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ADDITIVE MANUFACTURING OF 17-4PH STAINLESS STEEL A REVIEW OF PROPERTIES AND SURFACE MODIFICATION

ABSTRACT

Additive manufacturing (AM) of precipitation-hardened stainless steels, particularly 17-4PH (AISI 630), has gained significant attention due to its ability to produce complex geometries combined with high mechanical performance. However, despite the advantages of Powder Bed Fusion (PBF) technologies such as Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS), components fabricated via AM exhibit inherent surface and microstructural imperfections, including porosity, unmelted particles, and anisotropic microstructures, which may significantly reduce fatigue, wear, and corrosion resistance. This review provides a comprehensive analysis of additive manufacturing techniques applied to 17-4PH steel, focusing on the relationship between processing parameters, microstructure evolution, and resulting mechanical properties. Particular emphasis is placed on post-processing strategies, especially heat treatment and surface modification methods. Among these, shot peening is identified as one of the most effective and economically viable techniques for improving surface integrity. It induces compressive residual stresses, grain refinement, and phase transformation, leading to significant improvements in hardness, wear resistance, corrosion resistance, and fatigue life. Recent studies, including those by Walczak and Świetlicki, demonstrate that shot peening of additively manufactured 17-4PH steel can increase surface hardness by over 100% and significantly reduce wear rates while enhancing corrosion resistance. The synergistic combination of heat treatment and surface engineering is shown to be essential for achieving optimal performance. Overall, this work highlights that while AM enables superior design flexibility, the final performance of 17-4PH components is critically dependent on post-processing, particularly surface modification.

Keywords: 17-4PH; DMLS; surface modification; additive manufacturing

INTRODUCTION

The aim of this paper is to present additive manufacturing methods, with particular emphasis on powder bed fusion (PBF) technologies, in the context of producing components made of 17-4PH (AISI 630) steel. The article discusses basic manufacturing methods, associated challenges, the impact of process parameters on material properties, and the

characteristics of finished products. Particular attention is given to surface modification methods aimed at improving mechanical and performance properties.

Additive technologies are widely used in the production of conceptual and engineering models, demonstration and functional prototypes, as well as structural components and custom-made biomedical implants. They are also used in the production of molds and tools and in advanced industrial sectors such as aerospace and automotive [1,2]. In recent years, there has been rapid growth in AM technologies, with the most commonly studied materials being titanium alloys (36.3%), steels (34.8%), aluminum alloys (15.6%), and nickel superalloys (8.8%) [3]. The significant presence of steel in scientific publications indicates a growing interest in comparing conventionally manufactured materials with those produced using additive methods (see Fig.1). One of the key advantages of additive methods is the ability to produce complex geometries that are often unattainable using traditional manufacturing techniques [2], such as, for example, auxetic structures [4]. As a result, AM technologies offer an attractive alternative to conventional methods, especially since the properties of additively manufactured materials can be comparable and, in some cases, even superior compared to conventional counterparts [5–7]. This trend is also evident in the case of 17-4PH steel, or its equivalents shown in Table 1. Manufacturing costs, however, remain a significant constraint, despite literature suggesting that processes such as PBF are cost-effective, particularly for prototyping and small-batch production [7]. Among the many additive manufacturing methods, this paper focuses primarily on PBF technologies, such as selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), and direct metal laser sintering (DMLS), as these are most commonly used for processing 17-4PH steel. 17-4PH steel is characterized by a favorable combination of high mechanical strength, good corrosion resistance, and adequate ductility, which accounts for its wide industrial application [8]. The properties of 17-4PH steel products are highly dependent on the manufacturing method used, process parameters, and post-manufacturing treatments, including heat treatment. Therefore, process optimization and the selection of the appropriate technology for a specific application require a detailed analysis of the relationship between process parameters and the final properties of the material. The requirements for this steel are specified in a number of standards, such as ASTM A564, ASTM A693, EN 10088 (Parts 1–3), and EN 10021.

Table 1. Different designations of 17-4PH or its equivalents [4]

Standard	Designation
ASTM	17-4PH
ASTM	UNS S17400
ASTM	AISI 630
EN	X5CrNiCuNb16-4
EN	1.4542
DIN	X4CrNiCuNb16-4
DIN	1.4540
JIS	JIS SUSF630
JIS	JIS SCS24
ISO	ISO 4542-174-00-I
ISO	ISO PP20I
ISO	ISO X5CrNiCuNb16-4

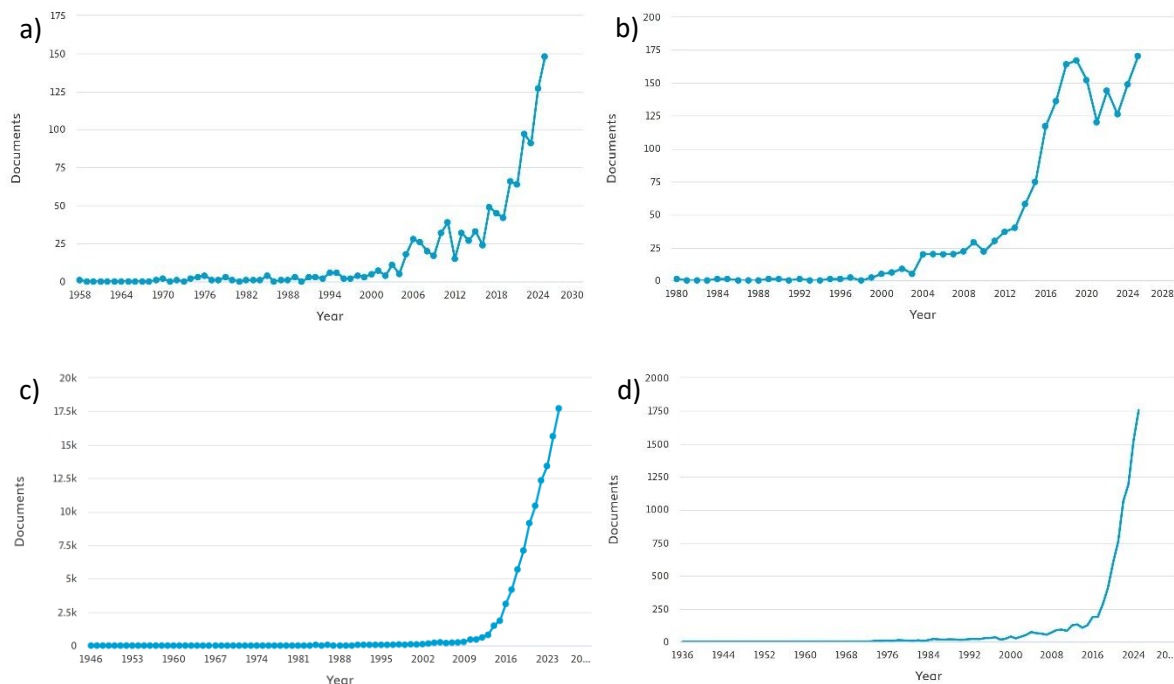


Fig. 1. Search in Scopus publications for a) 17-4PH, b) DMLS, c) additive manufacturing, d) PBF

17-4PH steel is a precipitation-hardening material characterized by a favorable combination of high strength, good corrosion resistance, and an appropriate balance between hardness and ductility. As a result, it is widely used in demanding industries such as aerospace, nuclear power, the chemical industry, and the oil and gas sector. It is used, among other things, in the manufacturing of turbine blades, fasteners, shafts, valves, and measuring equipment. [10,11]. In environments containing hydrogen sulfide (H_2S), this material may be susceptible to sulfide stress cracking (SSC), which poses a significant operational limitation [12]. This material is also used in medicine (surgical instruments and certain implants), the food and chemical industries (molds, agitators), and the power generation sector (steam and gas turbine blades), where resistance to fatigue, cavitation, and corrosion is required [11]. In offshore applications, it is used, among other things, in pump components operating under harsh pressure and corrosive conditions [13], and in the nuclear power industry in the production of turbine blades for light-water and pressurized-water reactors [14].

From a microstructural standpoint, conventionally produced 17-4PH steel is characterized primarily by a martensitic structure [9]. In the case of additive manufacturing methods, a more complex microstructure is observed, comprising martensite and retained austenite, as well as the presence of δ -ferrite resulting from rapid cooling [15–17]. The transformation of austenite occurs in the temperature range of approximately 880–910°C [11], which has a significant impact on the material's properties [18]. The quality of additively manufactured products depends primarily on process parameters such as laser power, scanning speed and beam focusing, as well as on the scanning strategy, the type of shielding gas and the orientation of the build. These parameters have a direct impact on the density, microstructure, residual stresses and surface quality of additively manufactured materials [2,16,17,19]. 17-4PH steel is also used in advanced material concepts. It can be utilised in processes such as laser solid forming (LSF) and laser forming repair (LFR) [10], as well as in fused filament fabrication (FFF) technologies, where it was one of the first metallic materials used in this method [20,21]. In addition, it is possible to produce porous biomedical structures that offer an

alternative to titanium foams [22], also using additive manufacturing methods [23]. Additive manufacturing technologies also enable the creation of multi-layer and gradient structures. For example, combining 316L and 17-4PH steel in laminated structures yields a favorable balance of strength and ductility due to the distribution of deformation across the layers and the reduction of stress concentrations [24].

