

“In-situ” X-ray Imaging Technology for Material and Manufacturing Science: A Review

Van Anh Nguyen^{1,2,*}, Duy Han Le³, Dilen Damian⁴, The Bach Tran¹, Quang Hung Le¹,
Nhu Tung Nguyen¹

¹International School, Vietnam National University, Hanoi, Vietnam

²Cranfield University, Bedfordshire, United Kingdom

³School of Mechanical Engineering, Hanoi University of Science and Technology,
Hanoi, Vietnam

⁴Charpak Ltd, Huntingdon PE29 7DG, United Kingdom

Corresponding author: Van Anh Nguyen (anhnguyenvan@vnu.edu.vn or
nguyenvananhbkh@gmail.com)

Abstract

"In-situ" X-ray imaging has become a powerful tool in materials and manufacturing science, enabling real-time observation of critical processes. However, access to X-ray facilities remains highly competitive due to limited availability, high operational costs, and technical complexity, restricting its use to a few research groups worldwide. This review addresses this challenge by providing a comprehensive analysis of X-ray imaging technologies, their historical development, and recent advancements in "in-situ" X-ray imaging. It explores applications across various materials and manufacturing processes, including welding, additive manufacturing (AM), casting, high-temperature furnaces, and novel materials. Key topics such as heat transfer, melt pool dynamics, solidification, microstructure evolution, and defect formation in manufacturing processes are systematically examined. Additionally, the review highlights the potential of "in-situ" X-ray imaging for discovering novel materials and advancing manufacturing technologies. It discusses current limitations, particularly the constraints of existing X-ray facilities, and outlines future directions for enhancing this technology. Expanding access to high-resolution X-ray imaging is crucial for accelerating advancements in materials and manufacturing. Integrating artificial intelligence and simulation models will further enhance its capabilities. Achieving these improvements requires upgrading existing X-ray facilities and developing new systems capable of capturing high-resolution, real-time imaging of complex material processes.

Keywords: X-ray imaging; “In-situ” observation; Welding; Additive Manufacturing; Casting; Furnace; Manufacturing; Materials

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1. Introduction

X-ray imaging is one of the most powerful tools for uncovering fundamental phenomena and physical mechanisms in material and manufacturing science. It enables the detection of various phenomena, including internal melt flow and defect, microstructure evolution, phase transformation, crack propagation, spatter formation. These phenomena are often impossible to explore using conventional methods such as high-speed cameras, thermal imaging, or acoustic and electrical signal sensors. However, the development of "in-situ" X-ray imaging for material and manufacturing sciences remains in its early stages and is primarily conducted by a limited number of research groups in developed countries. This is largely due to the high cost of X-ray facility investment and the complexity and expense of their operation. Consequently, the vast potential applications of "in-situ" X-ray imaging remain untapped and underexplored. This review paper aims to comprehensively discuss the development of X-ray facilities worldwide, from their early stages to their current advancements. It also discusses in-depth their applications in material and manufacturing sciences, focusing on welding, additive manufacturing (AM), furnace, and casting processes. This is because these manufacturing processes share common metallurgical and physical features, including the heating-melting-solidification cycle. The present review also addresses the future potential of X-ray imaging, including its role in novel materials and manufacturing processes, advancements in deep-learning models, and the development or enhancement of new X-ray facilities for emerging research areas. The paper is organized into nine sections:

1. Introduction: Discusses the principles of X-ray imaging, its history, development, applications, and major facilities.
2. "In-situ" X-ray Imaging for Melt Pool Dynamics and Heat Transfer: Explores the role of X-ray imaging in studying heat transfer and melt pool dynamics during materials processing and manufacturing.
3. "In-situ" X-ray Imaging for Flow Velocity, Convection Patterns, and Fluid Eddies: Examines the capability of X-ray imaging to analyze and visualize convection patterns, flow velocity, and fluid eddies.
4. Solidification and Microstructure Evolution: Investigates phase transformations and microstructural evolution using "in-situ" X-ray observation.
5. Defect Detection: Highlights the ability of X-ray imaging to identify internal defects such as porosity, pores, and cracks, as well as surface defects like spatter and roughness.
6. "In-situ" X-ray Imaging for Novel Materials and Advanced Manufacturing: Introduces innovative applications of X-ray imaging in novel materials and emerging manufacturing processes.
7. Future Vision: Discusses potential advancements and future directions for "in-situ" X-ray imaging in materials science and manufacturing.
8. Conclusions: Summarizes key findings and discussions.
9. References: Provides a comprehensive list of over 370 cited works.

1.1 Principles and features of X-ray imaging

X-rays were discovered by Röntgen in the 1890s [1], with their first application being the observation of a ring on his wife's hand, as shown in Figure 1 [2]. Since then, X-rays have been widely used in medical treatments to observe bone fractures [3], capture tissue details [4], detect cancers [5], and address various other medical applications [6]. The X-ray sources used in medicine are of relatively low power to minimize adverse effects, such as cell damage or burns [7]. However, the demand for advanced scientific exploration has led to the development of X-ray imaging in various fields beyond medicine [8,9,10,11,12,13]. Among these, the use of X-ray imaging in materials and manufacturing sciences—particularly in welding, AM, casting, and furnace applications—has been extensively studied.

The theory of X-rays is based on electromagnetic radiation with wavelengths shorter than ultraviolet rays but longer than gamma rays (see Figure 2 [14]). This enables X-ray imaging to capture images of matter at the atomic level, as illustrated in Figure 3 [15]. Like other electromagnetic waves, X-rays can penetrate matter. The intensity of transmitted X-rays diminishes depending on the density and structural attributes of the material [16]. Denser materials absorb more X-rays, leading to higher image contrast. A film or detector is placed opposite the X-ray source to capture an X-ray image, with the object of interest in between them. Based on power supply capability, X-rays can be categorized into two types: soft and hard. Hard X-rays are primarily used for applications requiring high penetration power, while soft X-rays are commonly used in medical diagnostics at low power. In medical X-ray imaging, stationary objects (e.g., patients or a cell or bone) are examined, and the film or digital detector provides an X-ray image that doctors can analyze and diagnose issues for patients. A schematic diagram of an X-ray radiography setup for medical purposes involving the film is shown in Figure 4 [6]. Additionally, a real-life X-ray image of the lungs and the methodology for capturing such radiographic images are presented in Figure 5 [17].



Figure 1. A real X-ray image of the bone and ring [2].

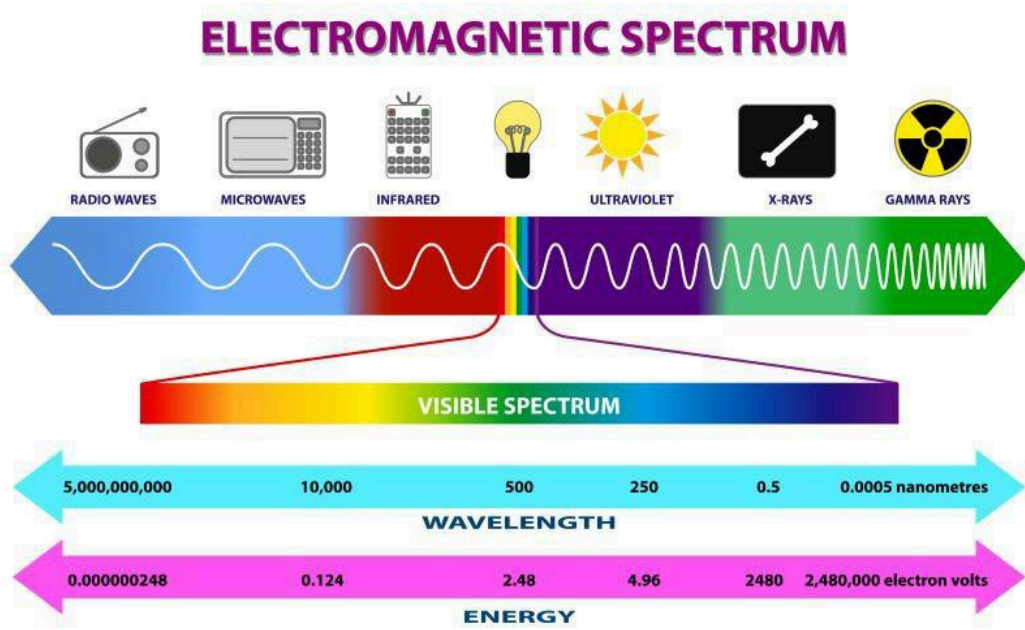


Figure 2. X-ray wavelengths, among other ones [14].

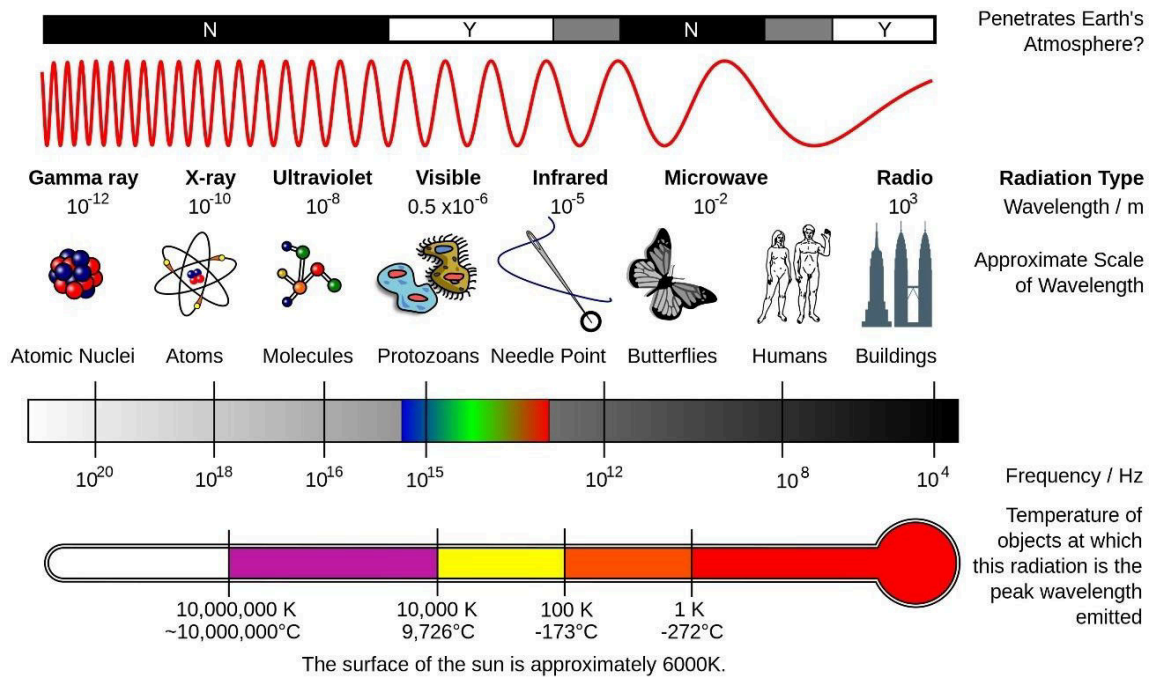


Figure 3. X-ray temperature and capability to interact with matters, among others [15].

In materials and manufacturing science, the object observed by X-ray imaging for the internal structure of the matter is often the "movement of matter." At the atom level. Consequently, instead of using traditional films, as in medical X-ray imaging, a high-speed camera paired with an intensifier records X-ray images in a nearly continuous sequence at very high resolution [18]. The X-ray imaging system enhances the object's brightness under observation, amplified by the intensifier. A high-speed camera then captures these enhanced images. During this process, any variations in X-ray intensity—caused by issues such as cracking, porosity, or changes in the liquid-solid state that alter the material's density—result in color changes in the captured images. These color variations on the camera indicate the differences in density and internal structures. For X-ray imaging techniques, the frame rate of high-speed cameras is critical for determining the quality and accuracy of the results. The duration of observation, or time resolution, is directly influenced by the camera's frame rate. Depending on the specific application and the object being observed, frame rates can range from hundreds to thousands and even hundreds of thousands per second [19,20]. With X-ray intensification, the captured images display regions of varying brightness: dark zones correspond to areas with less X-ray intensity, while bright zones indicate higher X-ray penetration. The X-ray imaging system converts transmitted X-rays into visible images, allowing for the evaluation of physical phenomena of the internal structures of matters. The detector, positioned behind the object, records transmitted X-rays, while the high-speed camera, located behind the detector, captures the disturbance X-ray signals. These patterns are then converted into visible two-dimensional (2D) or

three-dimensional (3D) radiographic images. The final contrast-based X-ray images are generated by analyzing the attenuation differences of the internal structure in response to X-rays [21].

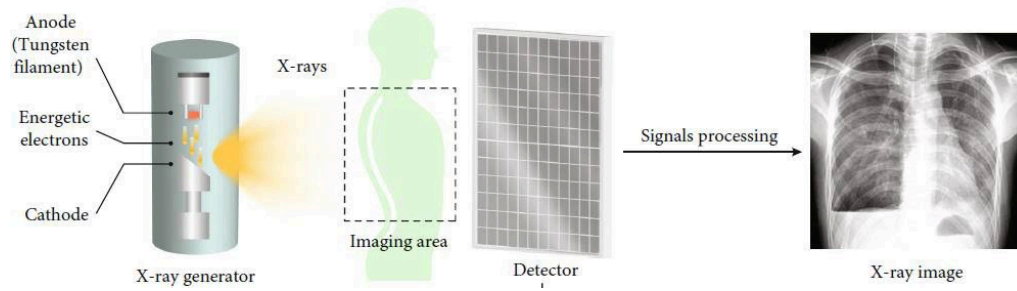


Figure 4. Principle of capturing X-ray radiography images in medicine [6].

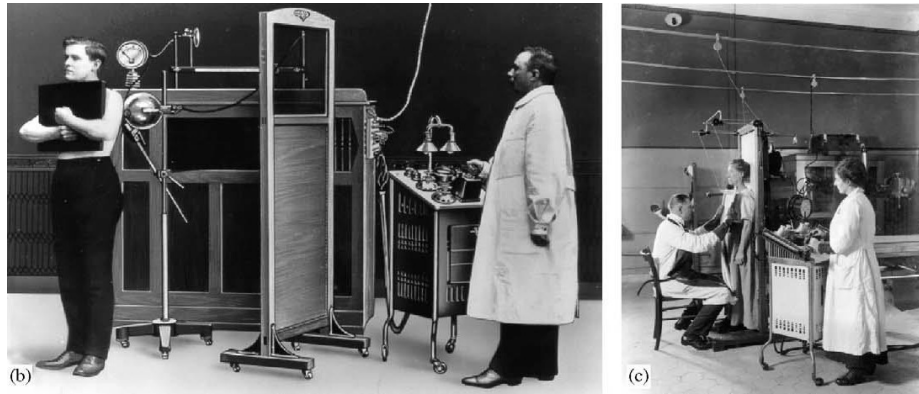


Figure 5. An example of capturing lungs by X-ray radiography image [17].

In materials and manufacturing processes, understanding and controlling material behavior during production is crucial [22,23]. Advanced X-ray imaging techniques enable precise observation of this behavior. Depending on the application, X-ray imaging is divided into two primary methods: X-ray diffraction and X-ray radiography, each designed for specific purposes. “In-situ” X-ray diffraction is primarily used to measure residual stress, phase transformations, and grain structures [24,25,26,27]. Conversely, “in-situ” X-ray radiography is widely applied to monitor fluid flow, melt pool dynamics, microstructure evolution, and dynamic phenomena such as porosity, spatter formation, and powder spreading during manufacturing [28,29,30]. It can be concluded that X-ray imaging techniques can be broadly categorized into radiography, tomography, and diffraction methods. Each has distinct advantages and limitations for materials and manufacturing applications, as seen in Table 1.

Table 1. A summary of X-ray imaging techniques.

Technique	Resolution	Acquisition Speed	Sample Requirements	Key Applications	Limitations
Radiography	1-10 μm	ms-s	Thin samples (<5mm)	Real-time process monitoring	2D projections only
Tomography	0.5-5 μm	min-hours	Small samples (<1cm)	3D microstructure analysis	Slow acquisition
Diffraction	0.1-1 μm	s-min	Crystalline materials	Phase/strain analysis	Limited field of view

Figure 6 illustrates the hierarchy of material internal structures and the capabilities of X-ray imaging in observing and analyzing them. Among these techniques, neutron diffraction (XRD/ND), small-angle X-ray scattering (SAXS), ultra-small-angle X-ray scattering (USAXS), and X-ray computed tomography (X-ray CT) are primarily used for surface imaging. Other techniques focus on analyzing internal structures in greater detail. Figure 7 portrays the transmission capability of X-ray with difference of materials. Aluminium, a pore material with low density has the highest transmission. This is an important feature of materials because it can significantly affect the observation of X-ray, and it is one of reasons that most papers of “in-situ” X-ray images for material and manufacturing science is focused on aluminium and titanium alloys. Meanwhile, Figure 8 indicates an important attitude of X-ray synchrotron facilities about the flux as a signal to indicate the capability X-ray to penetrate the light and pore materials such as aluminium and titanium is better than high density materials such as steels and Inconel.

