG et al.[160−162] have conducted research on locally corroded steel pipes and verified the feasibility of metal cladding in the repair of corroded steel pipes.

High-performance new materials for steel structures and composite structures: metal additive manufacturing can realize the integrated fabrication of different metals, effectively combine the advantages of different materials, and improve the strength, toughness, corrosion resistance, and other properties of the fabricated metals.

Optimized design of steel structures and composite structures: by combining metal additive manufacturing technology with topology optimization, shape optimization, and other methods, components and structures can be optimized. While ensuring mechanical performance, lightweight and function-integrated design can be achieved, giving full play to the technical advantages of additive manufacturing.

Additive manufacturing technology for steel structures and composite structures and machine learning···

Integrated application: Because the metal additive manufacturing process has strong randomness, traditional algorithms are difficult to make meet the relevant requirements[163]. Emerging machine learning has outstanding data-processing and analysis capabilities[164], and can be effectively integrated into additive-manufacturing design, monitoring, and process-parameter control, thereby improving the reliability and intelligence of the manufacturing process for steel structures and composite structures[165].

Integrated application of the additive-manufacturing process for steel structures and composite structures with digital twins: As steel-structure and composite-structure components are additively manufactured at large scale, manufacturing quality cannot be completely controlled during the manufacturing process, and data acquisition is relatively difficult[166]. Digital-twin technology can realize real-time transmission between the manufactured components and model data, reduce defects and errors in the manufacturing process, thereby shortening the time required for manufacturing steel structures and composite structures and reducing the costs caused by construction quality[167].

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