Although numerous studies have examined the additive manufacturing of 17-4PH stainless steel, existing reviews typically focus on specific aspects, such as microstructural evolution, heat treatment, or mechanical properties. An in-depth analysis combining additive manufacturing parameters, defect formation mechanisms, mechanical behavior, and post-processing surface modification strategies remains absent. Therefore, the innovative nature of this review lies in combining these aspects within a single framework, with a particular emphasis on the role of surface engineering methods in mitigating defects inherent to additive manufacturing and improving resistance to fatigue, wear, and corrosion. Furthermore, the article identifies current research gaps and discusses future development directions for 17-4PH steel components manufactured using additive methods.

MANUFACTURING METHODS AND MATERIAL PROPERTIES AFTER PRINTING

Additive manufacturing methods

Additive manufacturing (AM) offers a wide range of technological possibilities, but it also presents significant challenges related to quality control, repeatability, and process costs, among other factors. The commercialization of additive manufacturing techniques began in the mid-1980s [25]. Stereolithography (SLA), which was introduced to the market in 1987 by 3D Systems, is considered the first method to be implemented [26]. However, over the years, it has been possible to develop entirely new manufacturing methods and improve existing ones. Currently, additive manufacturing technology is undergoing rapid development, enabling the production of components with high technical performance and virtually unlimited geometries. Additive technologies can be divided into several main categories depending on the manufacturing method (Fig. 2).

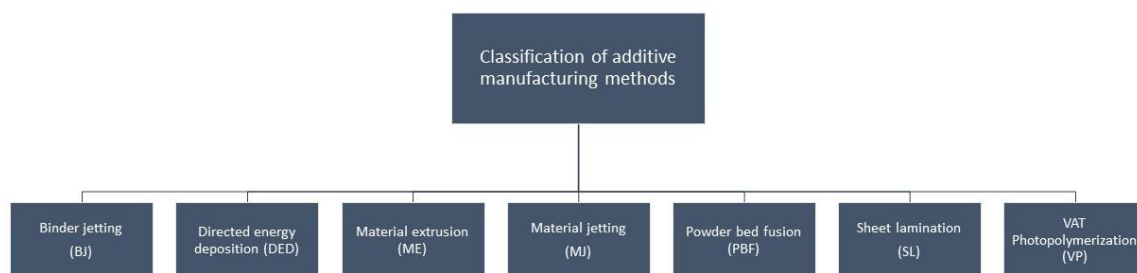


Fig. 2. Classification of additive manufacturing methods according to The International Organization for Standardization (ISO)/ American Society for Testing and Materials (ASTM) 52900:2021 standard classify standard prepared on the basis of [28]

There are many classifications, but this paper focuses on the one adopted in the ISO/ASTM 52900 standard. There are many additive manufacturing methods, but this paper focuses on the PBF group. PBF encompasses all processes that use thermal energy (laser or

electron beam) to selectively fuse areas of powder layer by layer. According to ISO/ASTM 52900:2021, additive manufacturing (AM) is “a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.” [27].

Among the highlighted categories, Powder Bed Fusion (PBF) technology is of particular significance, as it is widely used in industry due to its high geometric accuracy and the ability to process a variety of materials, such as metals, polymers, composites, and ceramics [29]. PBF processes involve the selective melting or sintering of powder using a concentrated source of thermal energy, most commonly a laser or an electron beam. According to the definition in ISO/ASTM 52900:2021, it is “an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.” [27]. PBF technologies are widely used to manufacture components with high added value, such as medical implants and aerospace components [30]. Their main advantages include high precision, good surface quality, and the ability to produce structures with high density and favorable mechanical properties. A distinctive feature of PBF processes is the use of powder as a feedstock, which also serves in part as a support for the component being manufactured. The process itself is cyclical and consists of several repetitive stages. First, a thin layer of powder is evenly distributed on the build platform using a recoater mechanism. Next, a laser or electron beam selectively melts the areas corresponding to the cross-section of the model for that layer. After scanning is complete, the build platform is lowered by the specified layer thickness, and the process is repeated until the finished part is obtained. Based on this, PBF technologies can be divided into several subgroups, presented in Fig. 3.

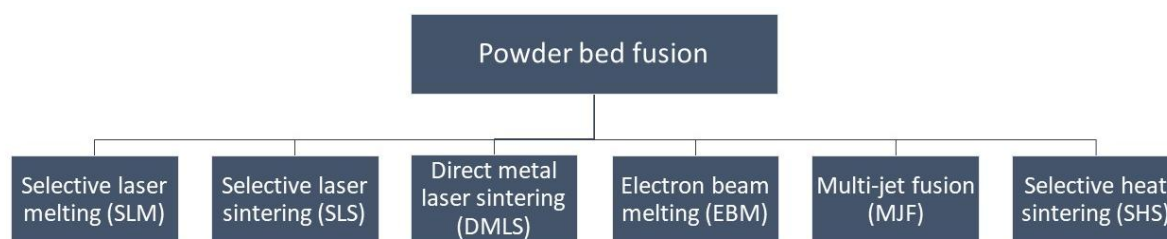


Fig. 3. Powder Bed Fusion classification prepared on the basis of [1]

PBF technologies also show great potential in biomedical applications, including the production of implants and drug delivery systems. They enable the creation of complex, personalized structures tailored to individual patient needs, in part through integration with 3D scanning techniques [31]. Compared to other additive manufacturing methods, PBF offers relatively high precision and the ability to control the material’s microstructure, which is crucial in medical applications. Current research areas also include the development of technologies for manufacturing multi-material structures using PBF [32]. This approach allows for the localized shaping of material properties through the appropriate selection of materials in successive layers, enabling the design of gradient and functionally diverse structures. Such solutions open up new possibilities for optimizing the mechanical properties, wear resistance, and functionality of manufactured components.

SLM

SLM is a manufacturing technology developed in the mid-1980s and patented by Carl Deckard [33]. It involves sintering powdered material using a laser beam, which melts the powder particles and bonds them together, this process takes place layer by layer [34]. Using this method, it is possible to produce nearly fully dense (99.99%) three-dimensional parts from metal powders [35]. Furthermore, these products do not require any additional processing after manufacturing. The basic principle involves melting powder particles using a powerful laser beam. In addition, parts manufactured using this method are comparable to those produced using traditional methods and are weldable [36].

SLS

SLS (Selective Laser Sintering) is a method used primarily for polymer materials. The difference between SLS and techniques such as SLM or DMLS lies mainly in the material produced and in the fact that the laser light does not completely melt the material but only sinters it (overheating the edges of the particles to fuse them together). In addition, SLS printing does not require the supports that are necessary in SLM or DMLS to dissipate heat, maintain geometry, and ensure that the part does not deform excessively.

DMLS

DMLS was developed in the 1990s by EOS, but the origins of the concept date back to the 1980s [37]. DMLS is the most commonly used PBF technique for manufacturing parts from solid metallic materials [38]. It is also sometimes referred to as SLS, although conceptually the methods are the same; DMLS, however, is a further development of SLS. DMLS is primarily intended for metal alloy powders, whereas SLS is primarily intended for technically pure metal powders [31]. As the name suggests, this method uses laser light to directly sinter a thin layer of powder in the powder bed. The process involves filling the chamber with powder, after which a laser beam fuses a layer of powder on the platform along a predefined path. After the recoater passes over the bed and the platform is lowered, the process repeats. The powder forms a solid metal material, and then another layer of powder is added from the reservoir, and the process is repeated until the finished component is obtained. Most often, protective atmospheres such as argon or nitrogen are used in machines of this type, which ensure the desired properties of the final product. CO₂, YAG, and fiber lasers are used for manufacturing [37].

EBM

Electron beam melting (EBM) is a technology similar to SLM, with the difference that the melting process takes place in a high vacuum and the heat source used to melt the material is an electron beam [39,40]. Due to the high concentration of heat, residual stresses in the material are significantly reduced. Furthermore, the use of a vacuum prevents oxidation during the manufacturing process [41]. For this reason, this method is widely used in the aerospace industry and in medicine [42]. EBM allows for the use of materials that react easily with the environment as well as difficult-to-melt materials. The material can be in the form of either powder or wire.

MJF

Multijet Fusion (MJF) is one of the latest PBF technologies, developed by HP. Thanks to its unique sintering technique, MJF printing allows for the rapid production of durable parts without compromising strength. In this technique, thermoplastic powder is heated using an infrared source after thermos reactive ink is sprayed onto the selected area [43,44]. The MJF method has also found application in so-called 4D printing that is, the production of three-dimensional functional components whose fourth dimension is time, meaning independent actions or reactions [45]. This allows for external triggering using certain environmental changes, such as an electric field, a magnetic field, osmosis-based activation, light-based activation, etc.

SHS

Selective Heat Sintering (SHS) is a powder bed fusion process based on the selective heating and sintering of powder material using a thermal printhead rather than a high-energy laser beam [1,46]. This technology is primarily used for polymer powders, whereas it is much less commonly used for metallic materials due to limitations regarding achievable density and mechanical properties [1,47]. As a result, SHS technology has limited applications in the production of 17-4PH stainless steel components, where laser-based technologies such as SLM and DMLS are typically preferred because they allow for nearly complete material densification and provide better mechanical properties [1,46].