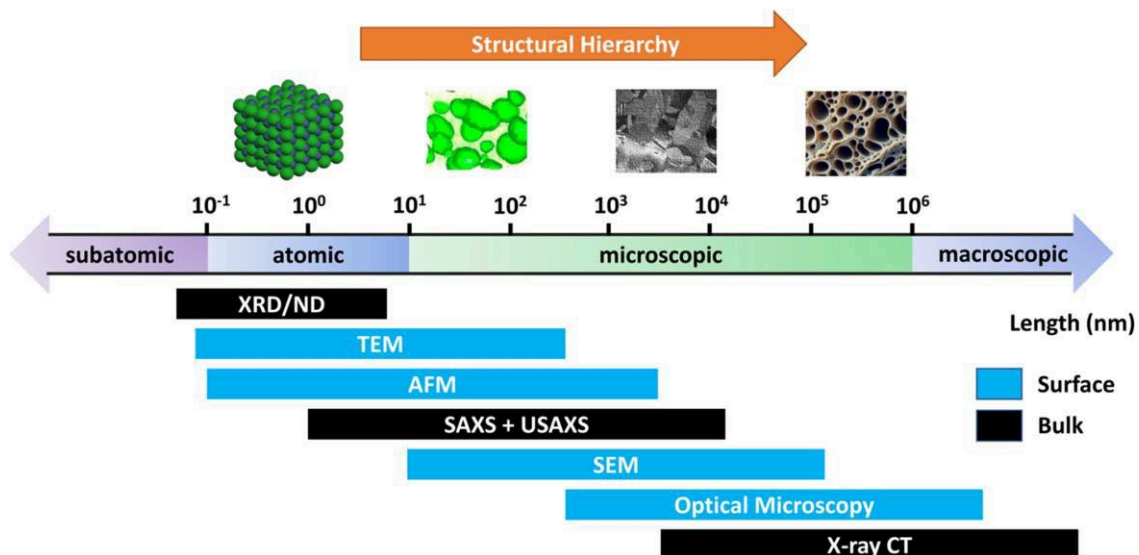


Figure 6. Hierarchy of internal structure of materials and the capability of X-ray imaging to penetrate and analytical techniques [31]. The structures above the length scale arrow (from left to right) are the crystal structure, precipitates, grain structure, and

meso-structure. The analytical techniques for structural measurements shown below the arrow are color-coded for surface and bulk methods. From top to bottom, they are X-ray diffraction and neutron diffraction (XRD/ND), transmission electron microscopy (TEM), atomic force microscopy (AFM), small-angle X-ray scattering and ultra-small-angle X-ray scattering (SAXS/USAXS), scanning electron microscopy (SEM), optical microscopy, and X-ray computed tomography (X-ray CT).

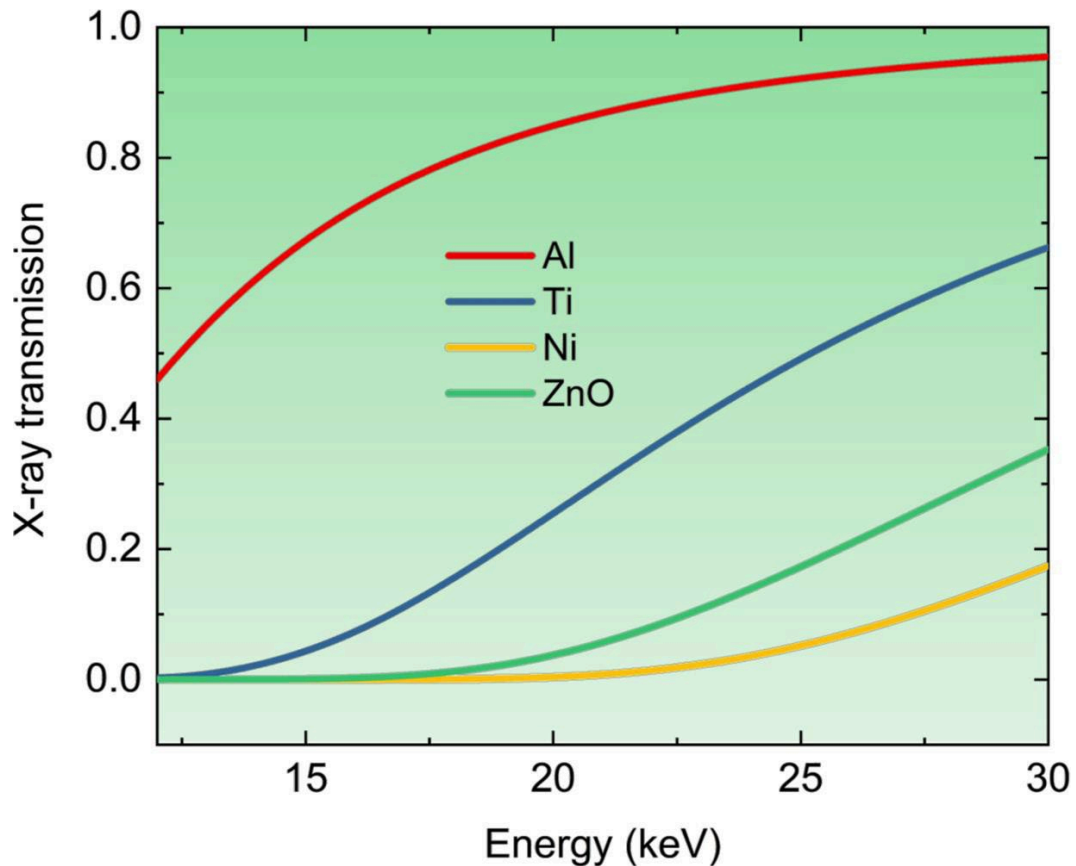


Figure 7. The capability of X-ray transmission with the difference of materials [31]. X-ray transmissions for various typical materials with different electron (mass) densities across an X-ray energy spectrum from 12 to 30 keV. The materials have a uniform thickness of 200 mm to ensure that the scattering data can reasonably represent bulk properties.

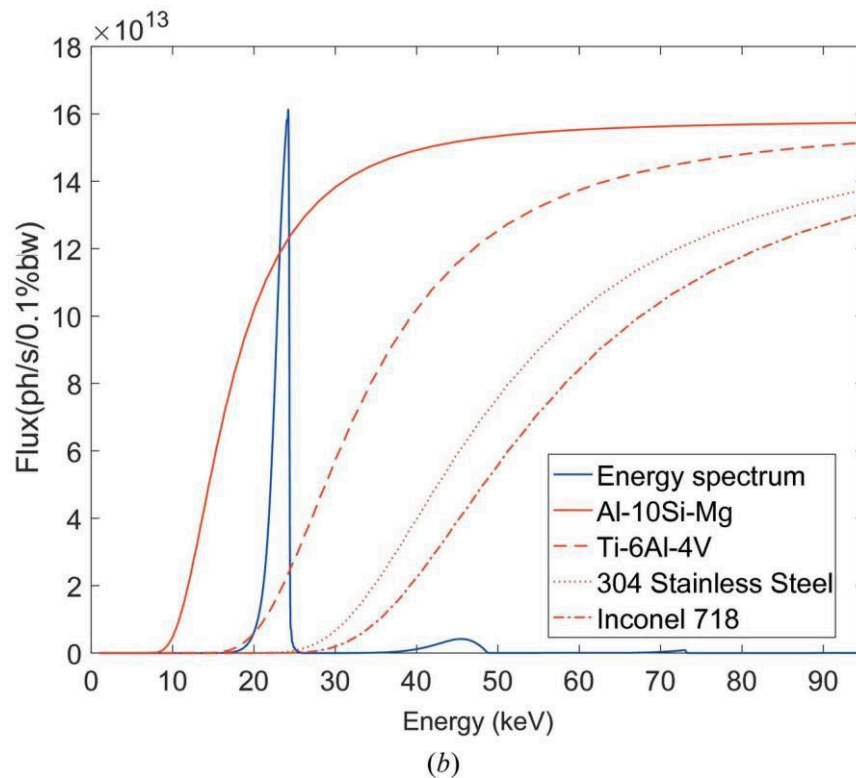


Figure 8. The capability of X-ray transmission at different energy levels with different materials [32].

1.2 Essentials of X-ray imaging for material and manufacturing science

Traditional metallographic techniques, such as optical microscopy, scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD), etc. are primarily post-processing techniques, called “ex-situ” techniques. These "ex-situ" techniques analyze materials after the manufacturing process is complete. However, a significant challenge in material and manufacturing science is detecting physical and metallurgy phenomena during the process itself ("in-process"), such as those occurring during material melting and solidification in casting, welding, AM, casting, or furnace process they are impossible to investigate by “ex-situ” techniques. To address this challenge, "in-process" X-ray (or “in-situ” X-ray) imaging has been developed and utilized to observe the material processes during manufacturing [33,34,35,36,37]. In these applications, high-power hard X-ray facilities with brilliant brightness are employed. Initially developed for fields such as astronautics, particle physics, and environmental science, these advanced X-ray systems have recently been expanded for material and manufacturing science. The first investigations into using X-rays in this field focused on their capabilities for non-destructive testing (NDT) of materials using compact, laboratory-scale X-ray systems [38,39,40]. These systems can detect defects such as porosity, pores, and cracks by observing color changes in the X-ray images. Figure 9 illustrates an example of an X-ray observation system for NDT in welding processes,

while Figure 10 presents a sample result from this system. In the X-ray image, defects such as lack of penetration and root gaps are clearly visible as distinct color variations compared to other areas.

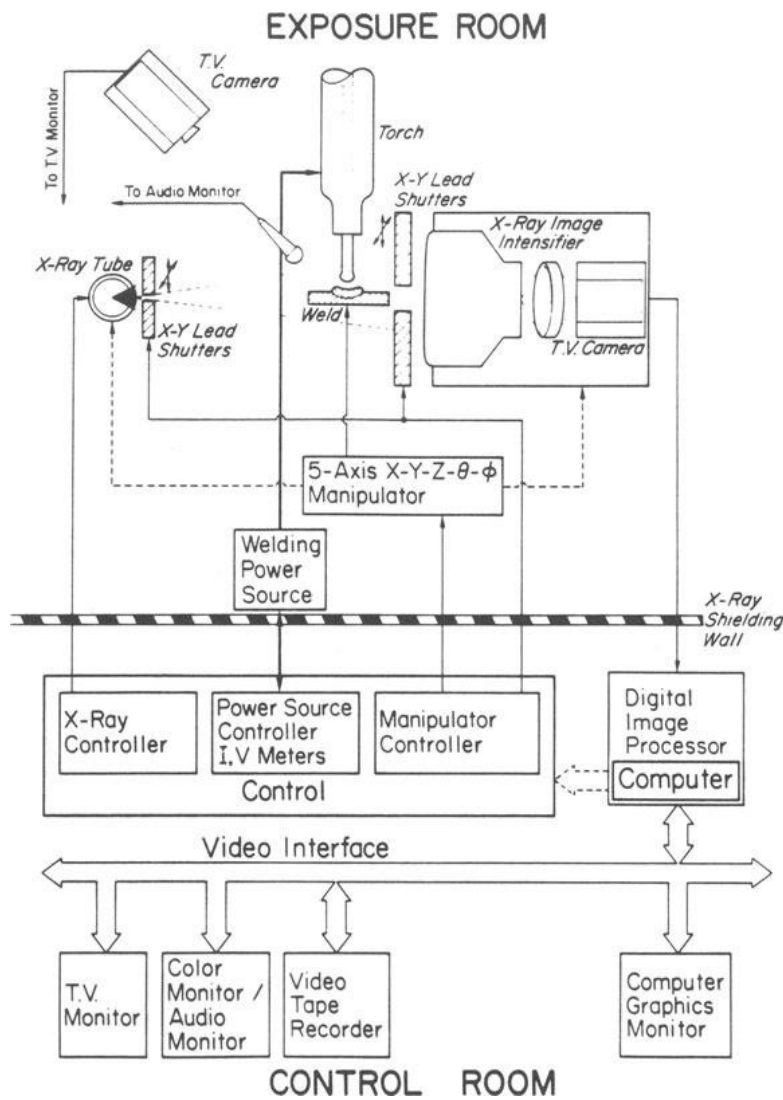


Figure 9. The first X-ray radiography schematic at Ohio State University 1988 [38]

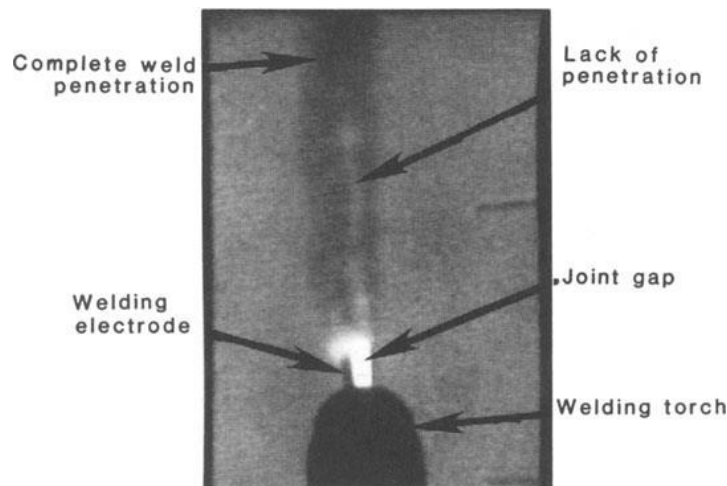


Figure 10. A real figure of X-ray images from an X-ray system at Ohio State University 1989 [39].

Using traditional X-ray techniques with films, as commonly employed in the medical field, is impractical for observing continuous material movement and fluid flow during the “heating-melting-solidifying” process in manufacturing. These processes often involve rapid changes occurring within microseconds or even femtoseconds, requiring the capture of thousands of images in extremely short intervals. To address this limitation, researchers have adopted high-speed X-ray imaging capable of capturing variations in X-ray intensity (color). These recorded videos enable detailed analysis of timing differences, providing insights into physical mechanisms and fundamental metallurgical processes. This research laid the groundwork for a new generation of X-ray light sources. Initially developed for particle physics and astronautics, these sources were later applied to material and manufacturing processes. This foundation led to the development of the world’s first mini-focused X-ray radiography system at Osaka University, Japan, in the 1990s [41,42]. Although X-ray radiography facilities had been established earlier in Japan and Germany [43,44,45], Osaka University pioneered the first system specifically designed for manufacturing processes—such as welding and AM—without relying on beam flux or a scintillator. In late 2017 and early 2018, synchrotron radiation X-ray facilities, including the Diamond Light Source in the UK, the Stanford Synchrotron Radiation Lightsource (SSRL) at SLAC National Accelerator Laboratory, and the Advanced Photon Source (APS) at Argonne National Laboratory in the US, were applied for the first time to study physical phenomena in welding and AM [46–50]. This milestone marked a significant advancement in X-ray imaging for material and manufacturing sciences, ushering in a new era of innovation. Since then, research and publications on X-ray imaging for manufacturing processes have grown rapidly, particularly between 2018 and December 2024. The publication peak occurred in 2019, with over 45 papers published, as illustrated in Figure 21.

In the development of novel materials and manufacturing processes, fundamental investigations of physical and metallurgical processes are essential for understanding the relationships between processes, structure, properties, and performance [51,52]. Various approaches are used to investigate these relationships, with post-processing

methods (“ex-situ” techniques) being the most common. As mentioned above, ex-situ techniques involve analyzing samples after fabrication using methods. However, this indirect approach provides limited insight and cannot capture “in-process” phenomena. To address this limitation, high-speed video cameras (HSVC) are increasingly used for “in-situ” observation, providing a direct method to monitor real-time process behavior [53,54,55,56]. Combining post-processing analysis with in-situ observations using HSVC allows for a more comprehensive understanding of the process-structure-property-performance relationship. This method has been widely applied to study the melt pool in laser welding [57,58,59] and investigate fluid flow behavior, convection patterns, and heat transfer in manufacturing processes such as welding, AM, casting, and furnace operations [60,61,62,63]. However, this approach is limited to observing surface-level phenomena, such as the external behavior of the melt pool, as shown in Figure 11 [64]. In this figure, two HSVCs are integrated to simultaneously observe the melt pool's top and bottom surfaces in Plasma keyhole arc welding process by zirconia powder as tracking particles. However, information about internal processes, such as fluid flow, structural changes, or metallurgical transformations inside the melt pool, is often more significant, as these factors are less influenced by external environmental conditions. To overcome this limitation, “in-situ” X-ray imaging has been introduced as a more advanced technique. X-rays can penetrate materials, including hard metals like steel and titanium, allowing researchers to investigate internal matter movement and physical behavior during manufacturing processes. This capability enables deeper insights into the internal dynamics and mechanisms of material and manufacturing processes.

