ASME Journal of Manufacturing Science and Engineering
Online journal at:
https://asmedigitalcollection.asme.org/manufacturingscience

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A Brief History of the Progress of Laser Powder Bed Fusion of Metals in Europe

The progress of additive manufacturing (AM) within the last few decades has been phenomenal, progressing from a polymeric technique to a method for manufacturing metallic aerospace components. We take a look at various technological advances which have helped paved the way for this growth, focussing on European input, as currently, 54% of AM machines are sold by European manufacturers (Wohlers, Campbell, Diegel, Kowen, Mostow, and Fidan, 2022, "Wohlers Report 2022: 3D Printing and Additive Manufacturing Global State of the Industry," Wohlers Associates, ASTM International, Fort Collins, Colo., Washington, DC). We take deep dives into several critical topics including sensing and monitoring, preheating, and multi-laser technology and illustrate how these develop from research ideas into industrial products. Finally, an outlook is provided, highlighting the topics currently gaining research traction, and which are expected to be the next key breakthroughs. [DOI: 10.1115/1.4062788]

Keywords: additive manufacturing, laser processes, process engineering, sensing, monitoring and diagnostics

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Manuscript received February 1, 2023; final manuscript received May 10, 2023; published online August 3, 2023. Assoc. Editor: Andreas Klink.

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Introduction

As we reached the 30th anniversary of laser metal powder bed fusion (PBF-LB/M), we decided to look back at the European contributions to the growth of this technology. In this review, we look through the main technological developments in PBF-LB/M, such as sensing and multi-laser, and discuss how the research into these has led to their industrial integration. The global market for Additive Manufacturing (AM) was estimated at 13.84 billion US dollars in 2021 [2].

Many technologies are reported by media as "revolutionary," but very few actually make it through to industrial use. The Gartner Hype Cycle was developed to visualize and understand the maturity of various technologies and how this compares with public perception. The key stages are the following [3]:

(1) *Innovation Trigger*: A technological breakthrough makes something new possible, and the media coverage often triggers public interest, despite no realistic industrial applications being proven.
(2) *Peak of Inflated Expectations*: One or two successful case studies cause widespread interest; often, failures are not as well publicized.
(3) *Trough of Disillusionment*: The technology does not advance as quickly as people expect, making it seem unsuccessful. Investment wanes and the number of companies in the sector typically decreases.
(4) *Slope of Enlightenment*: As the technology matures, realistic industrial applications are understood and funding starts to return.
(5) *Plateau of Productivity*: Widespread adoption begins with realistic expectations from the public.

Unfortunately, not all technologies make it to the plateau of productivity, with many becoming obsolete, often because they are understood to be unfeasible. In 2010, 3D printing was categorized as being within the innovation trigger phase [4], with powder bed fusion rising to the peak of inflated expectations in 2017 [5]. By 2018, it was in the trough of disillusionment, with a prediction that it would reach a plateau of productivity within 5–10 years [6]. Given the integration of PBF-LB/M into high-end sports cars and rocket engines within the past 3 years [1], it seems we are in the slope of the enlightenment phase. With companies such as Siemens and BMW opening large AM centers and working on metal AM [1], the plateau of productivity is rapidly approaching.

History of Powder Bed Fusion

The growth of PBF-LB/M can be seen in Fig. 1, showing the number of citations steadily increasing from 1995 onwards; similar

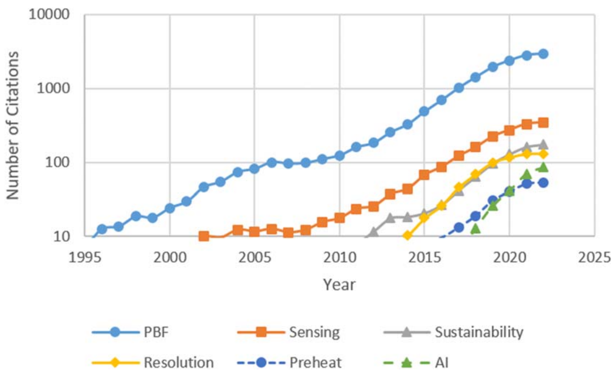

Fig. 1 Graph showing the growth of various subjects within the realm of PBF-LB/M, data collected using the Scopus search engine

literature surveys were performed for various other key PBF-LB/M technologies. For most technologies, the growth in the number of citations is quick to rise but typically plateaus after some years. Through the rest of this review, we are going to take several deep dives, specifically into sensing of PBF-LB/M, the preheating of machine substrates, and the increase in the number of laser sources used during PBF-LB/M. Afterward, a brief outlook is presented, showing which technologies are currently growing in research settings and so are expected to be the sources of key advancements in the near future.

Polymer additive manufacturing dates back to 1984, when Chuck Hull (co-founder of 3D Systems) first patented an "apparatus for production of three-dimensional objects by stereolithography (SLA)" [7] and commercialized it in 1987 with the launch of the SLA-1. This beta test system was the first commercially available AM machine [8]. From then on, AM of polymers steadily grew with the introduction of several new technologies like fused deposition modeling (FDM) and laminated object manufacturing (LOM) in 1991 and selective laser sintering (SLS) in 1992. In 1991, the AM group around Jean-Pierre Kruth of KU Leuven, Belgium, started investigating the possibilities to manufacture metallic parts by means of laser-based processes [9–11]. It lead to the development of an own-made PBF-LB machine equipped with an Nd: YAG laser and some successful tests with steel powder [12–14]. However, it took until 1994 to introduce the first commercial metal-processed AM machine. Electro Optical Systems (EOS), from Germany, commercialized the direct metal laser sintering (DMLS) process with their EOSINT M160 [15]. Since the CO_2 lasers used at the time had a wavelength too high to melt metals fully, the metal powders were coated with low melting point binders. The manufactured parts therefore exhibited high brittleness and lead to a cooperation of Fockele & Schwarze—now selective laser melting (SLM) Solutions GmbH—and the Fraunhofer Institute for Laser Technology ILT (both from Germany) with the goal to manufacture "parts that wouldn't break if they fell off the table" [16]. Therefore, the selective laser powder remelting (SLPR) process was introduced by Meiners et al. [17], which used a single component powder without any binder material. Using initial investigations [18,19] regarding optimal processing parameters, the SLPR process was capable of completely melting the powder of each single track and producing dense parts. Consequently, F&S delivered their first commercial selective laser melting (SLM) system for metal powders to Trumpf in 1999 [15].