Although several AM technologies can be used to process 17-4PH stainless steel, their suitability differs significantly. Among the available methods, LPBF-based processes such as SLM and DMLS are currently the most extensively investigated and industrially adopted for 17-4PH steel due to their ability to produce components with high density, good dimensional accuracy, and mechanical properties comparable to wrought materials [48–50]. In contrast, technologies based on selective sintering, such as SLS, typically result in lower density, making them less suitable for the production of high-performance structural components made of 17-4PH steel. EBM technology has the advantage of producing lower residual stresses due to higher printing temperatures; however, it results in poorer surface quality and lower dimensional accuracy compared to laser systems [39–42]. New technologies, such as MJF and FFF, offer cost and performance benefits; however, the available data on their long-term mechanical and fatigue strength remains limited [20,21,43]. Consequently, for critical engineering applications that require high strength and reliability, LPBF technologies remain the preferred method for producing 17-4PH stainless steel.

PROPERTIES

The process involves filling the chamber with powder, after which a laser beam fuses a layer of powder on the platform along a predefined path. The powder forms a solid metal material, and then another layer of powder is added from the reservoir, and the process is repeated until the finished component is obtained [10,48,49,51]. Basic data on the properties are presented in Table 2. Based on the available literature, it can be concluded that the mechanical properties of this steel, produced using additive manufacturing methods, exhibit significant variability, which is directly related to both process parameters (such as linear energy, scan speed, and microstructural orientation) and the heat treatment applied [48,52,53].

Table 2. Properties of 17-4PH stainless steel compiled on the basis of [54]

Property	Unit	Value
Density	g/cm ³	7.82
Solidification temperature range	°C	1400–1440
Electrical resistivity	μΩ·cm	70–80
Thermal conductivity at 260 °C	W·m ⁻¹ ·K ⁻¹	19.5
Coefficient of thermal expansion at (20 °C-100 °C)	μm/m·°C	10.8
Elastic Modulus at 20 °C	GPa	197
Tensile strength	MPa	1050–1150

17-4PH steel, along with other steel grades in the “PH” group i.e., those intended for precipitation hardening exhibit better radiation shielding properties than Fe-based steel concretes [54]. An analysis of the compiled results (Tables 3–6) indicates that the hardness of 17-4PH steel in its as-manufactured state and after various heat treatment processes can range from approximately 255 HV to 525 HV [48,52,53]. Similarly, tensile strength ranges from approximately 500 MPa to as high as 1478 MPa [48,50,55]. In contrast, the yield strength ranges from approximately 360 MPa to 1450 MPa [48,50,56]. Young's modulus, a parameter that is less sensitive to microstructural changes, ranges from approximately 163 GPa to 209 GPa [48,56,57]. Compared to conventionally manufactured materials, which have more uniform properties (e.g., a Young's modulus of approximately 197 GPa and a tensile strength in the range of 1050-1150 MPa), the observed wider range of parameters in additive technologies is primarily due to the presence of porosity, structural anisotropy, and microstructural variation [49,57]. An important step in determining the properties of 17-4PH steel following the additive manufacturing process is heat treatment, which affects both the material's microstructure and its mechanical properties, particularly hardness, strength, and ductility [58]. The most commonly used method is precipitation hardening, which is carried out at various temperatures (e.g., H900, H1025, H1150), enabling the controlled precipitation of copper-rich phases and, consequently, a significant improvement in mechanical properties [48,50,53]. The selection of heat treatment parameters, particularly the aging temperature, directly affects the balance between the material's strength, ductility, and corrosion resistance [59]. In addition, solution treatment is used to homogenize the structure, as well as processes such as hot isostatic pressing (HIP) and vacuum isostatic pressing (VIP), which reduce porosity and increase material density [57].

The data presented in the tables indicate that the material in its as-built state typically has a lower hardness (approximately 260-350 HV) and a tensile strength in the range of 900-1100 MPa [48,57,60]. Heat treatment, particularly ageing, significantly enhances the mechanical performance of 17-4PH steel, enabling hardness values above 500 HV and tensile strengths exceeding 1400 MPa to be achieved [50,52,53]. A similar trend is observed for the yield strength, which, after appropriate processing, can increase from approximately 500-800 MPa to values exceeding 1100 MPa [53,56]. In contrast, the Young's modulus remains relatively stable, and its slight deviations are most often associated with the presence of structural defects characteristic of additive manufacturing processes [56,57].

Table 3. Hardness comparison of 17-4PH steel

<u>Method</u>	<u>State/condition</u>	<u>Hardness</u>	<u>Unit</u>	<u>SD</u>	<u>Citation</u>
SLM	Conventional	~340	HV		[48]
	As-built	~260	HV		[48]
	Conventional	~320	HV		[48]
	Conventional H900	~290	HV		[48]
	Conventional H1025	~350	HV		[48]
	Conventional H1150	~425	HV		[48]
	Conventional H1150M	~350	HV		[48]
	H900	~255	HV		[48]
	H1025	~295	HV		[48]
	H1150	~325	HV		[48]
	H1150M	~380	HV		[48]
LBM	As-built XY	355	HV20		[49]
	As-built XZ	342	HV20		[49]
	As-built YZ	345	HV20		[49]
	H900 XY	386	HV20		[49]
	H900 XZ	379	HV20		[49]
	H900 YZ	381	HV20		[49]
	Conventional H900	396	HV20		[49]
	Conventional H1025	378	HV20		[49]
DMLS	As-built	428	HV10		[51]
	Conventional 1.4542	320	HV10		[51]
DMLS	As-built	296	HV	20	[61]
	H900	413	HV	22	[61]
	H1100	386	HV	23	[61]
SLM	As-built	335	HV	15	[52]
	Solution HT	355	HV	8	[52]
	Solution + H 900 HT	525	HV	6	[52]
	Conventional	384	HV	8	[52]
	Conventional Solution HT	368	HV	7	[52]
	Conventional Solution + H 900 HT	450	HV	9	[52]
SLM	As-built De-focal length 6	349	HV		[62]
	As-built De-focal length 1	367	HV		[62]
	As-built De-focal length -6	345	HV		[62]
	As-built De-focal length -5	409	HV		[62]
	As-built De-focal length -4	414	HV		[62]
	As-built De-focal length -3	395	HV		[62]
	As-built De-focal length -2	367	HV		[62]
	As-built De-focal length -1	381	HV		[62]
SLM	After stress relief in 650 for 2h	336	HV		[17]
	After stress relief in 650 for 2h x20 powder reused	320	HV		[17]
DMLS	Powder	260	HV0.1	25	[60]
	As-built	296	HV0.1	17	[60]
	Shot-peened	~452	HV0.1		[60]
	Conventional	385	HV0.1	16	[60]
DMLS	As-built	338	HV		[57]

SLM	Vacuum isostatic pressing	449	HV		[57]
	Hot isostatic pressing 1040	324	HV		[57]
	Hot isostatic pressing >100MPa	366	HV		[57]
	Hot isostatic pressing /	479	HV		[57]
	Hot isostatic pressing < 100MPa	355	HV		[57]
	As-built	333	HV	2	[53]
	H900	375	HV	3	[53]
	H1025	399	HV	8	[53]
	H1150	381	HV	3	[53]
	Solution treatment at 1040	330	HV	3	[53]
SLM	Solution treatment + H900	417	HV	5	[53]
	Solution treatment + H1025	350	HV	4	[53]
	Solution treatment + H1150	317	HV	3	[53]
	Conventional + solution treatment	357	HV	10	[50]
	Conventional + solution treatment + ageing	402	HV	6	[50]
	As-built	365	HV	7	[50]
	Solution treatment	420	HV	7	[50]
	Ageing	453	HV	5	[50]
	Solution treatment + ageing	489	HV	6	[50]

~- values are those taken from a plot.

Table 4. Comparison of Ultimate Tensile strength of 17-4PH steel

Method	State/Condition	UTS	Unit	SD	Citation
SLM	After stress relief in 650 for 2h	984	MPa		[17]
	After stress relief in 650 for 2h x20 powder reused	1038	MPa		[17]
SLM	As-built	1007	MPa	11	[48]
	Wrought	1017	MPa	2	[48]
	Surface -finished	1018	MPa		[48]
	As-built	1073	MPa	3	[48]
	H900	1068	MPa	8	[48]
	H1025	1243	MPa	14	[48]
	H1150	1073	MPa	10	[48]
	H1150M	1095	MPa	23	[48]
	Condition A	846	MPa	57	[48]
	Condition A + H900	1028	MPa	12	[48]
	Condition A + H1025	1128	MPa	6	[48]
	Condition A + H1150	970	MPa	14	[48]
LBM	Condition A + H1150M	958	MPa	8	[48]
	H900	1408	MPa		[49]
	H900	1395	MPa		[49]
	H900	1417	MPa		[49]
	Conventional H900	1387	MPa		[49]
	Conventional H900	1394	MPa		[49]
	Conventional H900	1387	MPa		[49]
DMLS	As-built	1130	MPa		[60]
	Shot-peened	1136	MPa		[60]