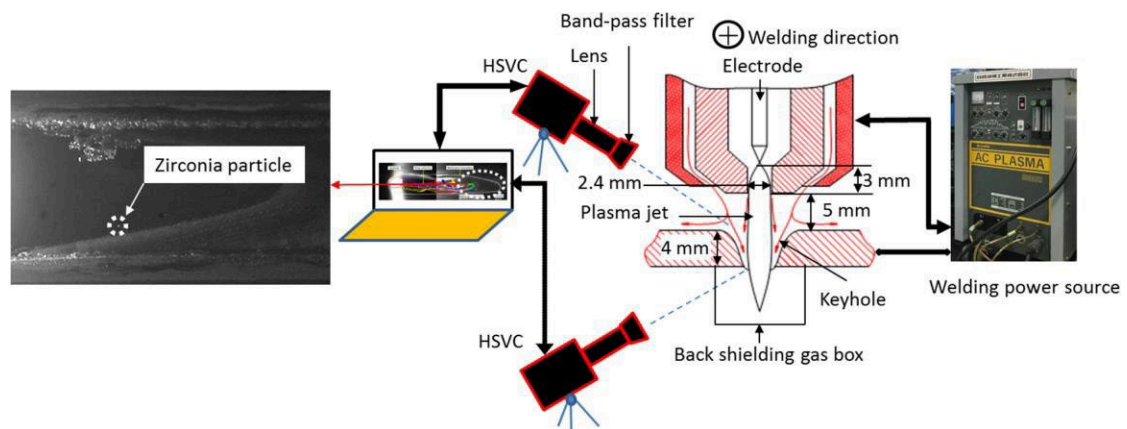


Figure 11. A typical example of fluid flow on the surface by using a pair of high-speed cameras in arc welding processes [64].

1.3. Classification and application of X-ray imaging

As discussed earlier, X-ray imaging has a wide range of applications, spanning agricultural engineering, water treatment, medical diagnostics, particle physics, material science, and manufacturing processes. Depending on the specific use, different types of

X-rays are employed. X-rays were first applied in medical treatment, imaging tissues, and diagnosing patients immediately following the discovery of X-rays by Röntgen in the 1890s. This breakthrough led to advancements in patient care, earning Röntgen the Nobel Prize in 1901 [65]. In the 1930s, X-rays were applied in agricultural science for treatments involving food, water, and fruits [66]. From the 1980s onward, X-rays became integral to non-destructive testing (NDT) for materials structures [38–40]. In the 1990s, the first mini-focused X-ray radiography system was developed at Osaka University in Japan, specifically for capturing the dynamics of the melt pool during laser and arc welding processes [41,42]. This system was a critical tool for observing manufacturing processes for a decade. Since 2011, a novel X-ray facility capable of capturing 3D images has been developed to replace the mini-focus system at Osaka University [67]. Since 2017, "in-situ" X-ray synchrotron images have been applied for the first time in AM processes [46–50]. From 2018 onwards, X-ray synchrotron images have been employed to observe and diagnose microstructure evolution, columnar-equiaxed transition (CET), and crystallization processes in welding and additive manufacturing [68,69,70,71]. Meanwhile, during the 1990s, X-ray synchrotron images were first used in casting and furnace processes to examine the physical phenomena and metallurgy process in developing materials [72,73,74,75,76].

1.4. X-ray Sources

Two primary X-ray sources—X-ray radiography and X-ray synchrotron—are utilized to investigate physical and metallurgical phenomena in manufacturing processes [77,78,79].

X-ray Radiography: X-ray radiography employs a mini-focus system with low power and limited beam flux. It is primarily a laboratory-based facility, though it remains both expensive and complex. Originally developed for specialized applications, X-ray radiography was widely used in Japan and Germany from the 1990s to the 2000s to study fundamental phenomena in welding processes. These early systems operated with low voltage (≤ 250 keV) and low current (≤ 1000 mA), producing 2D images of melt pools. However, they lacked the beam flux necessary for intensifiers or modulators. In 2011, Osaka University in Japan introduced a new X-ray radiography facility to replace older systems. This advanced setup featured higher power and a more complex experimental configuration, incorporating two synchronized X-ray sources. For the first time, this facility enabled the capture of 3D images of melt pools and physical phenomena in welding and AM processes. The resulting "in-situ" 3D images facilitated the investigation of numerous fundamental phenomena that had previously been impossible to observe.

X-ray Synchrotron: X-ray synchrotrons are large-scale experimental facilities known for their immense complexity and high operational costs. Typically found in only a few countries, these facilities serve multidisciplinary purposes, primarily for fundamental research. X-ray synchrotron radiation is significantly brighter—at least 6 to 8 times brighter—than mini-focus X-ray systems [80,81,82]. The development of X-ray

synchrotron technology began in 1947 with the invention of the first synchrotron [83]. Since then, the technology has undergone three generations of advancements, improving image quality, resolution, and applicability [84,85]. The fourth generation, characterized by exceptional brightness, high resolution, and temporal capabilities, represents a significant leap forward. Earlier generations of synchrotron radiation were primarily applied in quantum mechanics, particle physics, and medical treatments [86,87]. However, the fourth generation has broadened applications to include manufacturing processes such as casting, welding, AM, and furnace [88,89]. Figure 12 illustrates the first publication on X-ray imaging synchrotron radiation as one of the earliest synchrotron facilities—the 240 MeV storage ring Tantalus at the University of Wisconsin, constructed in the 1940s with a ring diameter of only 3 meters [90].

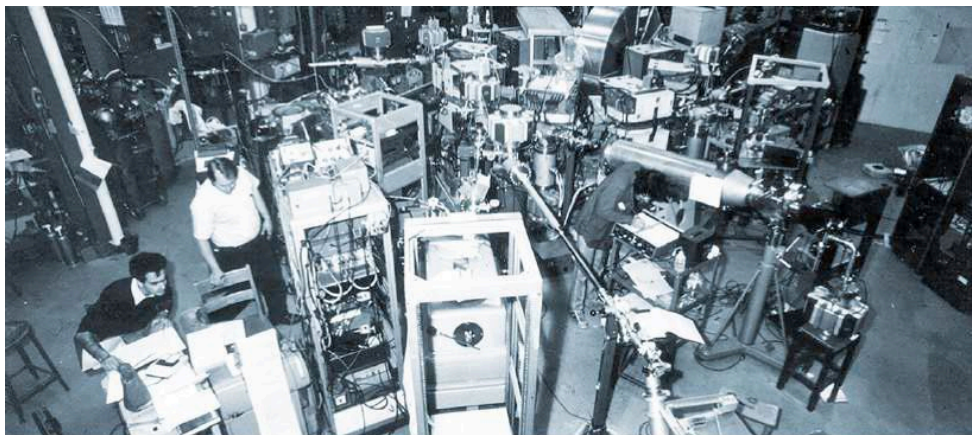


Figure 12. The world's first X-ray synchrotron radiation facility, developed in the 1940s [90].

Compared to other scientific fields such as medicine, water treatment, and particle physics, the application of X-ray synchrotron imaging in material and manufacturing sciences emerged relatively late. The first facility dedicated to materials and manufacturing processes was established at the APS of Argonne National Laboratory in 1984 [91]. Since then, synchrotron facilities have evolved through three generations, with the latest fourth-generation systems driving advancements in welding, AM, and other metallurgical processes such as casting and furnace operations. A report from Spring-8 in Japan highlights the existence of 26 X-ray synchrotron facilities worldwide that utilize "hard" X-rays with high power and brilliance [91] (see Figure 13). Among these, eight facilities are equipped with the necessary power and brightness to support materials and manufacturing science research. These advanced facilities are invaluable for investigating phenomena in welding, AM, casting, and furnace processes, particularly for samples at millimeter and larger scales. High-powered X-rays enable "in-situ" observations, providing real-time insights into complex physical phenomena.

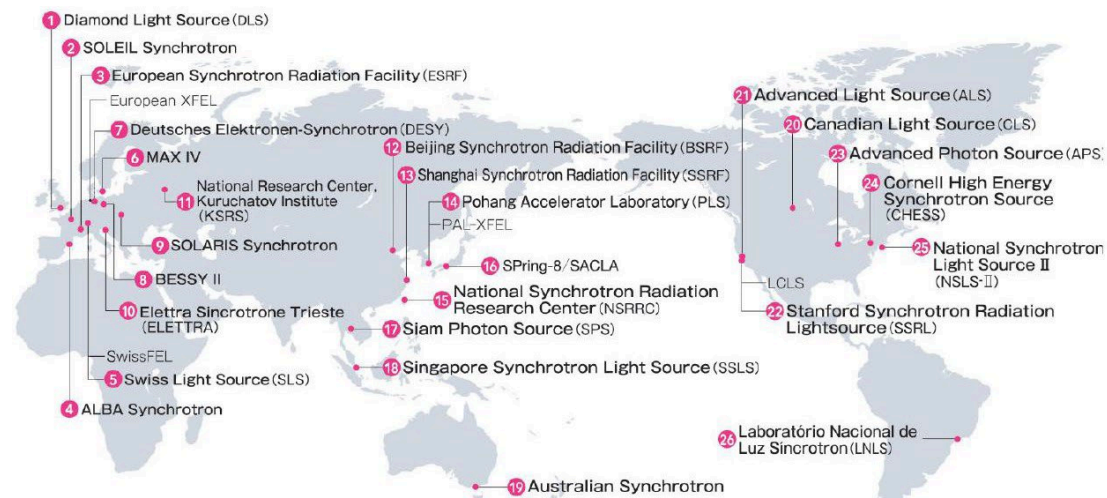


Figure 13. Map of X-ray synchrotron facilities in the world [91].

Below, we summarize the seven X-ray synchrotron facilities used in manufacturing sciences, including welding, AM, casting, and furnaces.

1. Petra III at DESY (Deutsches Elektronen-Synchrotron), Germany
Established in 1959, PETRA III is the world's second-largest X-ray synchrotron facility, operating at 6 GeV with a 2,304 m storage ring. Its research spans four key sectors: accelerators, photon science, particle physics, and astronomical physics [92,93]. Since 2020, PETRA III has expanded its focus to include materials and manufacturing processes, particularly for welding and additive manufacturing (AM) [94].
2. European Synchrotron Radiation Facility (ESRF), France
Established in 1988, with its first beamline becoming operational in 1994 [95,96,97], ESRF is located on the border of France and Switzerland. Operating at 6.0 GeV, it specializes in microscale sample studies. ESRF is a global leader in metallurgy research, particularly in casting, furnaces, welding, and additive manufacturing (AM), producing the highest volume of publications in these fields [98].
3. Spring-8, Japan
Located in Hyogo Prefecture, SPring-8 has been in operation since 1997 and remains the world's most powerful X-ray synchrotron facility, operating at 8 GeV (10 GeV for hard X-rays) [99]. While its primary focus is on materials science, biochemistry, and nuclear research [100], it has recently contributed to laser welding studies.
4. Advanced Photon Source (APS) at Argonne National Laboratory, USA
Originally established in 1947 as part of General Electric's research efforts [101,102], APS now operates at 7.0 GeV and has become a leading facility for metal 3D printing research. It plays a crucial role in additive manufacturing (AM), hosting a significant number of global experiments. Since 2017, Dr. Tao Sun's group at the University of Wisconsin has published over 80 papers based on research conducted at APS [103].

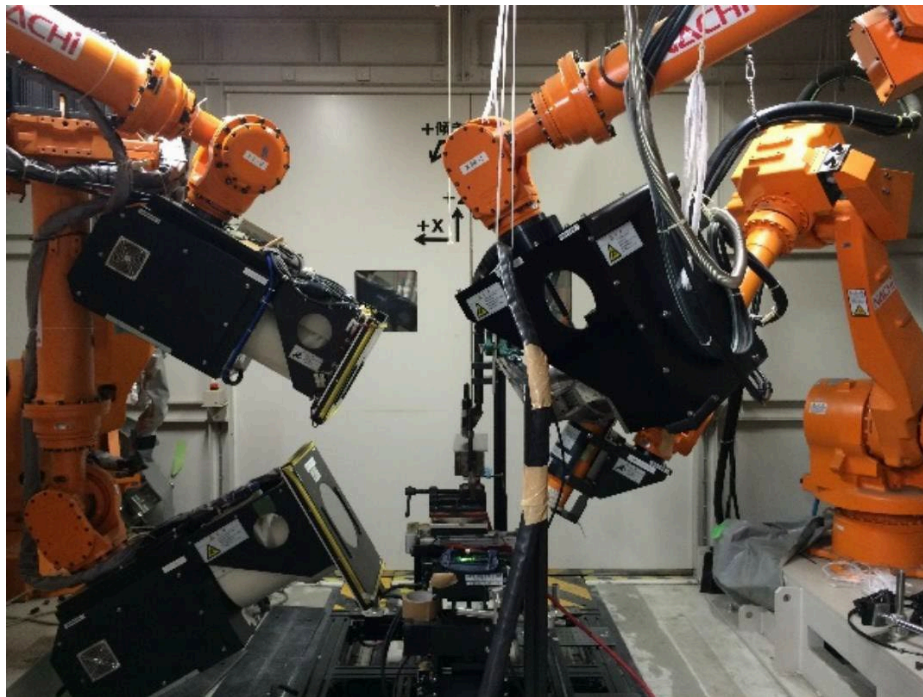
5. Stanford Synchrotron Radiation Lightsource (SSRL) at SLAC National Accelerator Laboratory, USA
Established in 1973, SSRL has operated at 3.0 GeV since 2004 [104]. Recent studies by Dr. Manyalibo Matthews' group at Lawrence Livermore National Laboratory have focused on melt pool dynamics and porosity defects in laser processes [105].
6. The UK's most powerful X-ray synchrotron, Diamond operates at 3.5 GeV and has played a key role in metallurgy research, particularly in melt pool dynamics for welding and additive manufacturing (AM). Notable researchers in this field include Prof. Pete Lee (University College London), Prof. Hongbiao Dong (University of Leicester), and Dr. Wajira Mirihanage (The University of Manchester) [106,107,108].
7. Swiss Light Source (SLS), Switzerland
Operating at 2.4 GeV with a 288 m ring length, SLS is a medium-power synchrotron facility. The Paul Scherrer Institute, under the leadership of Prof. Steven Van Petegem, is advancing research on operando Laser Powder Bed (LPB) systems [109].
8. Shanghai Synchrotron Radiation Facility (SSRF), China
Established in 2012, SSRF operates at 3.5 GeV with 34 beamlines. Initially dedicated to biomedicine and physical sciences [110,111], it has since expanded into welding research, including studies on melt pool dynamics in submerged arc welding (SAW) [112].

The development of X-ray facilities for materials and manufacturing science began early at Osaka University, led by Professor Katayama's group, and at the University of Stuttgart, under Professor Thomas Garf's group [41,42,43,44,45]. These pioneering X-ray facilities played a crucial role in advancing "in-situ" observations of physical phenomena in welding processes, contributing to most of the research in this field from the 1990s to 2017, before the advent of X-ray synchrotron technologies. However, these early facilities used mini-focus X-rays with limited power and a single X-ray source, lacking the beam flux necessary for clear observations of melt pool dynamics and boundaries. To overcome this limitation, researchers at Osaka University introduced a technique involving the addition of a metal with a lower melting temperature and significantly lower density than the base metal to the melt pool. This method created a distinct color contrast between the melt pool and the solid raw material, enhancing the visibility of melt pool boundaries and dynamics [113]. Despite its advantages, this method altered the solidification and crystallization processes due to changes in the chemical composition of the materials within the melt pool.