With the growth of metal AM since 1994, the laser was more frequently deployed as a driving force for particle consolidation. As time moved on, further pioneering work was done by Frank Herzog, who registered the idea to print metal parts with a laser beam as his master's thesis at the University of Coburg, Germany [20]. Consequently, he achieved the first full dense part in 1999 leading to the founding of Concept Laser GmbH (now General Electric (GE) Additive) [21]. This resulted in the M3 LaserCUSING originally equipped with an Nd: YAG solid-state laser and later on with a fiber laser. Both laser types exhibited a wavelength of 1064 nm, which leads to a far higher absorption for metals than previous CO_2 laser wavelengths. This development marks the true beginning of laser-based metal additive manufacturing. As more systems were developed over the subsequent years, new technologies were incorporated, sensing being the first to be discussed here in detail [15,22].

Deep Dive into Sensing and Monitoring. The development of AM in Europe is inseparably linked to the development of corresponding sensing technologies. Due to the complexity of the AM process itself, it is challenging to produce high-quality parts without the use of some form of process monitoring. Therefore, the European AM machine manufacturers included an array of sensors in their products, and the European research institutes developed or adapted concepts for process monitoring. This is an ongoing evolution.

In the first decade of the new millennium the interest in sensing technologies fit for AM started to rise in research and the number of investigations related to sensing in AM is increasing massively since 2010, compared to Fig. 1. This increase can be explained by the need for deeper process understanding. The sensors which were implemented in the first commercially available machines from companies like EOS, CONCEPT Laser, or SLM Solutions, were primarily already standard in the industry. Examples are oxygen and temperature sensors. Today, it is common knowledge that the substrate temperature and the oxygen content in the build chamber are important boundary conditions for the PBF-LB/M process, but more intricate reasons for process failure can neither be explained nor prevented by controlling these values alone. The topic of sensing in AM is a vast field, and to match the focus of this work, it will be discussed in terms of process monitoring for PBF-LB/M. Even with this limited view, it remains a multifaceted issue. So do Berumen et al. count in cooperation between KU Leuven and CONCEPT Laser GmbH in 2010 [23] five general aspects of the additive manufacturing process covered by a different quality management module and focus their discussion of available tools for laser machine manufacturers to the topic of melt pool analysis and control. The two common possible options for melt pool monitoring are camera based: for one an off-axis system covering the whole build area and secondly a coaxially mounted system which just monitors the area around the melt pool. As an argument for the use of coaxially melt pool monitoring the generated amount of data is given. In comparison, the coaxial system generates 636 Mbyte per second whereas the off-axis system generates 75,1 GByte per second. In 2012, Craeghs et al. describe the progress in this approach [24]. With a new way to present the data, the possibility to interpret these data was greatly improved. By mapping the signals received from a charge-coupled device camera and photodetector they created a graphical representation of the material surface. This could be used to identify thermal stress and overheating in for example overhang zones by mapping the surface of the parts. This shows a general problem with the approach to capture PBF-LB/M processes on video. Without additional data processing, the information cannot be interpreted by machines, and consequently, a closed-loop control is hard to achieve. More recent work in this area which will be discussed later [25,26] demonstrates the topicality of the issue. In the same year, cooperation between researchers of the University of Duisburg-Essen and the RWTH Aachen tackled the same issue with their work on error detection during the PBF-LB/M process by imaging [27]. The discussed error decision tree goes together with detected errors, and poor support connection is stated as one of the most grievous defects. In addition, the method is feasible for additional quality management interests like geometrical accuracy. Again, it is also stated that a connection to the process control software would be needed to create a real process control. As logical addition to video imaging, thermography was and is used to determine heat distribution on the powder bed surface [28]. Krauss et al. described the creation of heat accumulation in the PBF-LB/M process and argued and that this method could be used to avoid process interrupts. Their presented model for heat dissipation is valid for a stable PBF-LB/M process in the heat conduction mode. Similar to the idea of mapping, the surface from [24] industry in Europe turned to the use of optical tomography. In 2015, Zenziger et al. from MTU (Motoren- und Turbinen-Union) Aero Engines AG [29] presented their work on process monitoring of AM by using optical tomography. Instead of a couple-charged device, they used a complementary metal-oxide-semiconductor for creating a 3D map of the part surface. The PBF-LB/M system they used were machines from EOS which had the additional sensors integrated. Contrary to the approach to extract data from a specific build job, Grasso et al., from the Politecnico di Milano, argued that without the availability of statistical process monitoring, it will be challenging to compensate for the insufficient repeatability of powder bed fusion [30]. In the same year, Staudt et al. presented their new system for hyperspectral imaging in laser material processing [31]. Hyperspectral imaging compensates for a lot of the problems linked to machine view by thermography and pyrometry. The influence of the emissivity in this technique is reduced strongly, and therefore, the transition from solid to liquid phase loses significance. By the acquisition of two spatial and one spectral dimensions, hyperspectral imaging can be used to describe chemical composition and temperature of specimens.