SLM	As-built	906	MPa		[57]
	Vacuum isostatic pressing	1419	MPa		[57]
	Hot isostatic pressing 1040	919	MPa		[57]
	Hot isostatic pressing >100MPa	960	MPa		[57]
	Hot isostatic pressing /	1140	MPa		[57]
	Hot isostatic pressing < 100MPa	940	MPa		[57]
SLM	Horizontal	860	MPa	75	[63]
	Vertical	861	MPa	45	[63]
SLM	Wrought	1028	MPa		[64]
	Horizontal	1128	MPa		[64]
L-PBF	Gas-atomized D50=13 μm (63 J/mm ³)	1050	MPa	50	[55]
	Water-atomized D50=17 μm (63 J/mm ³)	500	MPa	30	[55]
	Water-atomized D50=24 μm (63 J/mm ³)	470	MPa	50	[55]
	Water-atomized D50=43 μm (63 J/mm ³)	490	MPa	15	[55]
	Gas-atomized D50=13 μm (80 J/mm ³)	1090	MPa	30	[55]
	Water-atomized D50=17 μm (80 J/mm ³)	650	MPa	40	[55]
	Water-atomized D50=24 μm (80 J/mm ³)	615	MPa	25	[55]
	Water-atomized D50=43 μm (80 J/mm ³)	590	MPa	75	[55]
SLM	As-built	1255	MPa	3	[53]
	H900	1417	MPa	6	[53]
	H1025	1358	MPa	8	[53]
	H1150	1319	MPa	2	[53]
	Solution treatment at 1040	1188	MPa	6	[53]
	Solution treatment + H900	1444	MPa	2	[53]
	Solution treatment + H1025	1172	MPa	2	[53]
	Solution treatment + H1150	1017	MPa	15	[53]
LPBF	As-built vertical	940	MPa		[56]
	As-built horizontal	1060	MPa		[56]
	Solution treatment + H900 (Vertical)	1150	MPa		[56]
	Conventional H900	1370	MPa		[56]
SLM	As-built	944	MPa	35	[13]
	650°C (2 h)	915	MPa	38	[13]
	788°C (2 h)	1487	MPa	10	[13]
	788 + 482°C (2 + 1 h)	1457	MPa	3	[13]
	Conventional 482°C	1310	MPa		[13]
SLM	As-built	944	MPa	35	[65]
	650°C (2 h)	915	MPa	38	[65]
	788°C (2 h)	1487	MPa	10	[65]
	788 + 482°C (2 + 1 h)	1457	MPa	3	[65]
	Conventional 482°C	1310	MPa		[65]
SLM	Conventional + solution treatment	1040	MPa	3	[50]
	Conventional + solution treatment + ageing	1188	MPa	2	[50]
	As-built	1228	MPa	8	[50]
	Solution treatment	1268	MPa	3	[50]
	Ageing	1478	MPa	1	[50]
	Solution treatment + ageing	1381	MPa	3	[50]

Table 5. Yield tensile strength of 17-4PH steel

<u>Method</u>	<u>State/Condition</u>	<u>YTS</u>	<u>Unit</u>	<u>SD</u>	<u>Citation</u>
SLM	After stress relief in 650 for 2h	859	MPa		[17]
	After stress relief in 650 for 2h x20 powder reused	770	MPa		[17]
SLM	As-built	605	MPa	2	[48]
	Wrought	914	MPa	7	[48]
	Surface -finished	638	MPa		[48]
	As-built	477	MPa	3	[48]
	H900	522	MPa	17	[48]
	H1025	465	MPa	7	[48]
	H1150	360	MPa	21	[48]
	H1150M	637	MPa	18	[48]
	Condition A	339	MPa	10	[48]
	Condition A + H900	602	MPa	11	[48]
	Condition A + H1025	575	MPa	7	[48]
	Condition A + H1150	592	MPa	18	[48]
	Condition A + H1150M	605	MPa	34	[48]
LBM	H900	1278	MPa		[49]
	H900	1295	MPa		[49]
	H900	1293	MPa		[49]
	Conventional H900	1243	MPa		[49]
	Conventional H900	1256	MPa		[49]
	Conventional H900	1253	MPa		[49]
DMLS	As-built	914	MPa	13	[60]
	Shot-peened	934	MPa	21	[60]
SLM	As-built	857	MPa		[57]
	Vacuum isostatic pressing	1405	MPa		[57]
	Hot isostatic pressing 1040	847	MPa		[57]
	Hot isostatic pressing >100MPa	841	MPa		[57]
	Hot isostatic pressing /	1431	MPa		[57]
	Hot isostatic pressing < 100MPa	872	MPa		[57]
SLM	Horizontal	860	MPa	75	[63]
	Vertical	861	MPa	45	[63]
SLM	Wrought	657	MPa		[64]
	Horizontal	485	MPa		[64]
LPBF	As-built vertical	580	MPa		[56]
	As-built horizontal	650	MPa		[56]
	Solution treatment + H900 (Vertical)	1020	MPa		[56]
	Conventional H900	1450	MPa		[56]
SLM	As-built	570	MPa	13	[13]
	650°C (2 h)	619	MPa	2	[13]
	788°C (2 h)	857	MPa	14	[13]
	788 + 482°C (2 + 1 h)	1126	MPa	14	[13]
	Conventional 482°C	1170	MPa		[13]
SLM	As-built	570	MPa	13	[65]
	650°C (2 h)	619	MPa	1	[65]

	788°C (2 h)	857	MPa	14	[65]
	788 + 482°C (2 + 1 h)	1126	MPa	14	[65]
	Conventional 482°C	1170	MPa		[65]
SLM	Conventional + solution treatment	820	MPa	19	[50]
	Conventional + solution treatment + ageing	1113	MPa	5	[50]
	As-built	803	MPa	49	[50]
	Solution treatment	966	MPa	42	[50]
	Ageing	1173	MPa	89	[50]
	Solution treatment + ageing	1276	MPa	16	[50]

Table 6. Young modulus of 17-4PH steel

Method	State/Condition	E	Unit	SD	Citation
SLM	As-built	176	GPa	1	[48]
	Wrought	209	GPa	14	[48]
	Surface -finished	181	GPa		[48]
	As-built	169	GPa	3	[48]
	H900	175	GPa	21	[48]
	H1025	176	GPa	5	[48]
	H1150	172	GPa	26	[48]
	H1150M	178	GPa	9	[48]
	Condition A	178	GPa	14	[48]
	Condition A + H900	186	GPa	8	[48]
	Condition A + H1025	182	GPa	3	[48]
	Condition A + H1150	183	GPa	9	[48]
	Condition A + H1150M	184	GPa	10	[48]
LBM	H900	202	GPa		[49]
	H900	204	GPa		[49]
	H900	204	GPa		[49]
	Conventional H900	201	GPa		[49]
	Conventional H900	201	GPa		[49]
	Conventional H900	201	GPa		[49]
SLM	As-built	171	GPa		[57]
	Vacuum isostatic pressing	174	GPa		[57]
	Hot isostatic pressing 1040	165	GPa		[57]
	Hot isostatic pressing >100MPa	172	GPa		[57]
	Hot isostatic pressing /	163	GPa		[57]
	Hot isostatic pressing < 100MPa	169	GPa		[57]
LPBF	As-built vertical	187	GPa		[56]
	As-built horizontal	187	GPa		[56]
	Solution treatment + H900 (Vertical)	187	GPa		[56]
	Conventional H900	197	GPa		[56]

Technological factors also have a significant impact on the variation in properties, such as the type of powder (e.g., gas-atomized powders exhibit better properties than water-atomized powders), processing parameters, and the direction of grain orientation, which leads to anisotropy in mechanical properties [55,56]. The anisotropic microstructure and the presence of local stress concentrators influence the mechanism of crack initiation and propagation in 17-4PH steels produced by additive manufacturing methods [66]. In addition, secondary

processes, such as surface treatments (e.g., shot peening), can locally increase hardness and fatigue resistance [60,67–69]. In addition to its favorable mechanical properties, 17-4PH steel also exhibits good functional properties, including the ability to effectively shield against radiation, outperforming some iron-based steel concretes in this regard [54]. Combined with the ability to precisely tailor its properties by adjusting process and heat treatment parameters, this makes the material particularly attractive for advanced engineering applications, such as the aerospace industry, the energy sector, and nuclear technology. In summary, 17-4PH steel produced using additive manufacturing methods is a material with significant application potential; however, achieving optimal properties requires strict control of both process parameters and subsequent processing stages [48,50,57]. The relationship between process parameters, microstructure, and mechanical properties is one of the key aspects of research on 17-4PH steel produced using additive manufacturing methods [70].

CHEMICAL COMPOSITION

The chemical composition of 17-4PH steel is specified in the ASTM A564, AMS 5643, and EN 10088-1 standards and consists primarily of chromium, nickel, and copper as key alloying elements. Based on the data compiled in Table 7, it can be concluded that both “as-fabricated” materials and powders used in additive manufacturing technologies (e.g., EOS GP1) exhibit a composition compliant with standard requirements, i.e., Cr: ~15-17.5%, Ni: ~3-5%, Cu: ~3-5%, with the remainder being iron [67,68,71,72]. Chromium provides high corrosion resistance by forming a passive layer, while nickel stabilizes the structure and improves plastic properties [10,67]. Copper, however, plays a key role in strengthening the material; during aging, it forms strengthening precipitates, leading to an increase in the material’s strength and hardness [52,53,68]. Another important additive is niobium, which stabilizes the microstructure by forming carbides and limiting grain growth.