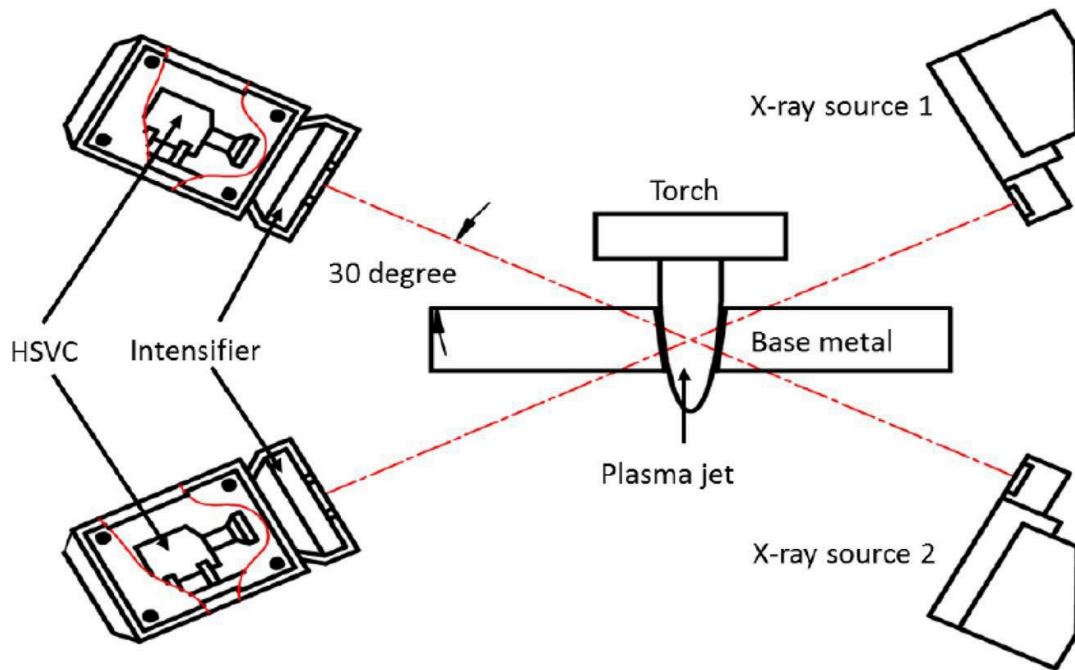
In 2011, Hitachi Corporation developed a new mini-focused X-ray facility to address these challenges [114,115]. This advanced system featured higher power, brightness, frame rate, and two synchronized X-ray sources. For the first time, it enabled the generation of 3D images of melt pools. With these enhancements, a series of detailed investigations emerged into physical and metallurgical phenomena, focusing on flow velocity, melt pool dynamics, keyhole phenomena, eddies, and other aspects of welding processes such as laser welding, friction welding, plasma keyhole welding, and submerged arc welding (SAW) [67,116,117]. The facility's ability to accurately

calculate and analyze physical phenomena and metallurgical processes in manufacturing remains unique, providing three-dimensional insights into melt pool dynamics. Unlike other mini-focused X-ray and synchrotron facilities worldwide, which capture only 2D images from a side view, this system can measure melt pool boundaries, velocity, eddies, and velocity distribution across three projected views.

Despite its innovative capabilities, the mini-focused X-ray system at Osaka University has limitations, including lower power and brightness compared to X-ray synchrotron facilities. Figure 14(a) shows an image of the dual mini-focus X-ray facility at Osaka University. This complex system integrates two robots holding high-speed cameras and detectors, along with two additional robots holding the X-ray generators. The two X-ray systems are synchronized and positioned at the center of the base metal (Figure 14(b)), all housed within an isolation room. Trigger systems and control desktops are located in separate rooms [117]. Figure 15 illustrates two images captured simultaneously by this X-ray facility. From these images, the (X, Y, Z) coordinates of each position within the melt pool can be precisely determined.



(a) Setup of mini-focused X-ray facility with two X-ray sources.



(b) Integration and synchronization of X-ray systems.

Figure 14. Osaka University mini-focused X-ray facility with two X-ray sources [117].

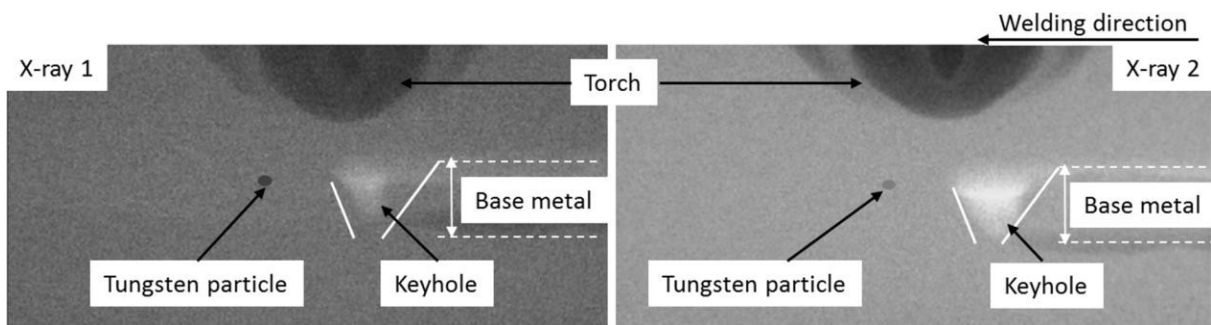


Figure 15. Two images were obtained from the Osaka University X-ray mini-focused facility with two X-ray sources [117].

Meanwhile, the mini-focused X-ray system in Germany has primarily been used for laser and arc welding experiments since the 2010s [118,119]. Between the 2000s and 2017, most research utilizing this facility was conducted by Professor Thomas Garf's group at the University of Stuttgart, resulting in numerous publications [120,121,122]. This X-ray system, similar to the earlier mini-focused X-ray facility at Osaka University (active from the 1990s to 2011), features a single X-ray source. The first study on melt pool dynamics in laser welding for aluminum using this facility was published in 2011 [123]. Figure 16 shows an image of the mini-focused X-ray facility in Germany. While it shares similarities with the X-ray system at Osaka University, it is equipped with only one X-ray source, a single detector, and one high-speed camera, allowing only one video to be captured per session. Due to its lower power, the images produced are less

clear than those obtained from X-ray synchrotron facilities (see and compare Figure 16 with Figure 26). Table 2 summarizes seven X-ray synchrotron facilities most utilized for material and manufacturing science.

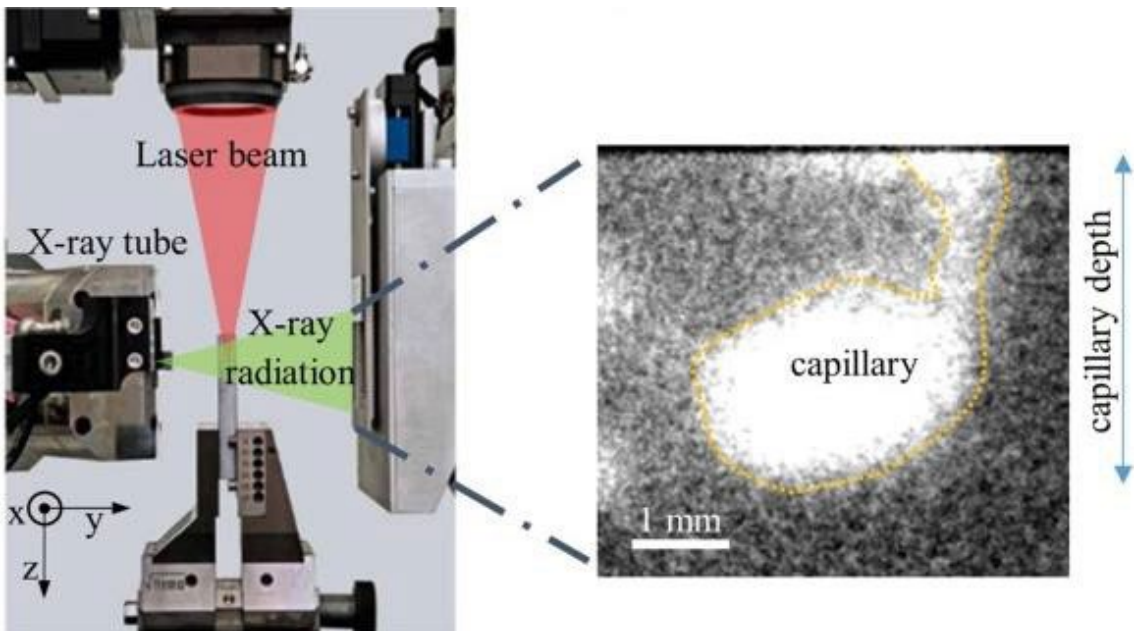


Figure 16. Germany mini-focused X-ray facility [123].

Table 2. X-ray synchrotron radiation facilities and their features [78,91,124,125] (all eight X-ray facilities introduced here are the highest power among others and have recently been applied for material and manufacturing science.).

	Features	Images
Desy (Petra III)	Country: Germany Power: 6 GeV Brightness: 2×10^{21} ph./s/0.1%/mm ² /mrad ² Current (mA): 100 Ring length: 2304 m Number of beamlines: 25 Commissioning: 1978	 <p>[126]</p>
Spring-8	Country: Japan Power: 8 GeV Brightness: 2×10^{21} ph./s/0.1%/mm ² /mrad ² Current (mA): 100 Ring length: 1435 m	

	Number of beamlines: 48 Commissioning: 1997	[127]
European X-ray Synchrotron Radiation Facility (ESRF)	Country: France Power: 6 GeV Brightness: 3.56×10^{21} ph./s/0.1%/mm ² /mrad ² Current (mA): 100 Ring length: 844 m Number of beamlines: 44 Commissioning: 1994	 [128]
Advanced Photon Source (APS)	Country: US Power: 7 GeV Brightness: 8×10^{19} ph./s/0.1%/mm ² /mrad ² Current (mA): 100 Ring length: 1144 m Number of beamlines: 76 Commissioning: 1997	 [129]
Diamond Centre	Country: UK Power: 3 GeV Brightness: 3×10^{20} ph./s/0.1%/mm ² /mrad ² Current (mA): 300 Storage ring: 561 m Number of beamlines: 32 Commissioning: 2001	 [130]
Stanford Synchrotron Radiation Lightsource (SSRL)	Country: US Power: 3 GeV Brightness: N/A Current (mA): 500 Storage ring: 234 m Number of beamlines: 17 Commissioning: 1973	 [131]

Shanghai Synchrotron Radiation Facility (SSRF)	Country: China Power: 3.5 GeV Brightness: N/A Current (mA): N/A Storage ring: 432 m Number of beamlines: 34 Commissioning: 2012	 <p>[132]</p>
The Swiss Light Source (SLS)	Country: Switzerland Power: 2.4 GEV Brightness: 4×10^{19} ph./s/0.1%/mm ² /mrad ² Current (mA): 400 Storage ring: 288 m Number of beamlines: 16 Commissioning: 2000	 <p>[133]</p>

Figure 17 illustrates various X-ray facilities' energy capacity and storage ring dimensions. The PETRA III and PETRA IV synchrotron radiation facilities at DESY have the largest storage rings, with PETRA IV also achieving the highest diffraction energy. Among these facilities, the Diamond Light Source in the UK has the smallest

storage ring diameter [134].

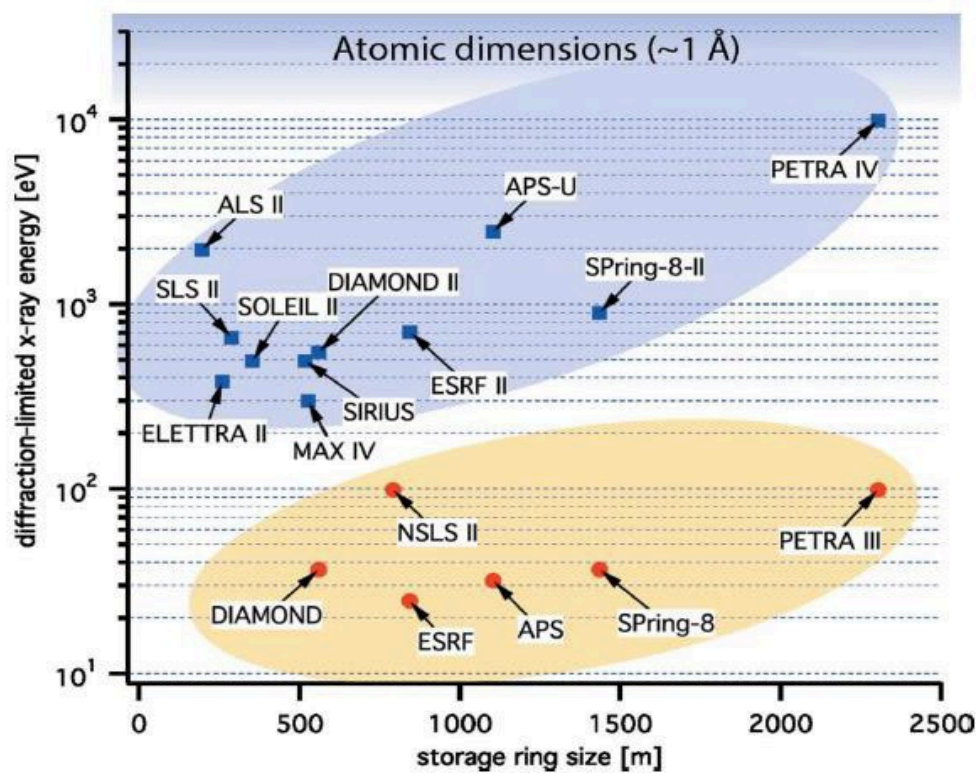


Figure 17. Summary of X-ray facilities with storage ring size and energy capability [134].

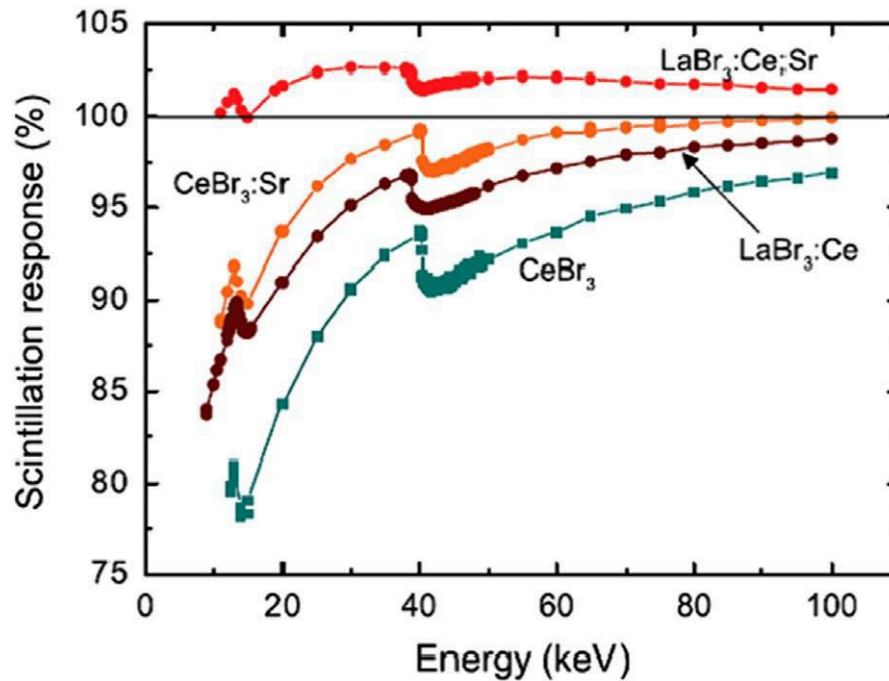
Table 3 presents several typical materials investigated using “in-situ” X-ray synchrotron facilities to analyze fundamental physical and metallurgical phenomena in manufacturing processes. The data indicates that most studies focus on Ti6Al4V and steel, with fewer examining aluminum. Notably, only one study has explored for high-entropy alloys, and no publications have investigated functionally graded materials, refractory materials, or other material types.

Table 3. Materials studied in manufacturing processes using “in-situ” X-ray imaging.

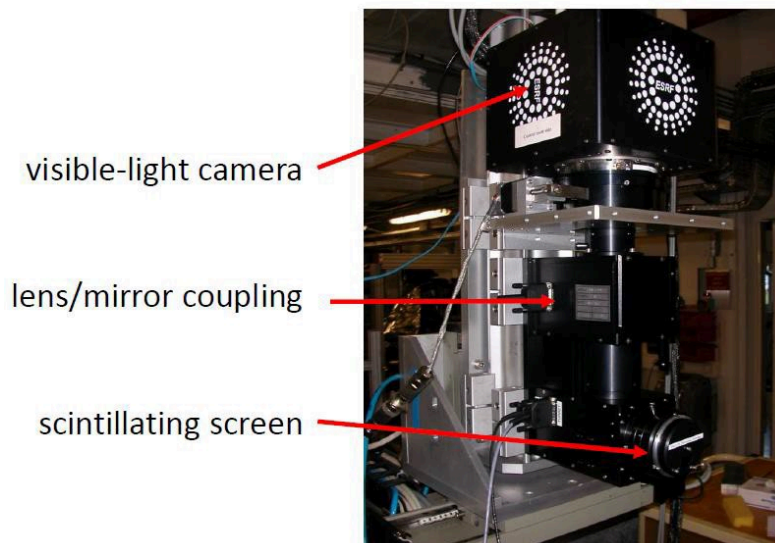
Titanium	Steel	Aluminium	High entropy alloy	References
X				[135], [136], [137], [138]
	X			[139], [140], [141], [142], [143]
		X		[144], [145]
			X	[146]

1.5. X-ray detector

The detector is a crucial component of X-ray facilities, playing a key role in image acquisition and imaging quality [147]. It absorbs radiation energy (photons) from X-ray sources as they pass through samples, converts the energy into visible light, and captures the resulting image using either a digital or film-based X-ray detector. To facilitate X-ray imaging, a thin scintillator layer is applied to the surface of the X-ray plate [148]. The chemical composition of this coating layer is a critical factor in determining imaging quality and acquisition performance in X-ray facilities. It directly affects the scintillator's intensification properties, which influence how CCD cameras capture images. Consequently, selecting scintillator materials and developing advanced detectors remain key research areas attracting attention from numerous research groups worldwide [149,150]. Figure 18(a) illustrates the differences between various scintillator materials [151], while Figure 18(b) presents an example of an imaging acquisition system. This system includes a detector (scintillating screen), a lens/mirror for diffracted photons/light, and a high-speed (visible-light) camera, as implemented at ESRF in France [152].