Besides the investigation of process-dependent melt pool metrics, the spatter formation during the powder bed fusion is also a possible indicator of process quality. To take that into account Eschner et al. [32] presented a system for the tracking of particle count and velocity in 2019. To achieve this, they placed two cameras off axis, nearly at 90 deg to the normal of the build area. The amount of spatters and the particle velocity were correlated to the specimen's quality. So the importance of visual approaches in the use of PBF-LB/M is still dominant in comparison to thermography or pyrometry. This trend continues unabated. Goossens et al. [33] push the envelope for this setup even further in 2021. Their coaxial monitoring system works with a photodiode and a complementary metal oxide semiconductor (CMOS) camera. With the combination of a high image rate and the signal of the photodiode, they calculate quite accurate measurements for the melt pool geometry of 316L specimens.

So far, no single measurement technology has emerged as the standard for PBF-LB/M in Europe. No specific process phenomenon is becoming the evident index for a good process either. The AM process is very temperature dependent, but due to the fast nature of the building and the complex optical relationship between emissions and temperature, optical temperature measurement in PBF-LB/M is still a hot topic in the European research community. Other approaches like machine learning in combination with a more general approach to machine vision on the other hand show great potential, but the amount of possible and available options to integrate those systems into existing machinery makes it challenging to decide which option is the best to assure a bright future for PBF-LB/M.

Deep Dive into Substrate Preheating. The high cooling rates associated with the PBF-LB/M process result in fast cooling of the material, which can again be detrimental when processing crack-sensitive materials. One potential way of reducing these thermal gradients was opened by the implementation of high-temperature platform preheating systems [34,35]. The integration of these systems allows heating the baseplate to designated temperatures, which can help in countering the crack formation during PBF-LB/M. Kempen et al. [36] further found that the high-speed tool steel M2 could be processed without cracks when applying a preheating of 200 °C. However, the selected processing strategies cannot necessarily be categorized as economical due to the low scanning speeds that are required for achieving nearly fully dense parts. Today, nearly every machine is equipped with a platform preheating of at least 150–200 °C. Preheating the specimens is also beneficial for lowering the distortion of the final part since too high-temperature gradients result in the warping of longish parts [37,38].

Moving onward, new systems were developed that incorporated high-temperature baseplate preheating systems. These machines needed to be advanced so components like axes and other moving components can withstand elevated temperatures during operation. Apart from the standard solutions, a preheating of up to 500 °C is most commonly available in commercial PBF-LB/M machines.

One of the first studies by Hagedorn et al. [34] used a preheating of around 1600 °C during PBF-LB/M. This temperature was needed to produce crack-free oxide ceramic parts. Due to the high temperatures, the viscosity of the melt was lowered, which negatively affects the resolution of the part's contour. This pathed the way for further investigations in the field of high-temperature preheating for PBF-LB/M and resulted in the spin-off company Aconity 3D, which is known for customized machines with the possibility of high-temperature preheating systems above 1000 °C.

Bischoff et al. [39] performed the first investigations on the application of a high-temperature platform heating unit when processing a carbon-enriched version of the tool steel H11 by means of PBF-LB/M. They used a preheating system capable of up to 500 °C on a commercially available SLM 280 machine. By continuously increasing the preheating temperature, both the crack tendency and the distortion of the final part could be reduced immensely. Building on this work, Huber et al. [40] have shown that a platform preheating of 500 °C is beneficiary when manufacturing parts from the unmodified version of this tool steel 1.2343. The as-built hardness was lower compared to one of the hardened specimens, which can be explained by the altered microstructure. Whereas the fast cooling during hardening results in a martensitic microstructure, the preheating and prolonged process times during PBF-LB/M favor the formation of a bainitic microstructure.

Around the same time, Vrancken et al. [41] studied the influence of substrate preheating on the material properties of Ti–6Al–4 V. Higher preheating temperatures reduced the residual stresses by around 50% and simultaneously favored the formation of the more-ductile β phase. However, the elevated temperatures were also associated with extensive oxygen and hydrogen diffusion into the workpiece, which lowers the ductility of the final component.

Boes et al. [42] investigated the influence of both different laser-scanning parameters and preheating temperatures on the material properties of the cold-work tool steel X65MoCrWV3-2. Even though the most suitable parameter combinations all exceeded a relative part density of 99.5% independent of the preheating temperature, the crack formation could only be reduced and avoided by elevated substrate temperatures.

Moritz et al. [43] have shown the potential of a high-temperature platform preheating for the defect-free fabrication of the tool steel 1.2343. In addition to safe and crack-free processing, applying temperatures of up to 800 °C allowed further tailor the microstructural properties of the resulting specimen. The corresponding hardness varied from 200 HV1 to around 700 HV1 depending on the applied temperature. This was caused by the manipulated transformation behavior of the steel in PBF-LB/M.

Panahi et al. [44] studied the influence of different preheating temperatures on the porosity and microstructure formation of a martensitic tool steel. When no preheating was applied, the crack tendency increased due to the higher thermal gradients. Moderate preheating temperatures in the range of 120–160 °C only moderately affected the crack tendency and resulting material properties. However, for the lowest preheating temperature, the highest hardness could be observed, which was caused by higher cooling rates and the reduced retained austenite content.

Saewe et al. [45] found that elevated preheating temperatures of up to 500 °C are beneficial in the successful processing of the high-speed steel M50 by means of PBF-LB/M. Higher substrate temperatures helped in reducing the temperature gradient, consequently resulting in fewer cracks. In addition to the improved processability, higher preheating temperatures also affect the microstructure formation. Whereas a low preheating of around 200 °C favored an epitaxial grain growth, a columnar dendritic microstructure was promoted when preheating the substrate to 500 °C. The latter case further supported the formation of a bainitic microstructure with precipitated carbides, which helped in increasing the overall material hardness.