Table 7. Chemical composition of 17-4PH according to ISO and ASTM standards and measured complied on the basis of [67,68,71,72]

wt. %	<u>C</u>	<u>Cr</u>	<u>Ni</u>	<u>Cu</u>	<u>Mn</u>	<u>Si</u>	<u>Mo</u>	<u>Nb</u>	<u>P</u>	<u>S</u>	<u>Fe</u>
17-4PH as-fabricated [67,71]	0.043	15.85	4.92	4.79	0.67	0.71	0.12	0.27	0.02	0.005	Bal.
GP1 [67,71]	0.01	15.8	4.02	3.9	0.7	0.7	0.4	0.29	-	-	Bal.
17-4PH as-fabricated [68]	0.043	15.18	4.503	4.734	0.665	0.694	0.121	0.028	-	0.051	Bal.
17-4PH as-fabricated [72]	0.04	15.95	4.72	4.6	0.69	0.71	0.12	0.26	-	-	Bal.
EOS GP1 powder declaration	< 0.07	15-17.5	3-5	3-5	< 1	< 1	< 0.5	0.15-0.45	-	< 0.07	Bal.
EN10088-1	< 0.07	15-17	3-5	3-5	< 1.5	< 0.7	< 0.6	5 *C - 0.45	< 0.04	0.03	Bal.
ASTM A564	< 0.07	15-17.5	3-5	3-5	< 1	< 1	< 0.5	0.15-0.45	-	-	Bal.

Analysis of literature data indicates that the chemical composition of 17-4PH steel produced using additive manufacturing methods remains essentially consistent with that of

conventional materials, as confirmed by studies conducted on various technologies, such as SLM, DMLS, and L-PBF [68,71–73]. Minor deviations in the content of individual elements are mainly due to the specific nature of the powder manufacturing process (e.g., gas or water atomization) and processing conditions; however, they remain within the limits permitted by material standards such as ASTM A564 or AMS 5643. This means that the observed differences in mechanical properties do not result directly from changes in chemical composition, but are a consequence of microstructural differences, including grain size and morphology, the presence of porosity, and structural anisotropy arising during the additive manufacturing process [74,75]. It is also emphasized that the high chemical homogeneity of powders used in additive manufacturing technologies contributes to consistent material properties; however, the final mechanical properties are strongly influenced by the material's thermal history and the post-processing treatments applied, particularly aging and precipitation hardening [73,74]. It is worth noting that the designation 17-4PH refers to a composition of approximately 17% chromium and 4% nickel, while copper despite its lower content plays a key role in the precipitation hardening mechanism [52,53].

GRAIN SIZE, MICROSTRUCTURE, PHASE COMPOSITION

In the context of the chemical composition discussed earlier, the phase composition of 17-4PH steel and its evolution depending on the manufacturing process are also of significant importance. Conventional 17-4PH steel is classified as a martensitic precipitation-hardening stainless steel, belonging to the group of chromium-nickel steels with added copper [60,76]. After solution treatment, its microstructure consists mainly of martensite, which provides the framework for subsequent hardening processes [60,76]. Copper plays a key role in this mechanism; during aging, it precipitates in the form of fine particles within the martensitic matrix, leading to a significant increase in the material's strength and hardness. Although this mechanism is beneficial from the standpoint of mechanical properties, under certain operating conditions it can lead to undesirable effects, such as degradation of properties under the influence of radiation, observed, for example, in pressure components of nuclear reactors [77]. In the case of additive technologies, however, a more complex phase composition is observed [60,76]. Rapid cooling rates, combined with cyclic heating and remelting of the material, result in the formation of a structure containing not only martensite but also significant amounts of retained austenite [60,76]. As a result, 17-4PH steel produced using additive manufacturing methods may exhibit characteristics of both martensitic and austenitic precipitation-hardening steels [60]. This two-phase (martensitic-austenitic) microstructure has a beneficial effect on the combination of performance properties, enabling the simultaneous achievement of high strength, good ductility, and corrosion resistance. Additionally, the presence of retained austenite can improve fracture resistance and the material's behavior at elevated temperatures. As a result, additively manufactured 17-4PH steel can maintain stable mechanical properties even at temperatures up to approximately 315°C, making it an attractive material for applications requiring high reliability under harsh operating conditions [78]. Depending on the manufacturing method used, it is possible to obtain different phase compositions in 17-4PH steel. In conventional 17-4PH steel, a martensitic structure with small amounts of δ -ferrite is most commonly obtained (see Fig. 4) [15]. In the analyzed samples, the α and γ phases appear in different proportions. The peaks for the α phase are located at $2\theta = 44.7^\circ$, 65° , 82.3° , and 98.9° . The peaks for the γ phase are located at $2\theta = 43.5^\circ$, 50.4° , 76.5° , 90.4° , and 95.0° . These positions correspond to the (111), (200), (220), (311), and (222) planes. In the diffractogram of conventional steel, the γ (111), α (110),

α (200), α (211), and α (220) peaks are significantly more intense, whereas in DMLS steel, the γ (220) and γ (311) peaks are more intense. In a similar case of conventional DMLS steel, martensite to austenite ratio appeared to be at around 85% to 15% for DMLS and 93% to 7% for the conventional [79]. Following the precipitation hardening process typical of this steel, an almost purely martensitic structure is obtained [80]. The situation is similar for additively manufactured steels, except that in the case of 17-4PH steel, a wide variety of phase ratios (austenite, martensite, ferrite) can be obtained following AM, depending on the manufacturing method used and the process conditions [81].

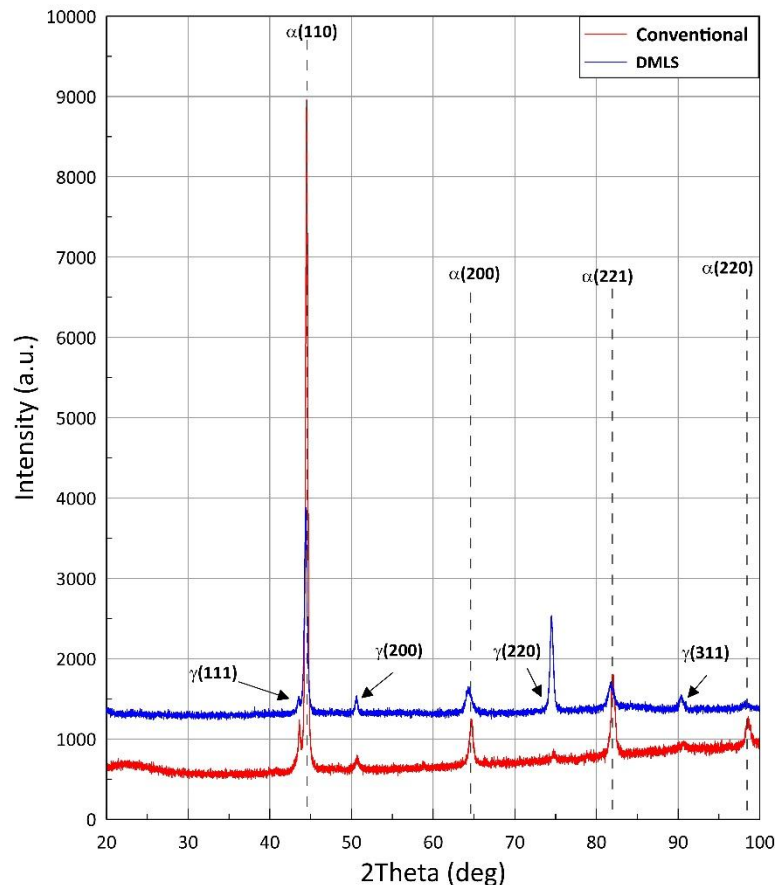


Fig. 4. XRD phase composition of conventional and DMLS steel

This is due to the microstructure being highly dependent on solidification conditions and phase transformations at the very high cooling rates characteristic of AM technology [81]. The strong relationship between thermal history, phase transformations and final microstructure is not unique to additive manufacturing and has also been observed in other laser-based processing technologies, including laser welding of stainless steels [82]. Similar effects were reported for conventionally manufactured 17-4PH steel subjected to elevated-temperature forming, where microstructural evolution and phase transformations were shown to significantly influence the final mechanical properties of the material [83]. Microstructure of 17-4PH DMLS shown in Fig. 5 consists mostly of austenite and martensite. Importantly, under conditions of extremely rapid cooling, it is also possible for structures with a high proportion of δ -ferrite, or even almost entirely ferritic microstructures, to form; this is due to what is known as ‘austenite bypassing’ [15,81].

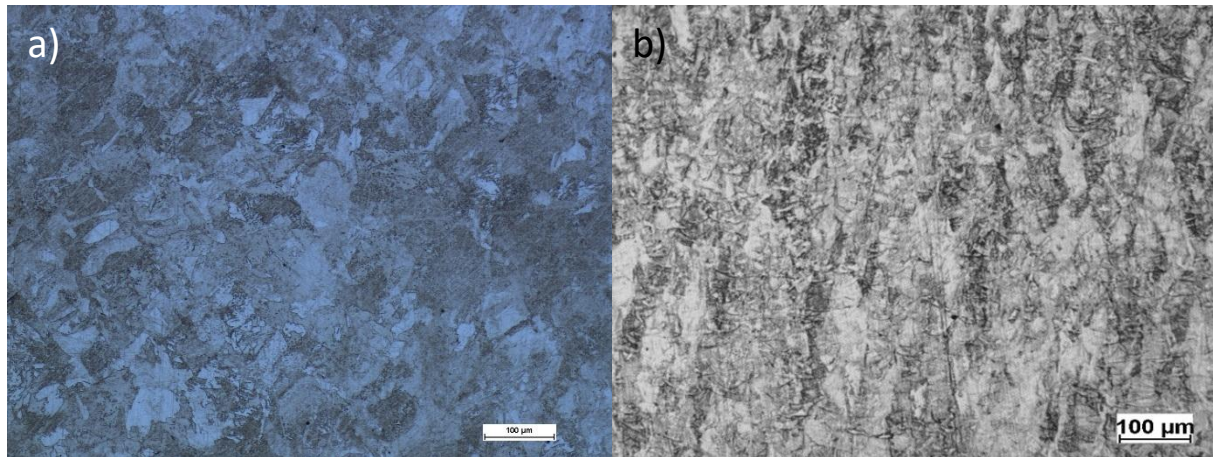


Fig. 5. Microstructure of 17-4PH DMLS steel: a) XY plane, b) ZX plane

The authors of the paper [84] indicate that the δ -ferrite content can significantly affect the microstructural stability and mechanical properties of the material following heat treatment. Due to the nature of AM manufacturing methods, where energy is applied locally to melt the material, an anisotropic structure and crystallographic texture are formed in the steel [15,81]. During the manufacturing process, varying cooling rates occur locally, and the component being produced is repeatedly heated, leading to complex thermal cycles and changes in microstructure (see Fig. 6) [15,81].