(a) Materials to manufacture scintillator and scintillator response (%) corresponding to various materials [151].



(b) The detector and the structure of acquired imaging system in X-ray synchrotron facility [152].

Figure 18. Detector in X-ray facilities.

1.6. Structure of an X-ray synchrotron facility and key parameters

Previous review papers [124,125] have thoroughly analyzed the experimental environments of various X-ray synchrotron facilities worldwide. In this review, instead of examining each experimental environment in detail, we provide a concise overview of the main components and parameters that have been underemphasized in prior studies. A typical X-ray synchrotron radiation facility comprises the following key components:

1. **X-ray Sources/Undulators**
These components generate X-rays for the observation system. The source consists of a large-diameter ring and a head designed to manipulate electron synchrotron particles. Electrons are accelerated to nearly the speed of light within the ring before exiting to interact with the sample.
2. **Detector and High-Speed Video Camera**
The detector acts as the system's "film," absorbing radiation energy (photons) from X-ray sources and converting them into visible light. Mini-focus X-ray systems, such as those at Osaka University and the University of Stuttgart, integrate high-speed video cameras directly aligned with the X-ray incident direction. In contrast, synchrotron X-ray facilities use diffraction at specific inclination angles, with mirrors reflecting the X-ray beam toward the camera.
3. **Fixation/Jig for Sample or Powder Holding**
This component securely holds samples during experiments, ensuring precise alignment for accurate observations. It is positioned between the X-ray source and the detector.

4. Control Program

This software system synchronizes the facility's components, ensuring precise timing and data collection during experiments. It also enables seamless video capture, enhancing the accuracy and reliability of observations.

Figure 19 illustrates two types of X-ray imaging systems: radiography and diffraction. X-ray radiography is primarily used to observe fluid dynamics, melt pool boundaries, internal defects, and other physical phenomena. Conversely, X-ray diffraction focuses on studying solidification processes, such as grain structure evolution and phase transformations. Figure 20 presents a schematic of a high-speed X-ray imaging setup for diffraction experiments during laser powder bed (LPB) processes at the 32-ID-B beamline of the APS. In this configuration, a laser heat source impinges on a miniature powder bed sample from above, while X-rays penetrate the sample from the side. Imaging and diffraction detectors are positioned downstream, with an inset (highlighted by a dashed circle) showing a close-up of the laser-sample and X-ray-sample interactions. Figure 21 provides an example of an X-ray synchronization experiment setup at the DESY PETRA III facility in Germany.

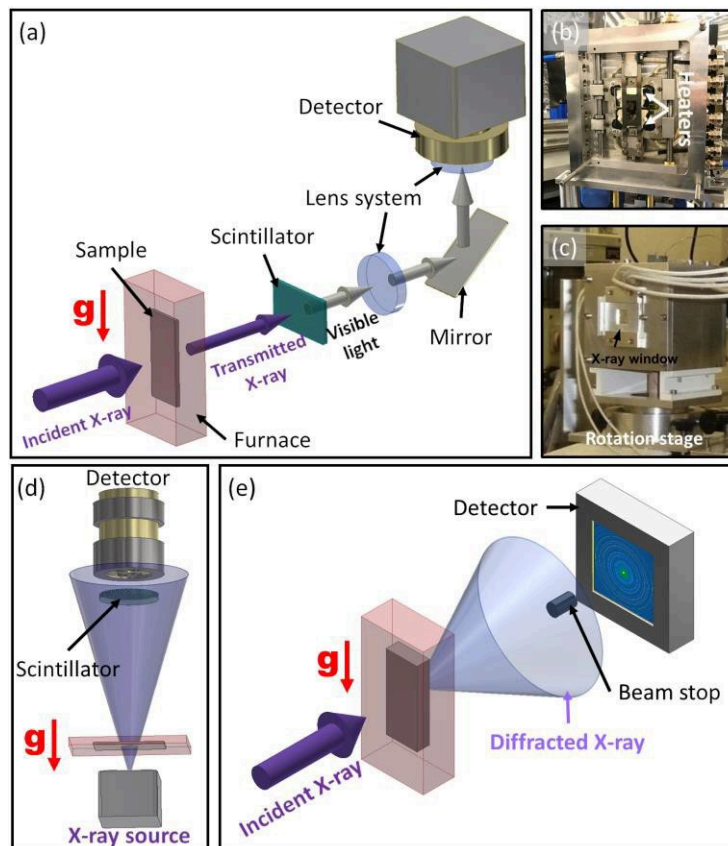


Figure 19. A typical X-ray radiography and diffraction [153]. (a) Schematic of the experimental set-up for synchrotron X-ray radiography of solidification, where the sample is solidified vertically [154]. (b) An example of a Bridgman furnace for radiography experiments. (c) An example of a furnace for tomography experiments

[155]. (d) Schematic of a typical experimental configuration for laboratory-based X-ray radiography of horizontal solidification (i.e., with gravity perpendicular to the sample surface). (e) Schematic of a typical experimental set-up for synchrotron X-ray diffraction.

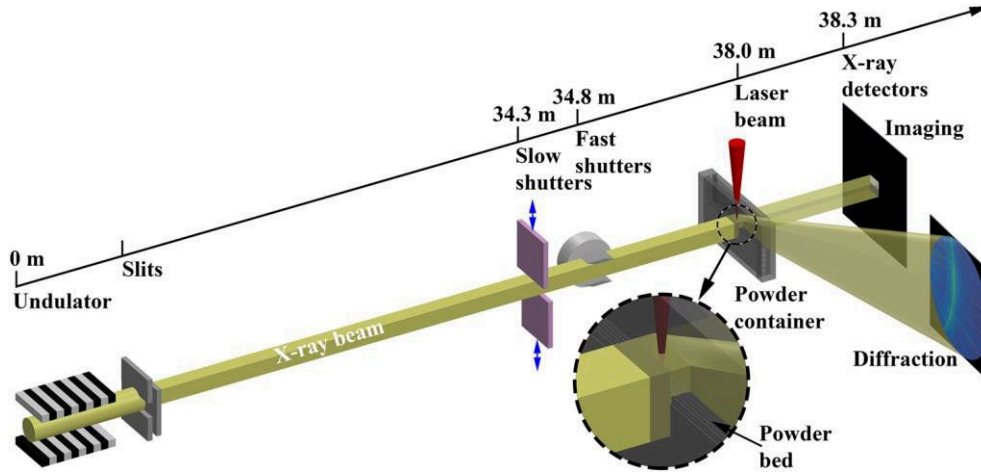


Figure 20. A schematic of X-ray facility at the APS Beamline 32-ID-B [156].

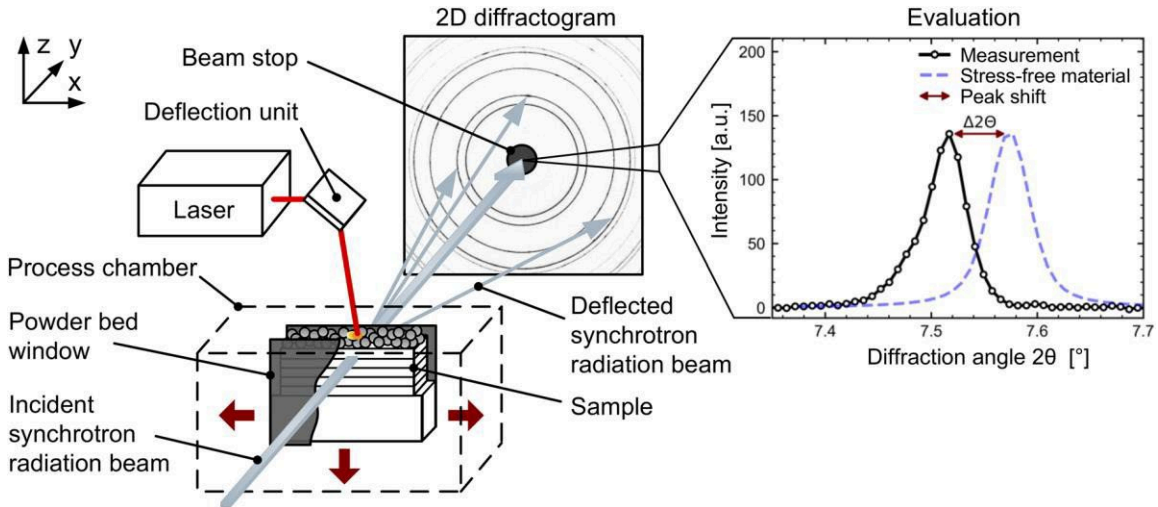


Figure 21. An example of an X-ray synchrotron system to observe the LPB process [163].

To obtain high-quality images from X-ray synchrotron facilities, it is crucial to configure the following key parameters properly:

1. X-ray Power

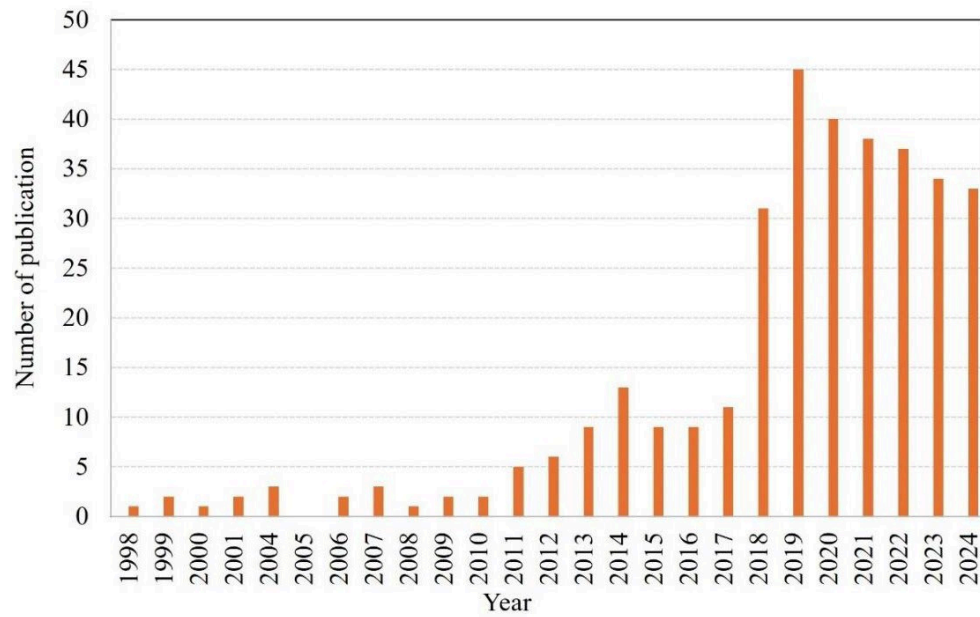
This parameter determines the ability to penetrate and observe materials of

varying thicknesses. Higher power facilitates imaging of thicker materials, while lower power is ideal for thinner materials.

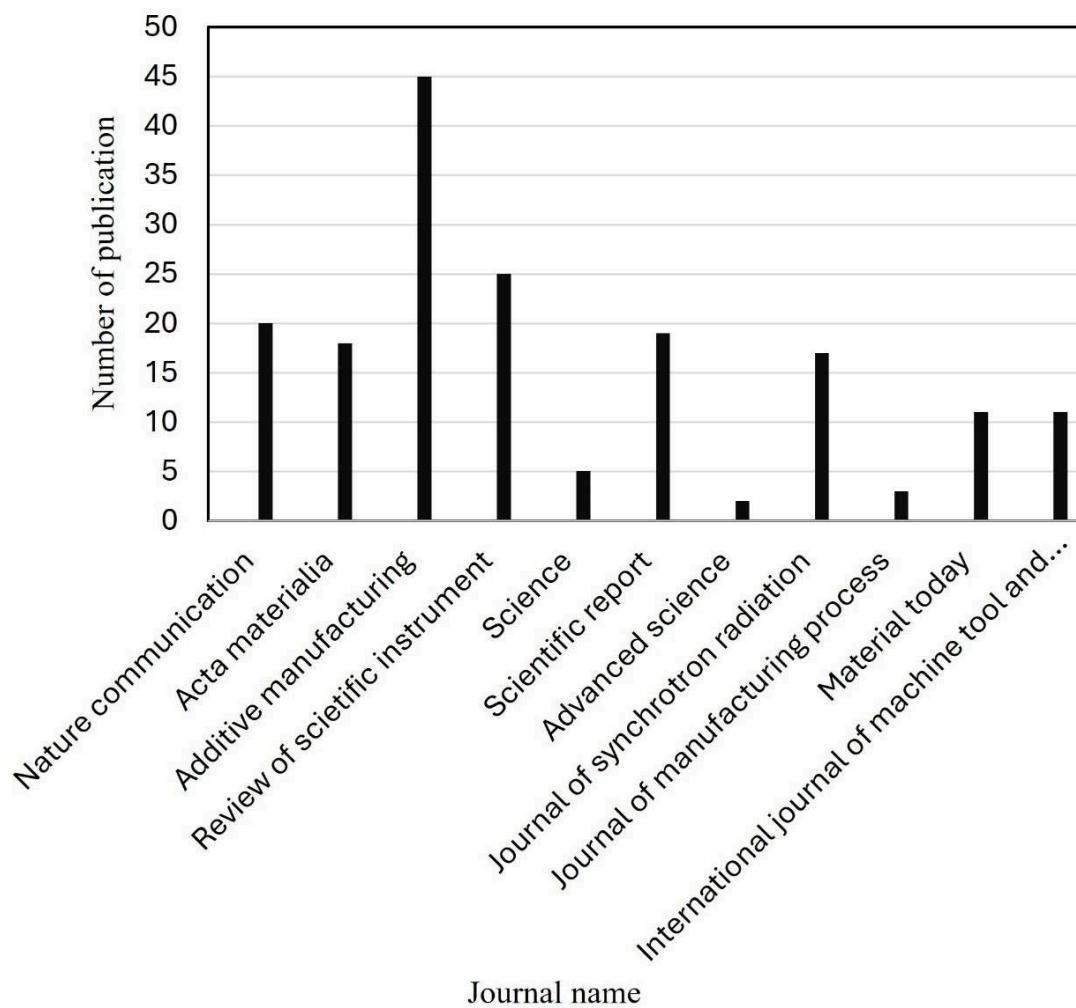
2. **Frame Rate and Resolution of the High-Speed Video Camera**
Frame rate specifies the number of images captured per second, while resolution dictates the level of detail and the observation area. High resolution provides greater detail for smaller areas but often reduces frame rates. In contrast, lower resolution allows for imaging larger areas with higher frame rates.
3. **Temporal and Spatial Resolution**
These settings influence the brightness and contrast of captured videos, enhancing the visibility of fine details in the observed phenomena.
4. **Observation Range**
This defines the area of the object visible within a single frame. The observation range depends on the design of the X-ray source and the camera system.

1.7. Publications on “in-situ” X-ray imaging for materials and manufacturing science

Based on data collected from Scopus and Google Scholar, over 300 publications using “in-situ” X-ray imaging for investigating the fundamental physical phenomena and metallurgy processes of additive manufacturing, welding, furnaces, and casting can be found from the 1980s to the present (December 2024). Figures 22 and Table 4 summarize the yearly publication trends and the targeted journals. Most publications were released between 2018 and now, primarily from the US, UK, Japan, Switzerland, France, and German research groups. Among these, Prof. Tao Sun and his team stand out for their prolific output, contributing the highest number of papers. Prof. Peter Lee and his group also pioneered X-ray imaging for metal additive manufacturing (AM), focusing on powder bed processes. Meanwhile, the group led by Prof. Tanaka and Dr. Van Anh made groundbreaking contributions by publishing the first 3D images of the melt pool. Their research detailed essential physical phenomena in arc welding, including velocity, eddies, convection patterns, and internal and surface defects. Many of these papers were published in prestigious journals such as Science, Nature Communications, Additive Manufacturing, Material Design, International Journal of Machine Tools and Manufacture, Advanced Materials, Advanced Science, and Acta Materialia, Journal of Manufacturing Processes (see Figures 22 (b) and Table 4). The significant attention garnered by “in-situ” X-ray imaging for advanced investigations highlights its critical role in materials and manufacturing science. However, Figure 22 indicates a slight decrease in publication numbers in recent years. This trend may be attributed to the saturation of research on melt pool dynamics and fluid flow in manufacturing processes, making it challenging to identify novel topics in traditional materials and manufacturing processes. To address this, future research must explore innovative directions, such as investigating internal defects (e.g., phase transitions and microstructure evolution) or integrating X-ray imaging with deep-learning and simulation techniques. These approaches represent cutting-edge advancements and have the potential to redefine research methodologies in materials and manufacturing science.



(a) Number of publications of “in-situ” observation by X-ray images of welding+additive manufacturing+casting+furnace following the year from 1998 to present (December 2024). The data is collected and analyzed from “google scholar” and “Scopus” by the authors.