Further investigations by Saewe et al. [46] show that despite the use of high-temperature platform preheating, cracks cannot be fully avoided when processing the high-speed steel HS6-5-3-8. It was found that a preheating in the range of 350 °C was favorable to reduce the initial crack formation to a minimum. Again, a strong correlation between the applied preheating and the resulting microstructural properties and material hardness could be identified.

In another recent work, Vogelpoth et al. [47] studied the influence of different preheating temperatures from 200 °C, over 300 °C to 500 °C on pore and crack formation when processing the tool steel Thermodour 2344. Even though high preheating temperatures surpassing the martensite start temperature were applied,

Table 1 Evolution of multi-laser PBF machines over the year from European manufacturers

Company	Machine	Max. number of lasers (laser power)	Max. build envelope	Year	
Aconity3D GmbH (Germany)	AconityONE^{2}	4 (400 W, 1000 W)*	Ø 400 mm × 400 mm	NA	[50]
	AconityMIDI	2 (400 W, 1000 W)*	Ø 170 mm × 250 mm	NA	
	AconityMIDI+	4 (400 W, 500 W, 700 W, 1000 W)*	Ø 250 mm × 250 mm	NA	
	AconityTWO	4 (400 W, 500 W, 700 W, 1000 W, 1200 W)*	Ø 400 mm × 400 mm	2021	
*	Dual 3D Scan Head	4	Mounted on top of Aconity machines	2019	[50,51]
Additive industries (Netherlands)	MetalFAB1	4 (500 W)	420 × 420 × 400 mm	2015	[52,53]
	MetalFAB G2	4 (500 W) 1000 W in development	420 × 420 × 400 mm	2021	
	MetalFab-600	10 (1000 W)	600 × 600 × 1000 mm	NA	
AddUp (France)	FormUp350	2 (2500 W)	350 × 350 × 350 mm	2019	[54–56]
DMG Mori AG (Germany, Japan)	Lasertec 30 Dual SLM	2 (600 W)	300 × 300 × 350 mm	2020	[57–61]
	Lasertec 30 SLM 2nd Gen.	2 (600 W, 1000 W)	300 × 300 × 350 mm	2019	
EOS GmbH (Germany)	EOS M 300-4	4 (400 W)	300 × 300 × 400 mm	2015	[62–64]
	EOS M 400-4	4 (400 W)	400 × 400 × 400 mm	2016	
AMCM (Germany)	AMCM M 290-2	2 (400 W, 1000 W)	250 × 250 × 325 mm	NA	[65,66]
An EOS group company	AMCM M 450-4	4 (400 W)	450 × 450 × 400 mm	NA	
	AMCM M 4K-4	4 (400 W, 1000 W)	450 × 450 × 1000 mm	NA	
GE Additive (Formerly Concept Laser, Germany)	M2 Cusing Multi-laser	2 (200 W, 400 W)	250 × 250 × 280 mm	2014	[67–70]
	Concept Laser X Line 2000R	2 (1000 W)	800 × 400 × 500 mm	2015	
	Project A.T.L.A.S	1 (1000 W)	1100 × 1100 × 1000 mm	2017	[68]
		4 (1500 W)	1300 × 1300 × 1300 mm	NA	[71]
Renishaw (Britain)	RenAM 500Q	4 (500 W)	250 × 250 × 350 mm	2017	[72,73]
SISMA (Italy)	MYSINT100 Dual Laser	2 (200 W)	Ø 100 mm × 100 mm	2014	[74]
	MYSINT200	2 (300 W)	Ø 200 mm × 200 mm	2017	
SLM Solutions AG (Germany)	SLM®280: Twin/Dual	2 (400 W, 700 W)	280 × 280 × 365 mm	2011	[75–77]
	SLM®500: Twin	2 (400 W or 700 W)	500 × 280 × 365 mm	2013	
	SLM®500: Quad	4 (400 W or 700 W)	500 × 280 × 365 mm	2013	
	SLM®800: Quad	4 (700 W)	500 × 280 × 850 mm	2017	
	NXG XII 600	12 (1000 W)	600 × 600 × 600 mm	2020	
			600 × 600 × 1500 mm		
Trumpf (Germany)	TruePrint 1000	2 (200 W)	Ø 100 mm × 100 mm	2017	[78]
	TruePrint 2000	2 (300 W)	Ø 200 mm × 200 mm	NA	
	TruePrint 3000	2 (500 W)	Ø 300 mm × 400 mm	NA	
	TruePrint 5000	3 (500 W)	Ø 300 mm × 400 mm	2017	

the crack formation could not be avoided completely within the specimens.

Applying preheating temperatures of up to 1000 °C even opens the possibility of processing high-melting materials like elemental tungsten in the absence of cracks. Porosity still is an issue in the current state that needs to be overcome to produce reliable parts. However, this shows the enormous potential of these high-temperature systems when aiming at expanding the use of PBF-LB/M within the industry [48]. Further studies by Fries et al. [49] have also shown the potential of a high-temperature preheating unit when processing WC-17Co steels by means of PBF-LB/M. At a substrate temperature of 900 °C, the porosity can be reduced to values as low as 2.0% during PBF-LB/M.