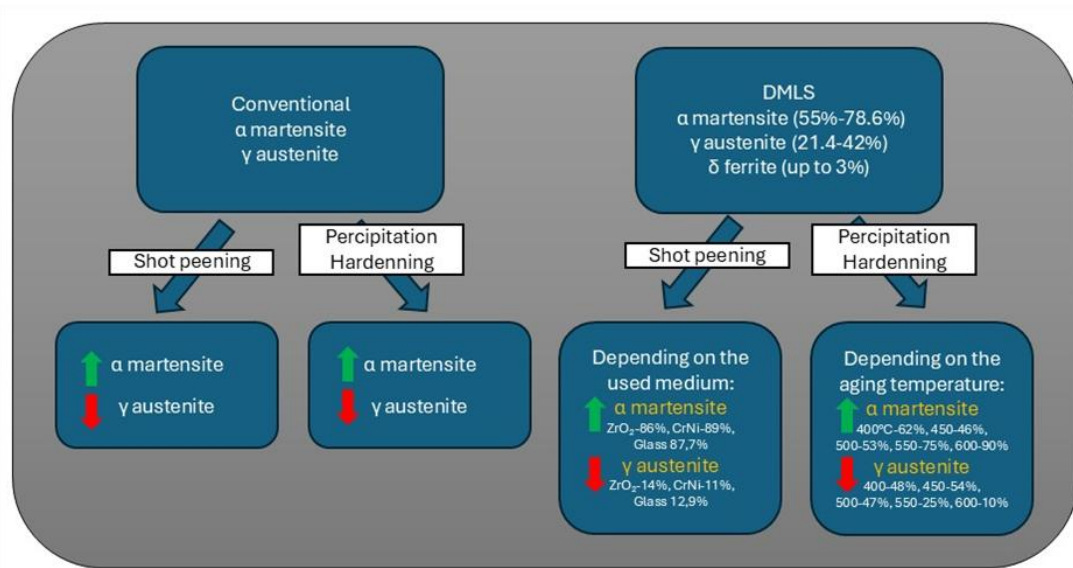


Fig. 6. Schematic illustration of phase composition of 17-4PH steel compiled on the basis of [68,69,71]

Furthermore, differences in the resulting phase composition of AM 17-4PH steel may be due, amongst other things, to the shielding gas used and the method of powder atomisation [80,85]. The working atmosphere has a significant impact on the properties of the resulting material, including through its effect on nitrogen content and heat dissipation kinetics [80,85]. In the case of powders atomized in nitrogen, increased stability of the retained austenite is observed, whereas materials produced in an argon atmosphere more often exhibit a more martensitic structure [80,85]. This heterogeneity also stems from slight variations in the

powder's chemical composition and in the conditions under which it is produced and solidifies, which affect the phase equilibrium and the material's position relative to diagrams such as Scheffler's [5,52,81]. Furthermore, in 17-4PH steel, copper (Cu) precipitates form, which many researchers consider to be a key mechanism in the strengthening of this steel [86]. These precipitates have been extensively analysed in the literature, alongside the proportions of austenite and martensite, as the main factor determining mechanical properties [57]. Other types of inclusions were also studied, including those containing Mn, Cr and Nb [57]. In additive manufacturing processes such as SLM, the formation of oxides, such as SiO_2 , is also observed; these may form during rapid cooling as a result of a reaction between oxygen and the silicon present in the alloy [87]. In addition to the precipitates mentioned earlier, carbides such as M_2C_3 , M_7C_3 and NbC are also formed. In the microstructure, these precipitate within the martensitic matrix, which further contributes to the strengthening of the material [10].

Recent studies also examine the formation of the so-called G-phase in 17-4PH steel [88,89]. This phase was originally identified by Beattie et al. [90] in A-286 (Fe-Cr-Ni) steel. This is an intermetallic phase rich in Ni, Si and Mn (or Fe), described by the approximate formula $\text{Ni}_{16}\text{Si}_7\text{Mn}_6$ [91]. From the perspective of material properties, the complex phase composition and the presence of various precipitates (Cu, carbides, intermetallic phases) are responsible for the high mechanical strength of 17-4PH steel, as well as its good resistance to corrosion and elevated temperatures [10,57]. Both experimental and simulation studies indicate that the average grain size of approximately $13.2\text{ }\mu\text{m}$ after over-saturation treatment ($1040\text{ }^\circ\text{C}/1\text{ h}$) can be reduced to approximately $2.2\text{ }\mu\text{m}$ after five heat treatment cycles (CHT) [92]. Recrystallised grains appear mainly at the primary grain boundaries. Both experimental and simulation studies indicate that the average grain size of approximately $13.2\text{ }\mu\text{m}$ after over-saturation treatment ($1040\text{ }^\circ\text{C}/1\text{ h}$) can be reduced to approximately $2.2\text{ }\mu\text{m}$ after five heat treatment cycles (CHT) [92]. Recrystallized grains form mainly at the primary grain boundaries. Recrystallized grains form mainly at the primary grain boundaries. Phase-field modeling has also shown that the kinetics of recrystallization are strongly influenced by thermodynamic parameters and interfacial energy. In particular, a decrease in the energy parameter α promotes the formation and growth of recrystallized regions, resulting in a higher volume fraction of recrystallized material. This behavior is associated with a reduction in the recrystallization energy barrier, which facilitates grain boundary migration and the nucleation of new, strain-free grains. In contrast, an increase in the gradient energy coefficient k_b leads to the formation of coarse-grained microstructures and an increase in the average grain size. Higher values of k_b increase the energy loss associated with grain boundary formation, thereby promoting grain growth and reducing the tendency to form fine-grained structures. These results indicate that the balance between accumulated deformation energy and grain boundary energy plays a key role in controlling microstructural refinement during heat treatment following the additive manufacturing of 17-4PH steel [92].

DEFECTS AND QUALITY

The quality of products produced using additive manufacturing technologies is influenced by a number of critical factors, among which the feedstock, and particularly the characteristics

of the powder, plays a key role. The characteristics of the powder used in additive manufacturing technologies, including particle morphology, particle size distribution and chemical homogeneity, have a crucial impact on process stability and the quality of the resulting components [93]. Key characteristics include particle size distribution, morphology, sphericity, the presence of oxides, and chemical homogeneity. These parameters directly influence the powder packing density, the stability of the melting process, and the susceptibility to defects such as porosity or lack of fusion [30,94]. In Powder Bed Fusion (PBF) technologies, the process parameters that determine the properties of the finished product are of particular importance. The most important of these include: laser power, scanning speed, layer thickness and hatch spacing. Additionally, parameters such as beam defocusing, scanning strategy and build direction are significant. These parameters influence the geometry of the molten metal pool, temperature gradients and solidification kinetics [30,95].

The volumetric energy density (VED) is defined on the basis of process parameters:

$$VED = \frac{P}{v \cdot h \cdot t}$$

P- laser power [W=J/s],

v - scanning speed [mm/s],

h - hatch spacing [mm],

t - layer thickness [mm]

However, this parameter is a simplification, as the actual amount of energy absorbed by the material is lower due to losses resulting from radiation reflection, thermal conduction and emission [96]. Incorrect selection of parameters leads to the formation of characteristic defects. The literature distinguishes three main types of porosity in AM materials: lack-of-fusion porosity, gas porosity (associated with gas trapped in the powder), and keyhole porosity (associated with the instability of the deep liquid metal pool) [96]. Lack-of-fusion defects most commonly arise when the energy density is too low (low laser power, high scanning speed), leading to incomplete melting of the powder and a lack of continuity between the tracks (see Fig. 7.) [91]. Conversely, when the energy is too high, a deep and unstable pool of molten metal forms, resulting in the formation of spherical keyhole-type pores [95,96]. Another significant source of defects is gas trapped in the powder, which may be introduced during the atomization process. During remelting, this gas can form pores within the material, adversely affecting its mechanical properties, in particular its impact strength and fatigue strength [94]. In addition, other defects are observed in materials produced using the PBF method, such as microcracks, geometric distortions and anisotropy of properties. These are associated with high temperature gradients and the generation of residual stresses during the cyclic heating and cooling of the material [97]. In the case of 17-4PH steel, it has been shown that the presence of porosity and structural discontinuities significantly reduces the material's mechanical properties, acting as stress concentrators and crack initiators [94]. Therefore, optimising process parameters and controlling powder quality are key to ensuring the high quality of additive manufacturing products.