(b) A list of popular journals targeted by authors for publication from 1998 to December 2024. Using the data from Figure 22(a), the authors have analyzed and quantified the number of publications in each journal at Figure 22 (b).

Figure 22. A number of publications and a list of several popular journals use “in-situ” X-ray imaging for “welding,” “additive manufacturing,” “casting,” and “furnace” fields [source: from “Scopus” + “Google Scholar”].

Table 4. Published publications and lists of typical journals (1998 to December 2024) [sources: from “Scopus” + “Google Scholar”].

	Country of corresponding authors)	X-ray facility	No. publication (estimated until 2024 December)	List journals (only some examples among all)
Tao Sun group	US	APS	>80	Science [158] MRS Bulletin [159]

				Acta Materialia [160] Physical Review Applied [161]
Peter Lee group	UK	Diamon and ESRF	>44	Nature communication [162] Scientific report [163] Materials Today Advances [164] Additive manufacturing letter [165]
Alexander and Yunhui group	France	ESRF	>15	Welding in the world [140] International journal of machine tools and manufacture [166]
Katayama group	Japan	Sping-8 and Mini-focus X-ray Osaka	>25	Japanese welding society [167] Journal of laser applications [168] Journal of Materials Processing Tech. [169]
Van Anh and Tanaka group	Japan	Mini-focus X-ray Osaka	>15	Journal of Cleaner Production [170] Journal of Manufacturing Process [171] Physic of fluid [172]
Thomas Graf group	Germany	DESY and Mini-focus X-ray	>20	Procedia CIRP [173] Metals [174]
Ning Guo group	China	SSRF	>2	Material & Design [112]
Hen-Ri Nguyen group	France	ESRF	>35	Journal of Crystal Growth [175] J. Phys. D: Appl. Phys [176] Materials Science and Engineering A [177]

				Philosophical Magazine [178]
Warija and Hongbiao Dong group	UK	Diamon	>8	Nature communication [107] Journal of Materials Engineering and Performance [179]
Manyalibo Matthews group	US	APS and SSRL	>10	Review of Scientific Instruments [48] Advanced engineering materials [180]
S. Van Petege group	Switzerland	SLS and ESRF	>10	Scripta Materialia [76] Additive manufacturing [181]
Other groups	Chinese Germany Japan	APS, ESRF, and Spring-8	>20	Communication material [182] Journal of Alloys and Metallurgical Systems [183] Journal of Applied Crystallography [184]

Even though “in-situ” X-ray imaging is one of the most powerful tools for uncovering the fundamental physical and metallurgical principles of materials and manufacturing science, its development and broader application remain relatively slow. Furthermore, only a limited number of review papers address specific aspects of this promising field.

The first notable review on this topic, published by Sarah K. Everton et al. in 2016, discussed the development of monitoring methods for metal additive manufacturing (AM) processes [185]. They emphasized the potential of X-ray radiography to detect internal defects during material processing. In 2021, M. Grasso et al. summarized advancements in “in-situ” measurement and monitoring methods for laser powder bed (LPB) processes [186]. Their work categorized the technological advancements into five levels, with X-ray imaging for studying internal structures (e.g., porosity, phase transitions, microstructure evolution, and melt pool dynamics) representing the most advanced stage in understanding material and manufacturing processes. Xiaolin Zhang et al. (2022) explored the applications of “in-situ” X-ray imaging in welding processes and its potential for metal AM processes [187]. Shyamprasad Karagadde et al. (2021) reviewed the role of “in-situ” X-ray imaging in studying solidification phenomena in

laser powder bed fusion and casting processes [188]. Several other review papers published between 2018 and 2024 contributed significantly to the field. For instance, works by Amir Mostafaei et al. (2022), Cang Zhao et al. (2022), and Tao Sun et al. (2022, 2024) focused on monitoring melt pools and defects in LPB processes [189,190,191,192,193]. Chrysoula Ioannidou et al. (2022) examined “in-situ” X-ray imaging in powder bed AM processes, specifically addressing its untapped potential for electron beam powder AM processes. Despite its promising applications, they highlighted that almost no publications exist on X-ray imaging for this topic [124]. While existing research provides valuable insights into fundamental phenomena such as melt pool dynamics and internal defect formation, the industrial implementation of X-ray imaging remains limited. Real-world manufacturing often involves process variations to improve quality and reduce defects, which remain critical areas for further investigation. Significant efforts are needed to bridge the gap between fundamental research and industrial applications to leverage X-ray facilities' potential fully. This review provides the first comprehensive and systematic summary of the progress of “in-situ” X-ray imaging in advancing materials and manufacturing science. Additionally, we propose a forward-looking perspective on this technology, highlighting its potential to drive innovations in materials and manufacturing processes. By fostering opportunities for junior researchers, promoting collaboration with leading experts, and encouraging broader experimental and research initiatives among international researchers and groups.

2. X-ray imaging for heat transfer and melt pool dynamics

This section explores the application of X-ray imaging in studying melt pool dynamics, focusing on changes in melt pool morphology, convection patterns, and keyhole formation in manufacturing processes such as welding, AM, casting, and furnace operations. In processes characterized by a "heating-melting-solidifying" cycle, heat transfer and melt pool dynamics are fundamental phenomena essential for understanding and controlling manufacturing operations [194,195,196]. These complexities underscore both the challenges and opportunities of employing X-ray imaging to uncover the underlying mechanisms governing melt pool behavior and heat transfer in advanced manufacturing. Figure 23 illustrates a schematic of heat transfer and melt pool dynamics in metal AM processes [51]. This process involves the intricate interplay of phenomena such as evaporation, melt pool dynamics, heat transfer, Marangoni convection, heat radiation, and heat conduction. Studies utilizing in-situ X-ray imaging in welding, AM, casting, and furnace processes primarily focus on melt pool dynamics. They aim to elucidate critical aspects such as keyhole formation, defect generation, and melt pool morphology (e.g., size and shape). Insights from these investigations are crucial for developing simulation models that not only validate experimental observations but also probe previously unexplored facets of these processes.

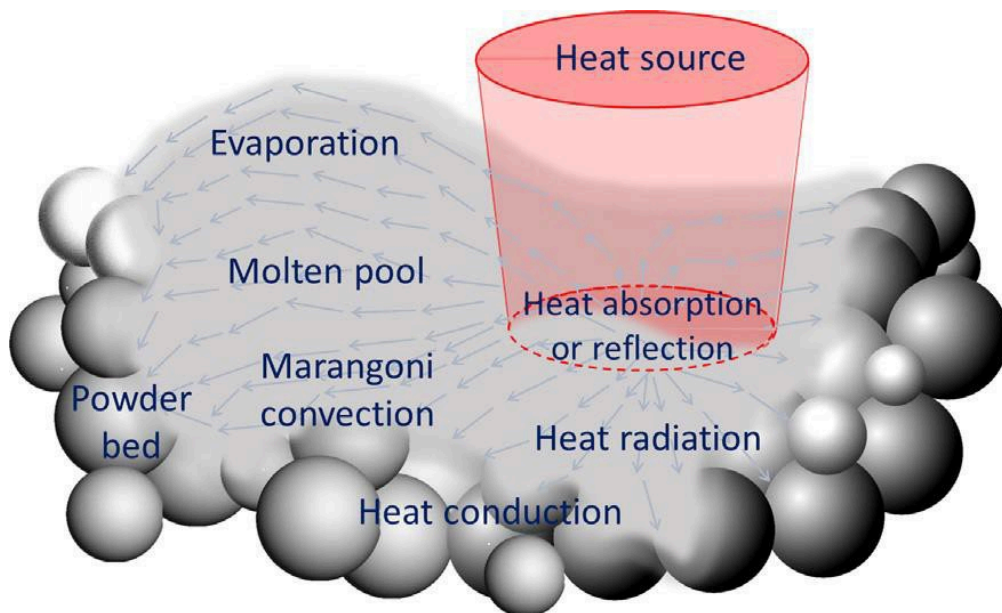


Figure 23. Schematic of heat transfer and melt pool dynamic in AM processes [51].

One of the earliest applications of “in-situ” X-ray imaging for manufacturing processes was demonstrated by Guu Adam Chenshow and his team at Ohio State University, USA. In 1991, Guu published pioneering works under his PhD thesis and conference

papers [38-40], where he utilized a mini-focused X-ray facility to observe the melt pool boundary during the arc welding process. This marked the first time “in-process” X-ray imaging was applied for manufacturing applications. This section presents and discusses investigations into melt pools, keyhole behavior, and heat transfer during manufacturing processes. These studies were conducted independently by groups utilizing various X-ray facilities worldwide.

2.1. Van Anh and Tanaka group

Van Anh and Tanaka Group significantly advanced this field by publishing papers exploring plasma welding processes. Their studies delved deeply into the formation of keyholes, heat transfer, eddies, and melt pool behavior and their connections to defect formation. These investigations determined that the shear force is the primary driving force in plasma keyhole arc welding, supported by high-speed and thermal camera data. They also highlighted the critical role of eddies in fluid flow, demonstrating that imbalances in eddies can lead to altered heat transfer and serious defects [64,197,198,199,200]. Building on the methodology established by Van Anh's group, Bin Xu and his team conducted studies using the same mini-focus X-ray facility to investigate aluminum alloys. Their research addressed the heat transfer and melt pool dynamics in welding aluminum, examining keyhole and melt pool mechanisms and defect formation. They explored fluid flow behavior under conduction, keyhole, and transition modes. By comparing their findings on aluminum alloys to results for stainless steel [170,201,202], they detailed differences in driving forces for the melt pool and keyhole. Another notable contribution came from Komen et al., who used X-ray imaging to investigate porosity formation in submerged arc welding (SAW) processes. Their results revealed changes in the melt pool profile and droplet transfer behavior from the wire, offering insights into porosity formation mechanisms [203].

Figure 24 (from [200]) illustrates the changes in keyhole channel morphology with variations in welding current. It reveals how changes in heat input and plasma column density affect keyhole dimensions, particularly the top and bottom surfaces in the welding keyhole mode. These alterations influence the inclination angle of the front side, thereby modifying plasma flow components. The study concluded that plasma flow dynamics, leading to changes in shear force, are the dominant driving force in plasma keyhole arc welding. Figure 25 (from [170]) presents a 3D visualization of the melt pool and fluid flow dynamics in arc welding of aluminum. The research captured comprehensive melt pool dynamics, fluid velocity, and convection patterns using two synchronized X-ray facilities at Osaka University. This enabled multi-aspect analysis of phenomena, offering a superior advantage not achieved by any other X-ray facility worldwide.

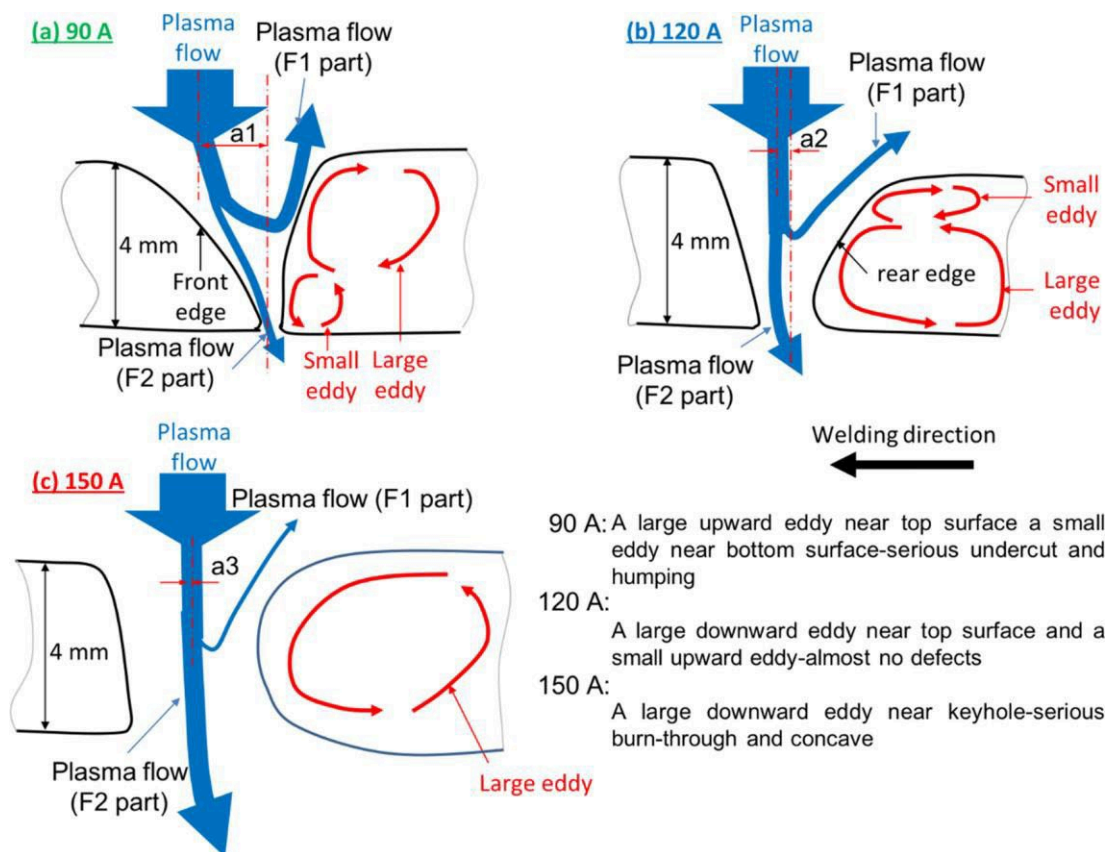
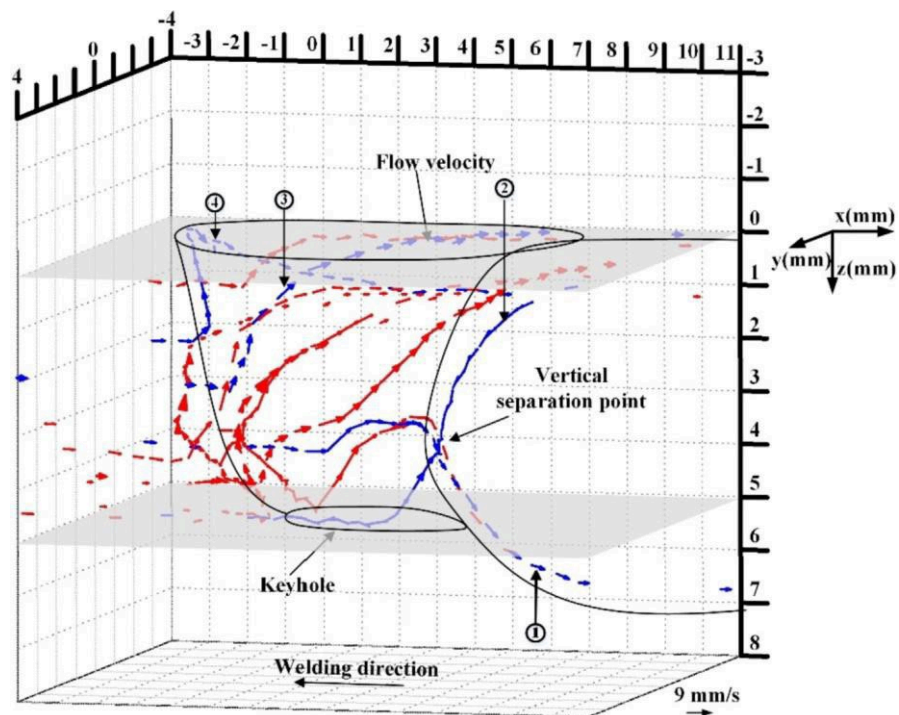


Figure 24. A schematic of keyhole channel and fluid eddies in Plasma keyhole arc welding for stainless steel [200].



(a) 3D flow velocity

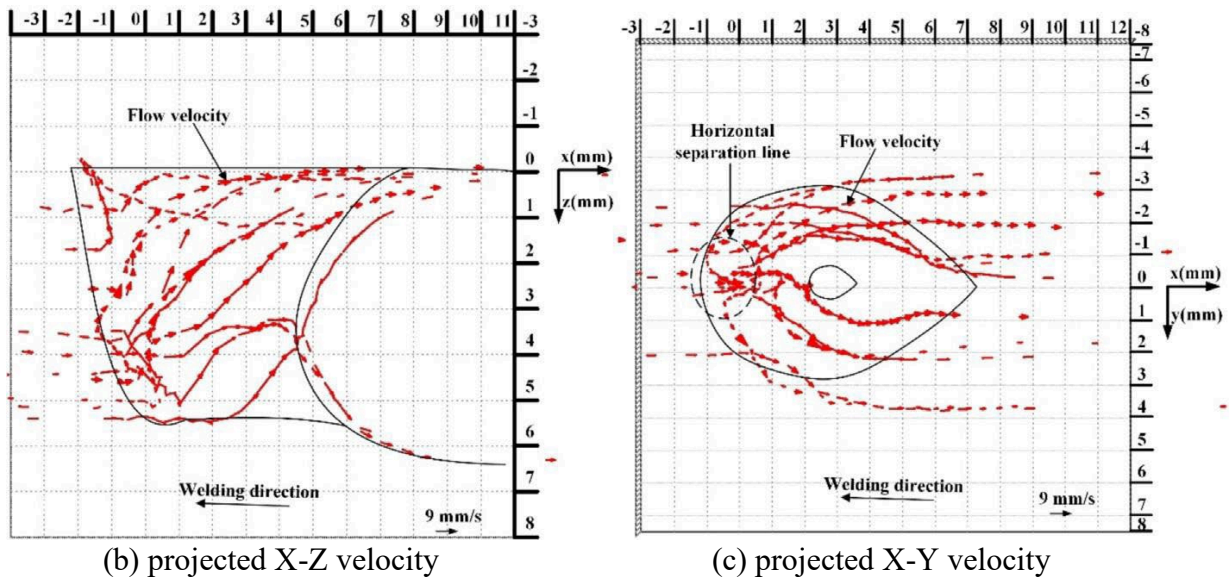


Figure 25. 3D flow velocity and melt pool dynamic in welding for VPPA welding of aluminium alloy [170].