Overall, the application of preheating temperatures exceeding the capable temperatures of comparable, state-of-the-art platform preheating units provides several levers for tailoring the final microstructure. Through the reduction of the thermal gradients and by surpassing critical specimen temperatures already within the first layers, defect-tendency can be reduced drastically. This allows the processing of materials that did not catch attention in recent years like high-carbon steels that are generally classified as non-weldable. However, apart from that, the application of a high-temperature platform preheating provides an additional control lever for tailoring the microstructural and corresponding mechanical properties. By holding the specimens at defined temperatures during the build-up, post-process heat treatments might no longer be necessary for tailoring the material properties since highly sophisticated microstructures can be achieved when controlling the thermal conditions locally.

Deep Dive into Multiple Laser Sources. One of the many challenges in powder bed fusion of metals is not only to produce as many parts as possible during a single-build job but also to reduce build cycle time while also ensuring high part quality. Therefore, multi-laser powder bed fusion is an emerging technology where additional laser beams are incorporated into a single-build chamber. In the following, the historical evolution of multi-laser PBF systems from European manufacturers is discussed as well as the areas of research in Europe.

Technological Development of Multi-Laser Systems. The first multi-laser system SLM 280 Twin from SLM Solutions was launched in 2011 as shown in Table 1. It was equipped with two 200 W lasers and had a build chamber with the dimensions of 280 × 280 × 365 mm. The next improvement was the implementation of four lasers with the SLM 500 Quad in 2013 [75]. Since then, the multi-laser technology was adapted by an increasing amount of manufacturers leading to the point that as of 2019 every European machine manufacturer offers a multi-laser solution for at least one of their machines. The most recent development is

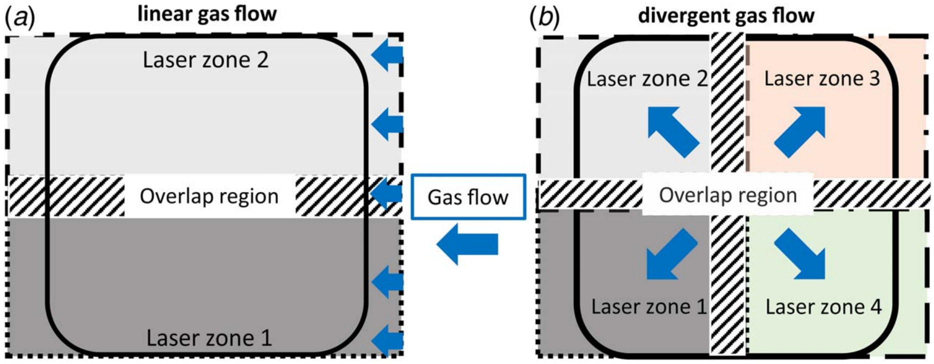

Fig. 2 **Multi-laser zonal configurations for (*a*) two and (*b*) four lasers in one build chamber as well as linear and divergent gas flow configurations**

the NXG XII 600 from SLM Solutions from 2020. The machine is equipped with 12 lasers, which can work simultaneously [76]. Concerning the development of multi-laser systems from 2013 to 2020, a stagnation in the number of lasers implemented in one build chamber is noteworthy. Instead, the focus was on enhancing the laser power of the single lasers. As can be seen in Table 1, the latest machine models support a laser power of up to 1200 W making higher scan speeds and thus faster production rates possible. Another factor, which comes with an increasing number of lasers as well as faster production rates, is the increasing build envelope. Newer machines offer to build chamber volumes of up to 360,000 cm^3 with chamber heights of 1 m (MetalFab-600, Additive Industries) [52] or 1.5 m (NXG XII 600, SLM Solutions) [71,77].

Research in Europe. The research in Europe regarding powder bed fusion with multiple laser beams focuses on a wide area of applications. These include the investigation of optimal scan strategies for multiple lasers setups, the effects on spatter formation as well as achieving good material properties while increasing production rates.

The first scan strategies for multi-laser systems involved zoning in which every laser had a separate field of exposure on the build platform. These zones were divided by overlap regions to secure a seamless part quality. Depending on the number of lasers, there could be up to four different zones as shown in Fig. 2. The number of lasers also had an influence on the gas flow management resulting in either a linear (a) or divergent (b) gas flow to avoid interaction from the laser emissions. Since zonal configurations have drawbacks like reduced productivity for non-symmetric builds, the possibility of thermal drift of the optical systems, or inhomogen melting conditions because of the divergent gas flow, a full laser overlap is featured in newer multi-laser machines. Therefore, each laser can address the whole build plate. However, multiple lasers processing in close proximity to one another as well as their relationship with the inert gas flow can lead to various unwanted effects like increased spatter or laser emissions influencing each other. The latter is especially important if one laser is downwind of another and must pass through the emissions from the upwind laser on its way to the powder. These factors made the development of new scan strategies a fundamental research topic [79,80].

The first report regarding the production rate of multi-laser PBF systems was published by Wiesner from SLM Solutions in 2014. An increase in build rate without any deficiencies in part density was addressed based on the addition of up to three lasers into a single-laser SLM 500 [81].

Saunders from Renishaw investigated the effect of multi-laser interaction on the manufactured part quality of Inconel 718. As Fig. 3 shows, tensile test specimens were arranged in a line to the shield gas flow. Four lasers addressed the parts simultaneously either in a column (a) or in a row (b) to analyze the influence of upwind and downwind manufacturing of the parts. Additionally, a third laser assignment consisted in building each part using the lasers simultaneously (c). The specimen of the columnar and third assignment exhibit the same superior mean tensile strength and elongation while the row configuration has an inferior mean elongation. The weaker samples were however located on the downwind side of the build plate. Airborne spatter can lead to a reduced intensity of the downwind laser affecting the surface roughness and lack of fusion effects, thus resulting in a decreased ductility. Furthermore, the downwind distance between parts as well as the number of upwind lasers plays an important role in the material degradation. While for a single upwind laser a distance of 100 mm leads to a significant degradation, the threshold for three lasers is only 60 mm [80,82]. Saunders also investigated the