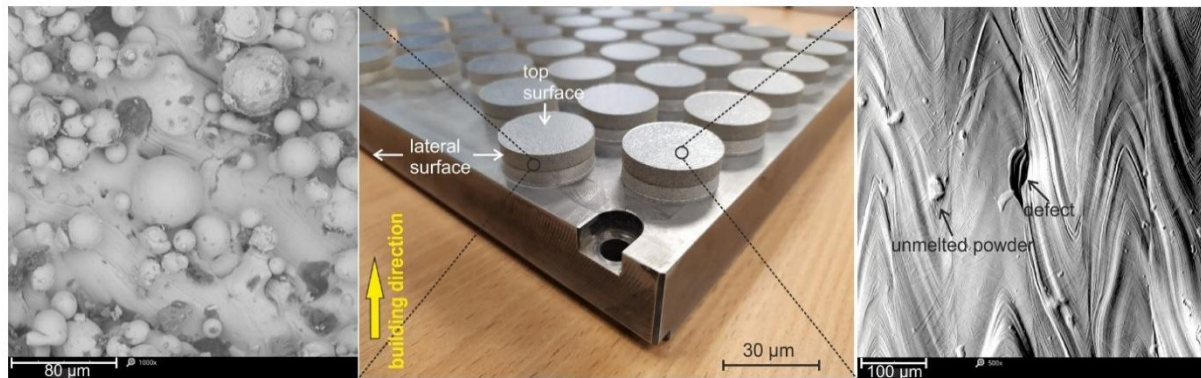


Fig. 4. Lateral and top surface characteristic for additively manufactured 17-4PH steel, SEM and visible defects [68]

Continuing the analysis of factors influencing product quality in PBF technologies, build orientation is also a significant aspect, as it has a direct impact on the anisotropy of the material's properties. This anisotropy stems primarily from the rapid solidification and directional heat dissipation characteristic of the PBF process, which leads to the formation of a crystallographic texture and elongated grains [30]. Furthermore, as successive remelting paths overlap, a characteristic structure is formed, consisting of overlapping pools of molten metal. This structure leads to local variations in grain size, micro segregation of elements, and the presence of defects such as porosity [30,98]. Metallographic cross-sections often reveal a dendritic microstructure, reflecting the direction of heat dissipation, which is usually perpendicular to the surface of the layers. The orientation of the structure also influences surface and mechanical properties. Studies by Bhardwaj and Shukla have shown significant differences in roughness and microhardness depending on the angle of the structure (0° , 45° , 90°), indicating a strong dependence of the properties on the direction of formation [99]. Roughness and microhardness dependence is shown in Table 8.

Table 8. Average surface roughness and average microhardness for different building orientations complied on the basis of [99]

Building orientation	Ra (μm)	Average microhardness (HV)
0°	2.45 ± 0.23	408.20 ± 4.84
45°	3.83 ± 0.49	396.93 ± 6.55
90°	2.26 ± 0.49	388.15 ± 6.98

Despite the possibility of optimizing process parameters, products manufactured using additive methods are not free from defects. The most commonly observed defects include: balling, warping, poor bonding and various forms of porosity [75,96]. In the case of 17-4PH steel, the presence of pores, inclusions, lack-of-fusion areas and gas pores has been reported [75,100]. These effects act as stress concentrators and crack initiation sites, which significantly reduces mechanical properties, particularly fatigue strength. However, products manufactured using additive technologies are not without defects, including balling, wrapping and poor bonding, as shown in Fig. 8.

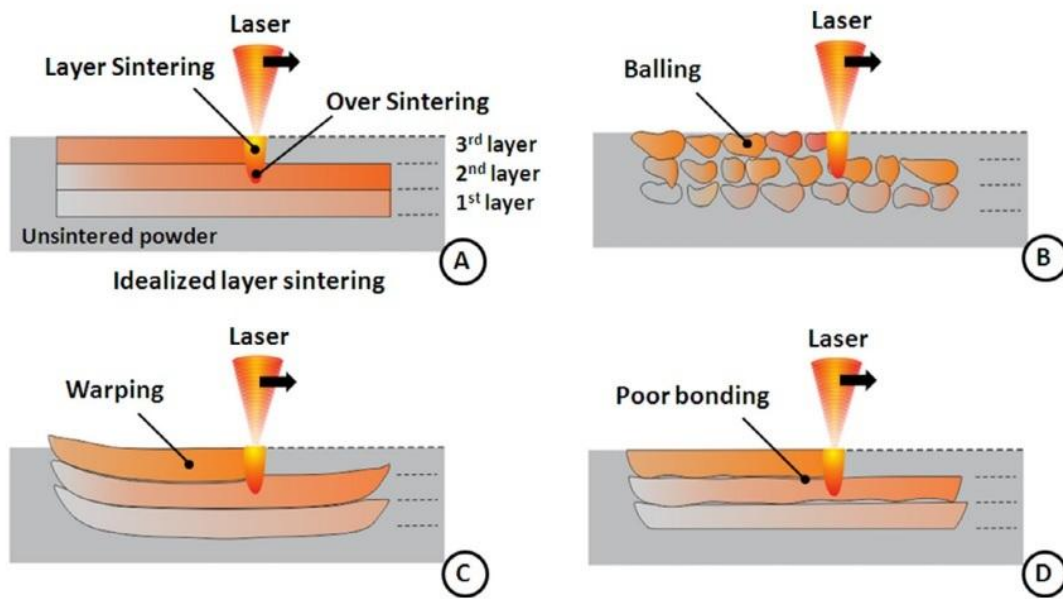


Fig. 5. Different types of defects in L-PBF fabricated parts due to improper laser energy density (A: normal; B: poor material fusion; C: overheating; D: insufficient heating). Adapted from Ref. [34]

Microscopic discontinuities, such as oxides, carbides and interlayer boundaries, also play a critical role in promoting the propagation of microcracks [100]. Analysis of inclusions in 17-4PH steel produced using the SLM method revealed the presence of amorphous oxide phases containing O, Si, Cr, Mn, Fe, Cu and Al, often with additional nanometer-scale crystalline inclusions [101]. These inclusions are mainly located in the areas between the melt paths, which further exacerbates the microstructural heterogeneity. The complexity of the phenomena occurring during the PBF process also gives rise to issues regarding the repeatability and reproducibility of material properties. As research by Dowling et al. indicates, factors such as powder morphology, laser parameters, scanning strategy, crystal orientation, thermal history and the post-processing method used are of key importance here [102]. In particular, the reuse of powder affects the material's properties; that is, it can lead to changes in both porosity and mechanical properties, such as strength and yield strength. Consequently, even when process parameters are optimized, post-processing is often necessary. In the case of 17-4PH steel, this typically involves heat treatments such as solution treatment and ageing, which lead to precipitation hardening and an improvement in mechanical properties. In addition, surface treatments such as cold working are used, which result in grain refinement in the surface layer, a reduction in discontinuities and improved fatigue resistance [103]. Another effective method is laser shock peening (LSP), which allows compressive residual stresses to be introduced into the near-surface layer. Studies have shown an increase in hardness of up to approximately 40 HV and the introduction of compressive stresses to a depth of around 400–600 μm [104]. It should be emphasized that, in the case of 17-4PH steel, fatigue properties are particularly sensitive to the presence of microstructural defects. Even minor discontinuities, such as non-metallic inclusions or micropores, can lead to a significant reduction in the fatigue limit. One of the significant challenges of additive manufacturing remains the high surface roughness resulting from the characteristic layered manufacturing process and the presence of partially remelted powder particles [105].

Consequently, the use of appropriate post-processing methods is crucial not only for additively manufactured materials, but also to a certain extent for conventional materials, particularly where high operational reliability is required.

MATERIAL AND SURFACE MODIFICATION

There are many surface treatment methods; however, this chapter will focus primarily on those used for steels employed in the engineering industry, with particular emphasis on the precipitation-hardened steel 17-4PH. Surface treatment processes can be divided into several main groups, such as mechanical, thermal, thermochemical and coating processes. Processes that modify the surface layer without altering its chemical composition, on the other hand, mainly involve mechanical and thermal effects, which lead to changes in microstructure, residual stresses and surface topography [106]. In the case of materials produced using additive manufacturing (AM) methods, these processes are particularly important due to the presence of characteristic surface defects, such as un-sintered powder particles, irregularities in the melt paths, or local porosity. In the case of materials produced using additive manufacturing methods, post-processing steps are of particular importance, especially surface treatments, which help to mitigate the impact of defects characteristic of PBF technology and improve the material's performance properties [107]. The integration of additive manufacturing methods with conventional processes is currently one of the key areas of development in modern manufacturing technologies, particularly for structural materials that require high precision and good mechanical properties [108].