2.2. Tao Sun group

Tao Sun and his group used the X-ray synchrotron facility at APS in the US to explore significant phenomena and mechanisms in laser powder bed AM processes. In a series of papers, they examined fundamental physical phenomena such as melt pool dynamics, fluid flow, powder movement, internal defects, and solidification for the first time. They proposed that among the driving forces in laser processes, Marangoni force, and recoil pressure are the dominant factors controlling these phenomena [26]. Escano et al. investigated the powder-spreading process of 316L material in another study. Using an X-ray source, they measured powder speed, but only 2D images were obtained, leading to significant velocity estimation errors [47]. Another series of papers from this group discussed differences in melt pool dynamics under both melting mode and keyhole mode in the LPB process. They proposed a keyhole formation threshold to distinguish between these modes. In a paper published in Scientific Reports, Cang Zhao and Tao Sun observed melt pool dynamics, estimated projected velocities, and predicted solidification rates and phase transformations in the LPB process for Ti-6Al-4V materials [46]. Niranjan D. Parab (2018) further explored evaporation, melt pool dynamics, and powder spatter ejection during an LPB process, contrasting Zhao's 2017 work on spot welding [32]. Quilin's 2018 paper presented detailed discussions on powder spatter in the LPB process [204]. Andrew's 2019 paper examined the relationship between melt pool dynamics and steel chrome-molybdenum melt pools' size (depth and width) [205]. In 2019, Brodan used a laser source to re-melt the surfaces of samples produced via LPB processes [206]. Zhao (2019) investigated the mechanism behind spatter phenomena in LPB processes [207]. In a paper published in Science,

Cunningham summarized the Tao Sun group's findings on keyhole formation mechanisms in LPB, focusing on vapor depression, laser power effects, and keyhole evolution over time [208]. S. Mohammad H. Hojjatzadeh et al. (2019) considered keyhole and melt pool formation and developed a simulation model to study pore evolution in LPB [209]. Nadia Kouraytem et al. developed a simulation model describing changes in the keyhole channel with varying printing parameters. They also observed melt pool dynamics and morphology to validate their numerical simulation model [210]. In a technical report, Niranjana D. Parab et al. (2019) used X-ray imaging to analyze keyhole morphology. They highlighted the importance of combining it with an IR camera to understand complex LPB mechanisms [211]. Another study by Parab et al. summarized the use of X-ray synchrotron imaging for observing melt pool dynamics in LPB processes [212]. Qilin et al. discussed how variations in heat input, such as laser scanning speed and power, influence welding modes (melting, transition, or keyhole) and compression volume changes [213]. A conference paper by Samantha Webster et al. (2019) introduced porosity, keyhole, and melt pool dynamics during the Laser DED process [214]. Building on this, Sarah J. Wolff et al. (2019) comprehensively discussed porosity evolution in Laser DED for Ti-6Al-4V using X-ray synchrotron images, examining spatter, powder blow, and other factors [215]. Brian J. Simonds et al. (2019) investigated keyhole formation, particularly keyhole depth, as influenced by laser heat absorption during transitions from conduction to keyhole modes. They also studied how keyhole width and depth changed with absorption rates [216]. Cang Zhao et al. (2020) explored pore formation and keyhole instability in LPB for Ti-6Al-4V powder, linking keyhole shape changes driven by forces to pore formation. X-ray images provided detailed tracking of pore movement and size [217]. S. Mohammad H. Hojjatzadeh et al. (2020) elucidated pore formation mechanisms in the LPB process for powders like AlSi10Mg and Ti-6Al-4V. They identified three mechanisms: (1) pore trapping by surface fluctuations, (2) pore formation due to shallow depression zone fluctuations, and (3) pore formation from cracks [218]. In another publication, Qilin Guo et al. (2020) discussed melt flow in the LPB process using APS beamline 32 for two materials, AlSi10Mg and Al-6061, with tungsten particles (5 μm diameter) as tracers. The results revealed a comprehensive melt pool flow, and the melt flow velocity was calculated. They also analyzed the melt flow changes driven by the Marangoni force, hydraulic pressure, and buoyancy force [219]. In another publication, Sarah J. Wolff et al. (2020) investigated the influence of external electromagnetic fields on the keyhole and melt pool formation in the laser welding process for 4140 sheets of steel with a thickness of 300 μm . The results showed significant changes in melt pool depth when external electromagnetic fields were applied [220]. Xuxiao Li et al. (2020) developed a simulation model for powder movement and its interaction with melt pool formation in the LPB process. X-ray experimental data were used to validate the simulation model [221]. Zachary A. Young et al. (2020) identified five types of spatters in the LPB process for AlSi10Mg materials, using ultra-high frame rates of 45,259 fps and 135,776

fps. The spatters included solid spatter, metallic jet spatter, agglomeration spatter, entrainment melting spatter, and defect-induced spatter. The mechanisms behind these spatters and prevention methods were discussed in detail. The findings provide critical insights for engineers developing simulation models and optimizing process parameters to improve LPB process quality [222]. Benjamin Gould et al. (2021) conducted experiments using an IR camera and X-ray synchrotron images to capture melt pool dynamics and powder movement in the LPB process for tungsten and Ti6Al4V materials at APS Beamline 32. The IR camera operated at 90,000 fps, while the X-ray high-speed camera ran at 50,000 fps. Initial results revealed multiple physical phenomena in the LPBF process, quantified with high thermal, spatial, and temporal resolution. Observations of temperature variations, vapor plume dynamics, solidification, and possible supercooling and recalescence provided valuable insights [223]. Brian J. Simonds et al. (2021) examined the correlation between laser power absorption rates and melt pool dynamics, noting abnormal absorption rate changes during keyhole regime transitions [224]. Hojjatzadeh SMH et al. (2021) studied pore formation and dynamics during the LPB process using pulsed waves for Al6061 powder and a Ti6Al4V substrate without powder. Results showed that vapor depression collapse upon laser irradiation cessation led to discontinuous pore formation. Additionally, melt ejection and rapid solidification contributed to pore formation in the melted track [225]. Sarah J. Wolff et al. (2021) investigated the influence of powder feed rates on the Laser DED AM process. Two feed rates, high and low, were applied, showing that higher rates reduced laser absorption and shifted from the keyhole to melt mode. However, this reduced powder melting efficiency and increased porosity [226]. Zhengtao Gan et al. (2021) comprehensively analyzed keyhole and melt pool dynamics, defining keyhole regimes and porosity through mathematical functions. A database of experimental results supported the development of mathematical models predicting keyhole and pore stability [227]. I. Bitharas et al. (2022) observed vapor-liquid-solid phase interactions in the LPB process for Ti6Al4V powder. They detailed keyhole formation timelines, plume progression, and depression behavior. The relationship between keyhole wall angles and input energy density was also examined [228]. Cang Zhao et al. (2022) explored the physical mechanisms behind laser melting modes (conduction, keyhole, and transition). The keyhole morphology (depth and width), energy density, and scanning velocity were analyzed over time. Using a power-velocity map, they identified regimes for defect-free operation and optimal quality [229]. Luis I. Escano et al. (2022) published the first study using X-ray synchrotron images for Electron Beam AM processes of Ti6Al4V. They integrated an operational Electron Beam facility with the APS X-ray facility, capturing melt pool temperature distribution with a thermal camera. Initial results demonstrated melt pool morphology and dynamic phase evolution observation capabilities [230]. Luis I. Escano et al. (2022) examined powder spreading dynamics in the LPB process at 500,000 fps in another study. Using a mixture of 90% AlSi10Mg and 10% Ti powders, with a spreading speed of 137 mm/s

and a layer thickness of 90 μm , the powder moved at an average speed of 88 mm/s in the spreading direction [231]. Marc Nielsen et al. (2022) developed an innovative algorithm for detecting melt pool boundaries in the LPB process using high-speed X-ray synchrotron images. This AI/ML approach replaces manual detection and significantly reduces time, labor, and computational costs [232]. Samantha Webster et al. (2022) created a novel high-throughput drum that allows the simultaneous printing of 32 samples during the Laser DED process setup. This innovation dramatically reduces resource demands, making beamline experiments more efficient [233]. Brian J. Simonds et al. (2024) from NIST summarized eight challenges in the metal AM process, focusing on LPB processes. These challenges include predicting laser power absorption and phenomena like keyhole and melt pool behavior, defect formation, solidification, and phase evolution [234]. Figure 26 presents typical results of the melt pool and keyhole during the LPB process of Tao Sun's group. Clear keyhole and melt pool boundaries are observed due to APS X-ray beamline brilliance and thin layer thicknesses ($<1\text{ mm}$). This beamline outperforms traditional X-ray facilities (Figure 29) and the SSRL beamline at Stanford (Figure 30).

Figure 26 illustrates the evolution of the melt pool and keyhole during laser melting in a stationary scenario. Initially, the melt pool forms as a tiny structure, then expands and evolves until reaching a stable vapor depression state. Concurrently, the shape of the keyhole and melt pool transitions from a quasi-semicircular form to a bimodal configuration, featuring a bowl at the top and a spike at the bottom.

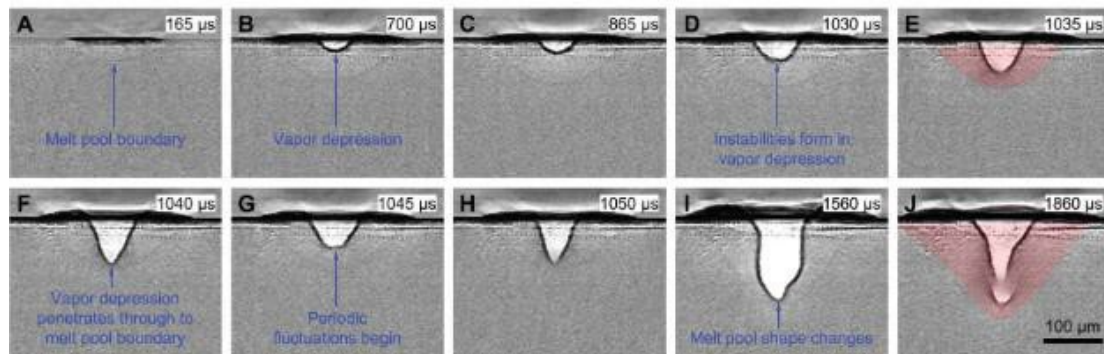


Figure 26. The melt pool and keyhole dynamic in the LPB process with X-ray imaging at the APS X-ray facility [208].

2.3. Peter Lee group

Using an independent investigation similar to the Tao Sun group, Peter Lee and his team investigated melt pool dynamics, keyhole formation, heat transfer, and defects in the LPB process. Similar results were observed for both single-layer and multi-layer LPB processes. The first paper from this group was published in 2018 by Chulun Alex

Leong (Chulun), a PhD student from this group. Before that, Chulun's PhD thesis was completed in 2017 [49]. The results of this thesis were presented at conferences in materials science and manufacturing processes in 2017 [235,236]. From this PhD thesis contents, this group and other groups worldwide explored a series of papers and investigations using X-ray synchrotrons. Chulun et al., 2018, published the first paper examining laser-matter interaction in the LPB process of mixture powders SS316L and 13-93 bioactive glass. This experiment was conducted at the UK's Diamond Centre X-ray synchrotron facility with an operand LPB system. Due to low viscosity, the authors explained that SS316L powder forms pores and spatter. Still, including 13-93 bioactive glass powder with high viscosity mitigates pore movement in SS316L, combining them into larger pore groups—up to 600 times larger than those in SS316L powder [237]. In another publication, Chulun et al., 2018, observed melt pool dynamics, pore, and powder spatter formation and evolution in another paper. They tracked their trajectories to study tendencies and estimate velocities. The results showed that laser-induced gas/vapor jets promote powder spatter formation, and the Marangoni force is key in controlling fluid flow and pore formation. Although their experiments were independent of the Tao Sun group in the US, the results were comparable [238]. In another publication, Yunhui Chen et al. discussed keyhole formation with four main stages and its linkage to pore and spatter formation using X-ray beamline 12 at the Diamond Centre in the UK. The spatter velocity was calculated, with a maximum velocity of about 2.2 m/s [239]. In Yunhui Chen et al., 2020, the formation of the keyhole, melt pool, pore, and spatter in the laser DED process was estimated and discussed for SS316L and Ti6242 powders. A comparison was made, highlighting differences due to the oxidation layer on the Ti alloy surface [240]. Other papers presented at the IOP Conference of Material Science and Engineering by Yunhui Chen and S.J. Clark discussed keyhole and melt pool morphology in the Laser DED process. They used tungsten particles to track fluid flow in the melt pool, identifying the activation of the Marangoni force [241]. Lorna Sinclair et al., 2020, explored porosity and pore formation in multilayer LPB processes of Ti6Al4V powder using “in-situ” X-ray synchrotron radiography at beamline ID19 of ESRF and “ex-situ” computed tomography at the Diamond Centre, UK. Results revealed three pore phenomena: (i) healing of previous layers' pores via remelting, (ii) insufficient laser penetration to remelt and heal pores, and (iii) keyhole-induced pores merging with existing pores, enlarging them [242]. In 2021, Yunhui Chen conducted experiments on the laser-blown DED process with IN718 powder. Using both "in-situ" X-ray radiography and diffraction images, phenomena related to solidification, phase formation, and melt pool fluid flow were explored. The Marangoni force was confirmed as the primary driving force, with tungsten particles used to track flow. Phases like Laves, MC carbides, and gamma were analyzed via X-ray diffraction, and stress distribution in the melt track was examined. However, no detailed discussion on melt pool formation mechanisms under driving forces was included [243]. In another 2021 publication, Yunhui Chen et al.

investigated surface roughness, melt flow dynamics, and build stage direction in laser-blown DED processes for multilayer printing. They varied printing parameters like scanning speed, laser power, and powder feed rate. Results showed that higher laser power increases surface roughness, higher scanning speed reduces it, and increased powder feed rates heighten surface roughness [244]. Lorenzo Massimi et al., 2021, proposed a beam-tracking X-ray imaging method, providing absorption, phase, and angle scattering signals at high frame rates. This technique enabled early segmentation of droplets, tracking powder dynamics, and elucidating unmelted powder amounts [245]. Chu Lun Alex Leung et al. experimented at Beamline I12 of the Diamond Centre in the UK using X-ray radiography and computed tomography in the LPB process for IN625 powder. A range of specific energy levels was used to analyze melt pool and keyhole dynamics, porosity, and pore evolution. A simulation model was developed to complement experimental data, showing the melt pool dynamics, keyhole, and defects. Mathematical equations were presented linking factors like pore growth, melt pool volume, and surface roughness [246]. Yuze Hoang et al., 2022, examined pore formation mechanisms during LPB processes for Al7A77 powder using the X-ray synchrotron beamline 32-ID-B of APS in the US. They divided keyhole formation into stages, discussing stability, instability, and pore formation. The study proposed that porosity forms during keyhole instability and collapse, driven by pressure equilibration and vapor condensation [247]. Gowtham Soundarapandiyam et al., 2023, studied the impact of powder contamination in recycling processes for Ti6Al4V in LPB. Higher oxygen content in powder reduced spatter, increased surface accuracy, and decreased defects while increasing microhardness due to solid solution strengthening [248]. Tristan G. Fleming et al., 2023, presented a novel observation method for melt pool and keyhole in laser welding of aluminum alloys using X-ray radiography and Inline Coherent Imaging (ICI). While ICI and X-ray radiography showed differing results under multiple imaging light reflections, matching results were observed for bubble formation measurements [249]. Finally, Daguo et al., 2024, analyzed the linkage between vapor depression shape and spatter dynamics in LPB for aluminum alloys using X-ray synchrotron imaging. They revealed how Kelvin-Helmholtz's instability and Marangoni's force drive spatter formation. Kai Zhang et al., 2024, discussed pore evolution mechanisms in Laser DED processes for Ni-based superalloy RR1000, proposing a simulation model tracking pore dynamics and detailing five stages of pore evolution [251]. Figure 27 is a typical example of melt pool dynamic and morphology in a laser powder-blown DED process observed by X-ray synchrotron at ESRF in France. In this paper, the authors observed the movement of bubbles (pore/porosity) with the melt pool dynamic and explained the mechanism to form them in detail. A typical result of the keyhole and melt pool dynamic along the time in the LPB process with X-ray imaging is presented in Figure 27. In the evolution and dynamic of the keyhole and melt pool process, the authors have devised them in terms of three statuses: (I) quasi-stable, (II) transition, and (III) unstable regimes.