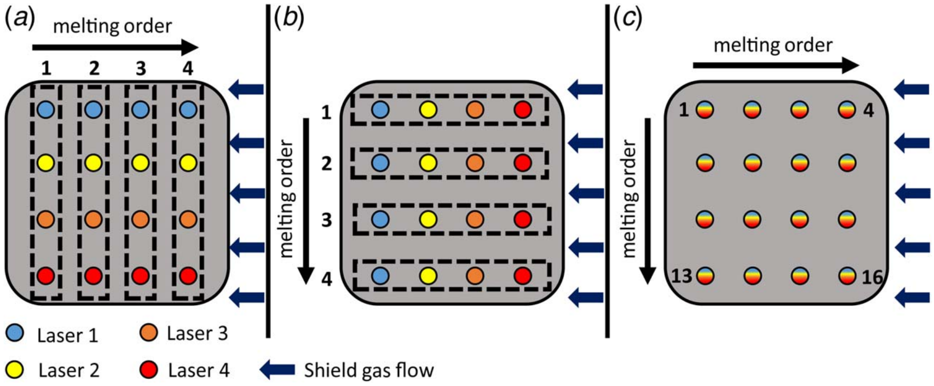

Fig. 3 **Multi-laser strategies for four lasers covering the whole build chamber. The lasers simultaneously address either a column (*a*), (*b*), or the same part (*c*).**

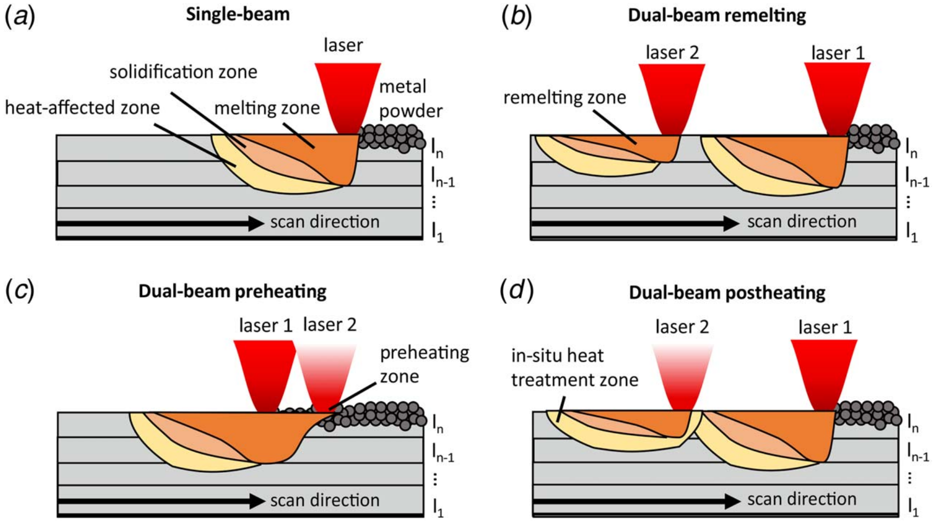

Fig. 4 **(*a*) The normal single-beam and different multi-beam strategies for (*b*) remelting, (*c*) preheating and (*d*) postheating**

optimum overlap between neighboring melting regions for multiple lasers per part builds. Based on various mechanical parameters as a function of strip offset, a stripe offset of −200 μm was chosen as an optimum. For this offset value, microstructural and mechanical properties were compared between single-laser per part and multi-laser per part samples for the Nickel super alloy 718 and Ti–6Al–4 V. For both alloys, no differences in tensile properties were found and the microstructure between single-laser and multi-laser processing was similar [83].

Zhang et al. employed thermomechanical simulations to predict the optimum multi-beam scan strategy for Ti–6Al–4V parts regarding temperature, residual stresses, and z-(build) direction deflections. Single-laser beam, dual-laser beams, four laser beams, and 30 laser beams were separately employed as the heat source. The results showed lower residual stresses for a larger number of laser beams. Similar to single-beam scan strategies, 90-deg layer rotation after each layer is necessary for minimizing residual stress in the final part. Moreover, 45-deg layer rotation resulted in the lowest *z*-direction deflection [84]. Wong investigated the effectiveness of multi-laser systems for Inconel 625 in powder bed fusion and the influence of increased build rates on the mechanical properties of the specimen. Two different arrangements were involved in this study. The single-laser configuration used one laser for a single specimen while in the multi-laser configuration, four individual lasers were directed to a single specimen. The multi-laser setup resulted in an increased build rate of 2.74 compared to the single-laser configuration. Furthermore, no change in microstructure or compromise of mechanical properties could be detected [85]. Tenbrock studied the influence of the interaction between a laser beam and the ejected plume from an adjacent melting zone on the properties of simultaneously manufactured parts. A correlation was found between the volumetric plume propagation and occurrence of part defects for simultaneous multi-laser processing. While the specimens are not affected by the simultaneous processing for small distances and large angles between the melting zones, a significant increase in the number of voids is observed for distances larger than 35 mm within an angular range of ±22.5 deg [86].