HEAT TREATMENT

17-4PH steel is most commonly used in two basic heat-treated conditions: H900 and H1100, which correspond to ageing at 482°C for 1 hour and 593°C for 4 hours respectively [109]. In the H900 condition, the highest mechanical strength is achieved due to the intensive precipitation of strengthening phases; however, this material may be prone to brittle fracture, which limits its use in critical components. For this reason, in applications such as the nuclear power industry, higher grades (e.g. H1100) are preferred, where a balance is achieved between strength, wear resistance and corrosion resistance [110]. Research by Kossman et al. has shown that 17-4PH steel exhibits its highest corrosion resistance after ageing at a temperature of approximately 480°C for 1 hour [111]. Yeli et al., on the other hand [109] They analyzed the evolution of the microstructure during ageing, highlighting the sequential formation of phases: from the segregation of CrN and NbN nitrides at dislocations and lattice defects, through Cu- and Nb-rich precipitates, to the formation of Cr-rich phases and multicomponent phases containing Mn, Ni and Si. Extending the ageing time, particularly at lower temperatures (~480°C), does not result in a significant decrease in hardness, which indicates the stability of the strengthening precipitates [109,112]. Appropriately selected heat treatment helps to reduce residual stresses and improve the strength and hardness of materials produced using additive manufacturing methods [113]. In the case of additively manufactured materials, however, it should be emphasized that heat treatment alone does not eliminate surface layer defects, which have a significant impact on fatigue and tribological properties. It is therefore necessary to employ additional surface modification methods.

SURFACE MODIFICATION

One of the primary machining methods used for 17-4PH steel is face milling, which enables the required geometry and surface quality to be achieved. It has been demonstrated that process parameters such as cutting speed and feed rate have a significant influence on both surface roughness and the material's corrosion resistance, with optimal properties being achieved for moderate values of the cutting parameters [114]. In addition to conventional heat treatment, it is also possible to use thermochemical treatments such as nitriding, carburizing or carbonitriding [115,116]. For example, in the case of 17-4PH steel produced using the Metal Injection Molding (MIM) process, the nitriding process made it possible to increase the surface hardness from approximately 414 HV to as much as 1255 HV, whilst simultaneously reducing the coefficient of friction and changing the dominant wear mechanism from adhesive to abrasive and oxidative [117]. In the case of carbonitriding with the addition of rare earth elements, it is possible to increase the thickness of the diffusion layer by approximately 29% and achieve a hardness increase of 70–120 HV [118]. Another important area of research is boron coating, which leads to a significant increase in surface hardness (up to approximately 980 HV) and improved wear resistance [13]. Alternatively, laser methods such as laser surface alloying are used, which enable the hardness to be increased from around 350 HV to 650 HV whilst maintaining a favorable gradient of mechanical properties into the material [14]. In the case of materials produced using additive manufacturing methods (e.g. DMLS, Material Extrusion-MEX), surface modification techniques are of particular importance, as the post-print surface is characterized by high roughness, the presence of un-sintered powder particles and microstructural heterogeneity, which can lead to the initiation of fatigue cracks. One of the most effective methods for improving the properties of the surface layer is shot peening, which has been extensively studied, for example, in the following publications [67,67–69,72]. This process introduces compressive stresses in the surface layer, increases dislocation density and refines the grain size to the nanometer scale, resulting in improved mechanical and performance properties. Studies have shown that for 17-4PH steel produced by the DMLS method, the application of shot peening can lead to an increase in surface hardness of up to over 100% (from approximately 247 HV to over 540 HV), which translates into a significant improvement in wear and corrosion resistance [119]. At the same time, phase transformations are observed, involving an increase in the proportion of martensite and a reduction in residual austenite. Subsequent studies have shown that the type of shot used has a significant effect on the properties of the surface layer. Świetlicki et al. demonstrated that the highest corrosion resistance is achieved for samples shot-peened with steel shot (lowest corrosion current density), whereas other media (e.g. ceramic or glass beads) lead to different microstructural effects [67]. Furthermore, it has been shown that shot peening affects not only hardness but also tribological properties – a reduction in the wear rate of up to 25–30% has been observed, along with a change in the dominant wear mechanisms [68]. A significant development in this technology is its combination with heat treatment. Research has shown that the combination of ageing and shot peening results in the formation of a nanocrystalline surface layer and a significant improvement in fatigue properties, whilst crack initiation is shifted from the surface to subsurface regions [120]. Although advanced surface strengthening methods, including laser shock peening and cavitation water jet peening, may provide deeper compressive residual stress layers, conventional shot peening remains one of the most cost-

effective and industrially accessible approaches for improving the surface integrity and fatigue performance of 17-4PH steel [103,121]. Other mechanical surface strengthening techniques, including ultrasonic shot peening and ultrasonic surface rolling, have also shown promising results through grain refinement, texture modification and increased hardness, leading to enhanced wear and corrosion resistance [122,123]. In addition, NiP coatings applied to FFF-produced 17-4PH steel have been shown to increase hardness and improve resistance to solid particle erosion [124].

Surface modification processes play a key role in improving the wear resistance and performance properties of 17-4PH steel. As demonstrated by Esfandiari et al. [116], The use of plasma nitriding leads to a significant increase in hardness and wear resistance, whilst raising the process temperature further improves the material's corrosion resistance. Selected surface modification methods and their effect on the tribological properties of 17-4PH steel are summarized in Table 9.

Table 9. *The influence of surface modification and post-processing methods on the tribological properties of 17-4PH steel*

Surface modification method	Technology / Material	Result	Citation
Shot peening (SP)	17-4PH DMLS	A significant increase in resistance to abrasive wear and improved fatigue strength due to the reinforcement of the surface layer	[68]
Laser shock peening (LSP)	AM 17-4PH	Reduction of wear intensity and improvement of fatigue resistance through the introduction of compressive residual stresses	[104]
Heat treatment H900	SLM / LPBF 17-4PH	Improved wear resistance due to increased hardness	[58]
Solution treatment + ageing	SLM 17-4PH	Reduction of surface wear through microstructural homogenization and precipitation hardening	[59]
Hot Isostatic Pressing (HIP)	SLM / LPBF 17-4PH	Indirect improvement in wear resistance through reduced porosity and defects	[86]
Mechanical polishing	LPBF 17-4PH	Reduction of roughness and stress concentrators limiting abrasive wear	[105]
Hybrid treatment (AM + machining)	Hybrid metallic components	Improvement of surface quality and tribological properties	[108]
Surface finishing / post-processing	LPBF / SLM 17-4PH	Improvement of operational durability through the reduction of surface defects	[70]
Surface modification after AM	AM 17-4PH biomaterials	Improvement of the corrosion and tribological resistance of the surface	[125]

Electropolishing is another surface modification method that yields favorable results in terms of corrosion resistance, particularly for AM-manufactured products. Electropolishing enhances corrosion resistance and reduces surface roughness through the anodic dissolution of unmelted metal powders and surface defects resulting from additive manufacturing processes. The increase in corrosion resistance is associated with an increase in the proportion of Cr_2O_3 at the expense of Fe_2O_3 . This method appears to be particularly effective for steels with austenitic-martensitic structures [126].

CONCLUSIONS

The conducted review of additive manufacturing and surface modification of 17-4PH stainless steel leads to the following conclusions:

17-4PH steel produced using additive manufacturing methods exhibits a very wide range of mechanical properties, which are highly dependent on process parameters and heat treatment. Appropriate control of the manufacturing process allows for the achievement of properties that match or exceed those of conventional materials, making this steel highly attractive for engineering applications.

Additive manufacturing technologies, particularly PBF-based methods such as SLM and DMLS, enable the fabrication of complex geometries and components with mechanical properties comparable to or exceeding those of conventionally manufactured materials. However, these processes inherently introduce microstructural heterogeneity, porosity, and surface defects.

- The microstructure of AM 17-4PH steel differs significantly from its conventional counterpart, often consisting of a martensitic-austenitic mixture with retained δ -ferrite, resulting from rapid solidification and complex thermal cycles.
- Heat treatment, especially precipitation hardening (H900, H1100), effectively improves bulk mechanical properties but does not eliminate surface-related defects that dominate fatigue and tribological behavior.
- Surface modification is therefore essential for achieving optimal performance. Among the available techniques, shot peening is one of the most effective and industrially applicable methods.
- Shot peening significantly enhances surface properties by inducing compressive residual stresses, refining grain structure, and promoting phase transformations. Studies have shown increases in surface hardness exceeding 100%, along with substantial improvements in wear and corrosion resistance.
- The combination of heat treatment and surface modification provides a synergistic effect, leading to improved fatigue performance and shifting crack initiation from the surface to subsurface regions.
- Future research should focus on hybrid post-processing strategies, optimization of shot peening parameters, and the integration of advanced techniques such as laser shock peening and ultrasonic surface treatments.

- One of possible new approaches for AM 17-4PH steel is application of hybrid modifications to strengthen the surface and improve corrosion resistance such as electropolishing and shot peening combination. These two methods may enable to achieve surface with both high mechanical performance and corrosion resistance of treated surface.

Future developments should focus on the integration of additive manufacturing, heat treatment and surface engineering strategies. Particular attention should be paid to fatigue, and critical defects, relationships between process structure and property as well as development of standardized post-processing routes for industrial implementation. Such efforts are expected to accelerate the qualification and wider adoption of additively manufactured 17-4PH stainless steel components. While shot peening, ultrasonic surface rolling, and laser shock peening have been extensively investigated for 17-4PH stainless steel, studies concerning water peening and cavitation peening remain scarce.

In summary, while additive manufacturing offers significant advantages in design and production flexibility, the final performance of 17-4PH components is strongly dependent on post-processing, particularly surface engineering techniques.

Conflicts of Interest

The authors declare that they have no competing financial interests or personal relationships that could have seem to influence the study reported in this paper.

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