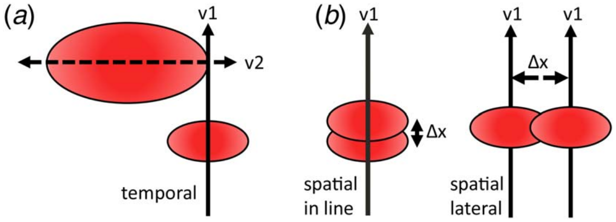

Fig. 5 **(*a*) Layerwise and (*b*) spatially synchronized multi-laser strategies**

For increasing the productivity of multi-laser systems, one focus lies in either the simultaneously processing of different parts or one single part with multiple lasers as shown before. Another approach to increase productivity in powder bed fusion using multiple lasers is the utilization of multi-laser arrays. The individual lasers follow a fixed geometrical relationship with each other. As shown in Fig. 4, this arrangement can be used for various melt strategies. In comparison with a single-beam strategy, (a) the welded track can either be remelted or (b) an in-situ heat treatment with lower laser power can take place (c) before or (d) after the melting process [87]. Graf et al. investigated the dual-laser processing strategies in powder bed fusion on the material structure and the resulting mechanical properties of a newly developed tool steel FeNiCoMoVTiAl [87]. A second laser beam was used for in situ heat treatment by remelting a fraction of the welded track. It was found that a short offset distance as well as a higher laser power lead to an increased hardness compared to the single-laser. For 125 W laser power, on the other hand, a decrease in hardness was detected. The results can be explained with short-time aging effects (high laser power) or solution annealing effects (lower laser power). Heeling [88] compared the effects of dual-beam preheating and postheating on the spatter characteristics for a stainless steel 316L with the characteristics of a single-beam strategy. Additionally, a wobbling strategy was applied for which the second beam circularly moves around the first beam. While the preheating and wobbling strategy reduces the amount of spatter because of the agglomeration of smaller powder particles, constant postheating can lead to the disintegration of larger particles into smaller ones, thus resulting in an increased spatter count [88]. Lantzsch developed an optical system to combine two fiber lasers with a single galvanometer scanner and integrated it into a PBF-LB/M machine to scale the productivity within one scan field for the stainless steel 316 L. By varying the laser spot distance between the two lasers and altering the hatch distance, a theoretical increase in build rate by 90% in comparison with a single-laser could be achieved [89].

Heeling also investigated the influence of synchronized multi-beam strategies on the process dynamics and melt pool gradients of steels. Therefore, two different synchronized scan strategies were used as can be seen in Fig. 5. For layerwise synchronizations (Fig. 5(*a*)), one beam melts the material as usual while the much faster second beam is used to heat the whole part to establish a homogeneous temperature field aiming for a reduction of residual stresses by lowering temperature gradients. Spatially synchronized strategies (Fig. 5(*b*)) on the other hand are characterized by a defined offset of both beams to each other. An offset in the scanning direction can be used to preheat the material as mentioned before, while an offset in the lateral direction can be used to influence the melt pool cross sections to be wider and therefore to increase the connection to previous layers. Simulations and preliminary experiments showed that both scan strategies reduce the temperature gradients by about 10% to 20%, thus reducing residual stresses. Furthermore, a defined positioning of the beams to each other can lead to higher remelted depths by supporting the downward streams in the melt pool front. Because of these stronger downward streams, less energy is necessary to reach sufficient melt depths resulting in higher possible scan velocities [88,90–92]. Further investigations for a stainless steel 316L showed that the highest part densities are achieved for an offset of 90 μm between the two beams while offsets as low as 45 μm have a negative impact on the part quality. In addition, the multi-beam strategies showed smoother surfaces compared to a single-beam reference [91].

Another aspect of using multiple lasers in powder bed fusion lies not only in the increase of productivity but also in the improvement of inclined surface quality. Therefore, Metelkova et al. introduced a novel methodology combining "selective powder removal" and subsequent remelting. The powder is thereby blown away from undesired areas using shock waves produced by a nanosecond pulsed wave laser. These newly exposed surfaces can then be remelted with a continuous wave laser, reducing the surface finish significantly by a Pa reduction from 12.9 μm to 5.4 μm [93]. Ordnung et al. further developed this method by applying it to a tool steel M789. The surface roughness could be improved significantly for inclinations of up to 45 deg. An inclination of 60 deg showed no improvement due to possible overheating or increased impact of the stitching zones [94].

Overall, the current state of art European research shows that multi-laser systems improve the production rate of parts without a loss in quality. Even further, dual-laser setups can be used to enhance material properties by using a second beam for remelting the scan tracks or a pre- or post-in situ heat treatment. Since multiple lasers can also have negative effects on one another through emission or spatter effects, the experiments mostly focused on the optimum scan strategies. However, except for Renishaw, most of the research was conducted on dual-laser setups. With the current trend for implementing more and more lasers in a single-build chamber, scan strategies for a higher number of lasers have to be studied more extensively.

Outlook into the Future Development of PBF-LB/M. As discussed, powder bed fusion has grown at an almost unbelievable rate over the past 25–30 years, with average annual growth of 21.2% between 1990 and 2021 [1]. It is now estimated that 2397 AM metal machines were sold in 2021 [1], and both suppliers and customers expect the rate of sales to increase by 95% between 2021 and 2026 [95]. Horizon Europe funding is secured for €95.5 billion, running until 2027; this promises the continuation of manufacturing research [96].

Figure 6 shows the most recently advancing fields within PBF-LB/M, the research into which has gained much traction over the past 5 years. Since they are currently rapidly growing, it can be assumed that their growth will continue and it is hoped that they yield key advancement within the realm of PBF-LB/M. We focus on several aspects of this, namely digitalization and the laser wavelengths used, although other aspects such as multi-material printing and laser beam shaping are also rapidly growing.

There are several aspects regarding the digitalization of AM which are prevalent in literature, these are the following:

- **The Internet of things** is often called Industry 4.0., which refers to the digitalization of all data and logging of all sensors in a central repository; each sensor can communicate with each other sensor. This allows for live observation of the manufacturing process and stores a full digital record for each component.

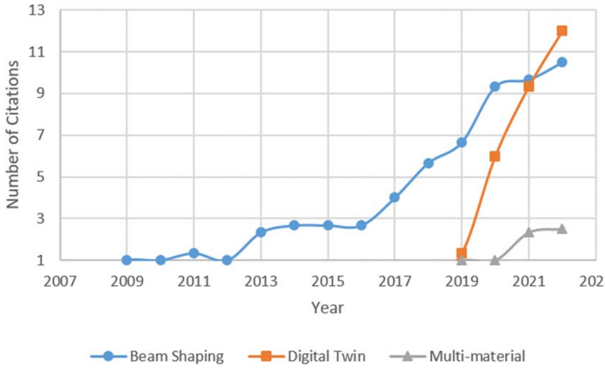

Fig. 6 Graph showing the recent growth of various subjects within the realm of PBF-LB/M which are currently growing, data collected using Scopus search engine digitalization of AM

- **Modeling** aims to predict various aspects of the manufacturing process, so they can test manufacturing runs virtually before starting the physical run, catching any potential errors before large time/cost investments are made.
- **A Smart Factory** is a facility incorporating the digitization concepts explained; Internet of things sensors are widely used to improve efficiency. Frequently, a digital twin will exist, allowing further efficiency improvements as compared to a conventional factory.

Sensor development has occurred widely, but is not specific to AM; digital twins, however, must be specifically designed to capture the multi-scale complexity of the process. The requirement for this was initially realized in the USA [97,98], but since Europe contains the majority of L-PBF manufacturers, industrialization of digital twins has blossomed in Europe [99].

Additive Industries are collaborating with Chagne2Twin to incorporate a digital twin system for quality control [100]. Since 2020, EOS has offered a service of factory digitalization, mentioning both digital twins and Industry 4.0 [101] with a similar offer available from Trumpf [102] and Siemens [103] creating future-proof smart factories. The Horizon Europe project envisages a future, where "efficient and smart factories can fully offer and deploy their capabilities in dynamic and sustainable manufacturing ecosystems", confirming that research into digitalization of AM will continue until at least 2027 [104].

Artificial Intelligence. AI is a broad term which encompasses machine learning, neural networks and many other computational techniques. There are many applications for AI in AM, mostly using AI for computer vision; according to the 2022 Gartner hype cycle for AI, computer vision is on the slope of enlightenment, expecting to reach the plateau of productivity within the next 2 years [105]. Research has started to use computer vision AI to analyze in situ monitoring and determine which signals are representative of defects [25,106]. If successful, this would allow for defects to be detected live; this could allow for the build to be canceled, reducing waste, or these defects could be mended in subsequent layers.

AI has also been used to estimate the mechanical performance of L-PBF components, using the input geometry, both for complex lattices [107] and using tomographic data of the defect distribution [108]. Combined with defect detection during building, this could allow for accurate determination of the exact mechanical properties of each individual component. Further applications of AI in AM include process and parameter optimization [109,110] and design of new alloys [111]. The "Made in Europe" project funded by Horizon Europe (2021–2027) makes numerous references to the use of AI for "productive, excellent, robust and agile manufacturing chains" [104], confirming that research into AI for AM will continue into the future.

Visible Light Sources. To contribute to global challenges like e-mobility and reduced energy consumption, the processing of copper-based alloys due to their excellent electrical conductivity or aluminium-based high-strength alloys due to their potential for lightweight applications is essential. However, due to an unfavorable absorption of the laser light at higher wavelengths in the (near-)infrared region, the laser-based processing of these materials can be demanding. Recent developments in the field of laser technology have led to high-power systems characterized by shorter wavelengths like green (515 nm) or blue (445 nm) lasers. Whereas frequency-doubled disk lasers are commonly used for generating green laser irradiation, diode lasers are more typically used for blue laser sources. In the field of PBF-LB/M, however, blue laser sources are currently disadvantageous due to their lower beam quality compared to green laser sources. First research using visible light was already performed using green lasers [112,113], since these systems are now commercially available and integrated into PBF-LB/M machines.

When processing copper alloys, the shorter wavelength results in an increase in the energy input into the material, which helps in stabilizing the melt pool. This supports the defect-free fabrication of complex structures during the layer-by-layer manufacturing approach.

In the upcoming years, we expect the research on PBF-LB/M, and laser-based additive manufacturing in general, using shorter wavelengths like green or even blue to intensify. Future work will most likely include comparisons of the energy efficiency for different material classes, how to expand the material portfolio in PBF-LB/M by using more suitable processing wavelengths, and maybe even hybrid manufacturing approaches using different laser sources for multi-material processing.

Summary

As shown clearly throughout this review, both European researchers and European manufacturers have paved the way for the rapid, worldwide rise of powder bed fusion. With the majority of AM manufacturers based in Europe and major contributions in developments such as sensing and substrate preheating, the hope is that the growth in this sector continues. We showed that growth is not stalling yet, as the technology is not yet fully mature. Significant research is still being led by European parties on topics such as digitalization and the use of visible light sources. Given the vast industrial investment in AM worldwide, it seems like we will reap the rewards from this industry for many years to come.

Acknowledgment

This study has been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—Project-ID 61375930—SFB 814, Subproject A5. The financial support is gratefully acknowledged. Furthermore, we acknowledge financial support by Deutsche Forschungsgemeinschaft and Friedrich-Alexander Universität Erlangen-Nürnberg within the funding program "Open Access Publication Funding". Support from the Erlangen Graduate School in Advanced Optical Technologies (SAOT) in the framework of DFG's excellence initiative is also gratefully acknowledged.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The data sets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

AM = additive manufacturing
Pa = arithmetical mean height—surface roughness
PBF-LB/M = powder bed fusion of metals using a laser beam

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