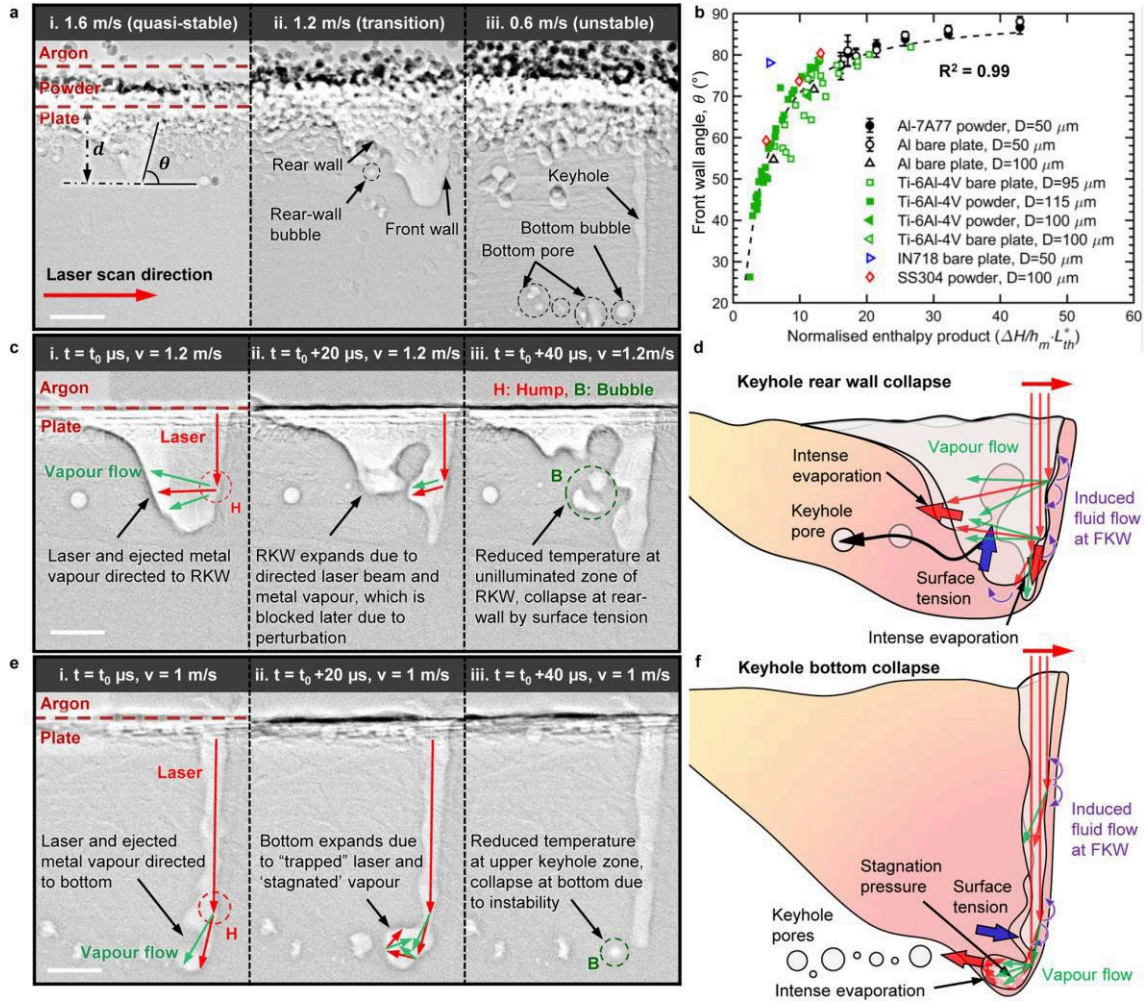


Figure 27. Keyhole and melt pool dynamic in LPB process [247]. Keyhole collapse mechanism and related keyhole melting regime transitions in LPBF. (a) Keyhole morphology variations from wide and shallow to narrow and deep across the (I) quasi-stable, (II) transition and (III) unstable keyhole regimes under different laser scan velocities. (b) Front keyhole wall (FKW) angle as a function of normalized enthalpy product for 9 datasets with four different materials. (c) Radiographs of laser melting with a bare aluminum plate in (II) transition regime, showing rear keyhole wall collapse with associated illustration (d). (e) Radiographs of laser melting with a bare aluminum plate in (III) unstable regime, showing keyhole bottom collapse with associated illustration (f). t_0 is the time of the captured frame before the RKW or bottom keyhole expands. The red, blue, and green arrows in d and f represent the laser beam, fluid flow, and vapor flow, respectively. d and θ represent the keyhole depth and FKW angle, respectively.

2.4. S. Van Petege group

Unlike the publications from Peter Lee's and Tao Sun's groups, S. Van Petege's team investigated melt pool dynamics and keyhole evolution in LPB processes using external sensors and acoustic signals synchronized with X-ray imaging frames. An example of their findings is illustrated in Figure 28 [255]. Prof. S. Van Petege and his group focused on diagnosing fluid flow, cracking defects, and phase transfer in LPB processes using an operando LPB system integrated into an X-ray radiation facility at the Swiss Light Source. In a 2016 publication, C. Kenel et al. observed the behavior of Ti-48Al alloy during heating and solidification using two laser heat sources and a micro-X-ray diffraction facility. They observed solidification and phase transfer, noting that upon solidification, the formation of the β -phase was fully suppressed [252]. Samy Hocine et al. (2020) reported a novel operando LBP system integrated into an X-ray diffraction facility to observe the evolution of phase transfer and microstructure in the Ti6Al4V powder process. This experiment was conducted at the Swiss Light Source [253]. Hossein Ghasemi-Tabasi et al. (2022) used this operando LBP system integrated with the X-ray radiation facility at the Swiss Light Source to directly observe the formation of cracks in the case of CM247LC nickel-based superalloy powder, with the printing parameter fixed at a typical value [254]. Milad Hamidi Nasab et al. (2023) observed the stability and instability of the melt pool and the formation of pores in the LBP process of Ti6Al4V powder using the operando system developed in previous studies. They also estimated laser absorption during the process to create the melted and keyhole modes by analyzing acoustic signatures from a high-sensitivity optical microphone to assess the changes in stability and instability of each mode [255]. An example of their results is shown in Figure 28. In another investigation, Charlotte de Formanoir et al. used high-sensitivity optical microphone signatures to detect porosity during the LBP process in a remelted mode. This study aimed to understand and control the keyhole defect in the LPB process to ensure high-quality printing [256]. In a separate publication, Jian Yang et al. (2024) predicted the Marangoni flow in the LPB process of 316L powder during the transition from conduction mode to keyhole mode with changes in laser power and scanning speed. They detected the fluid flow in a projected plane using tracking particles and then estimated its velocity [257].

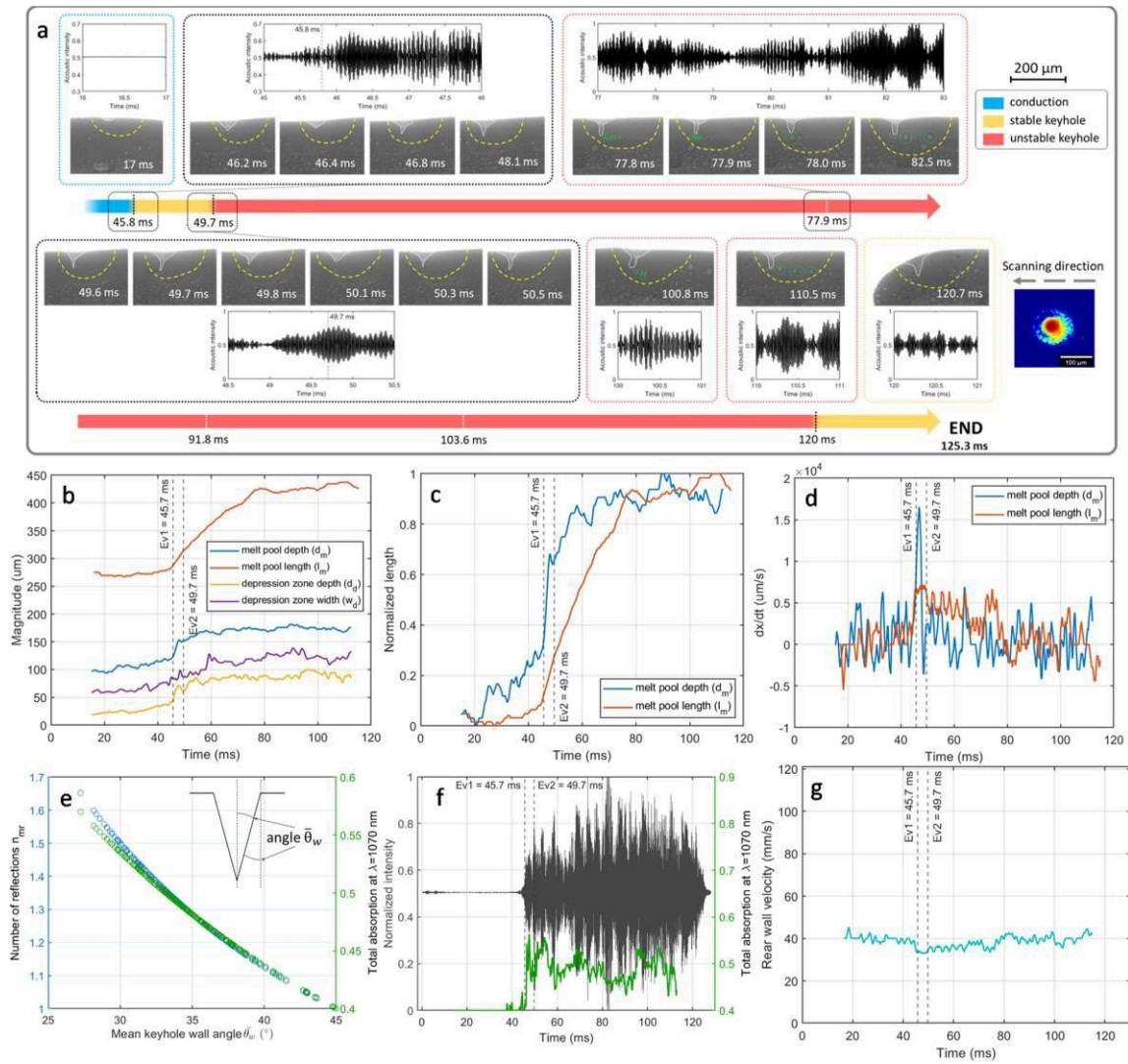


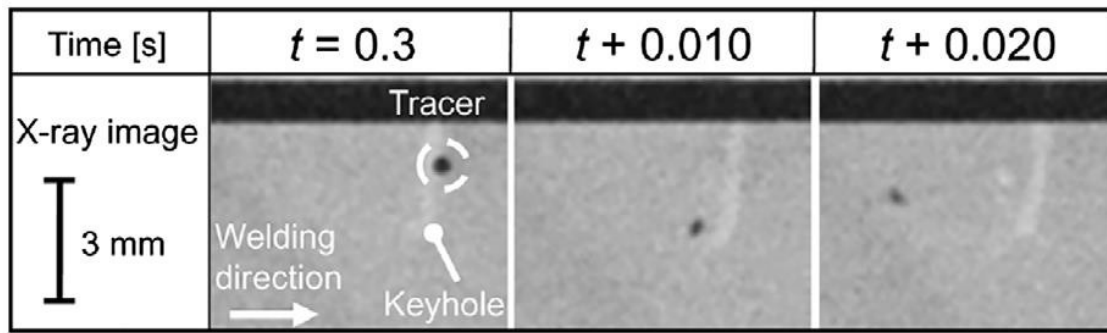
Figure 28. Investigate the keyhole and melt pool dynamic by using external sensors and acoustic signals synchronized with X-ray imaging frames [255]. **a)** Melt pool morphology variation under constant laser process parameters in a single scanning vector of 316L stainless steel. The normalized and filtered acoustic signal for each time frame is illustrated for each image set with event annotations represented by vertical lines. The boundaries of solid-liquid (melt pool) and gas-liquid (depression zone) are illustrated by yellow and white dashed lines, respectively. The time bar depicts the regime changes from conduction to stable keyhole ($t = 20$ ms), stable keyhole back to conduction ($t = 21.1$ ms), conduction to unstable keyhole ($t = 23.4$ ms), and unstable keyhole back to conduction ($t = 41.2$ ms). The resultant pores in the unstable keyhole regime in the vicinity of each timeline are encircled by dashed green lines. The scale bar for all the images is shown in the bottom right corner. **b)** Melt pool length, depth, keyhole depth, and widths at the top of the depression throughout the scanning vector. **c)** The normalized magnitude of melt pool length and depth over the scanning vector. **d)** The first derivative of the melt pool length and depth magnitude over time. **e)** Relations between mean keyhole wall angle and the number of laser reflections

and total energy absorption. **f)** Superimposition of total energy absorption evolution and the normalized and filtered acoustic signal (band-pass: 35–105 kHz). **g)** Melt pool rear wall velocity is measured via summation of laser velocity and melt pool length variations over time.

2.5. Katayama group

Katayama and his colleagues were the first group in the world to use “in-situ” X-ray images to observe melt pool dynamics and defects in the welding process. Their first publication on this topic was presented at ICALEO in the US in 1998 [43]. From the 1990s to the 2000s, his team published a series of papers on laser welding processes related to this topic. One of the earliest papers on melt pool dynamics in laser welding was by Akira Matsunawa et al. in 1998 and 2000 [43,44]. They observed the melt pool flow and calculated its velocity using tungsten particles. Based on “in-situ” X-ray images, they discussed the phenomenon of porosity and ways to prevent it [258,259]. Subsequently, this group significantly focused on the use of “in-situ” X-ray images for arc welding and laser welding processes, publishing numerous papers on three key topics: melt pool dynamics and heat transfer, fluid flow and velocity, and defects in welding processes (such as porosity, cracking, spatter, and solidification) [260,261]. In 2011, Hitachi Corporation developed a novel X-ray facility with two X-ray sources to capture 3D images of the melt pool. This is the only X-ray system in the world capable of visualizing 3D melt pool dynamics in welding and additive manufacturing processes. In 2015, this group was the first to use the new X-ray facility with two integrated and synchronized X-ray sources to observe the melt pool and spatter in laser welding for titanium materials [262]. From that period, this X-ray facility has produced a series of publications on this topic [28,263,264,265,266,267,268,269].

By using tiny tungsten particles as trackers, the Katayama group observed the melt pool, keyhole, and heat transfer during the laser welding process. The movement of tungsten particles was detected and analyzed to understand the physical phenomena and estimate regime changes at each frame of X-ray imaging. A typical example is presented in Figure 29. However, a significant challenge with this approach is that the particle size can influence movement. If the particles are sufficiently heavy, they may sink to the bottom surface and move downward rather than upward, following the fluid flow.



(a) Micro- focused X-ray transmission images

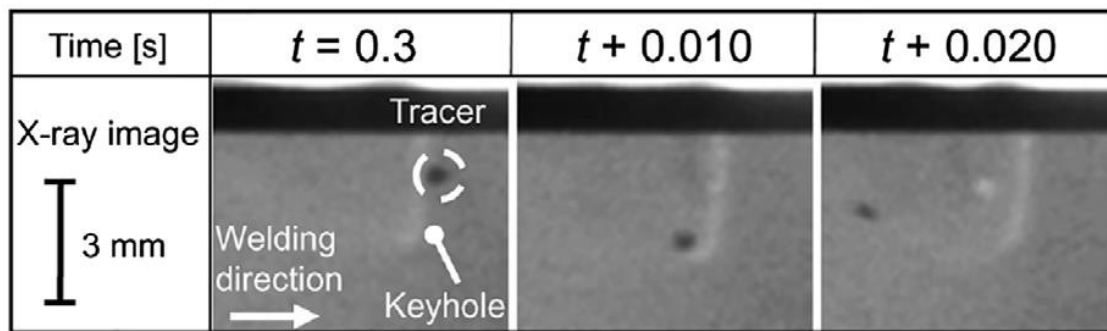


Figure 29. Melt pool and keyhole dynamic in laser welding by mini-focused X-ray imaging of Ossaka University [263].

2.6. Manyalibo Matthews group

Manyalibo Matthews and his group used a similar approach to the Tao Sun and Petter Lee groups. They utilized the X-ray facilities at the Stanford Synchrotron Radiation Lightsource (SSRL) and APS to observe melt pool dynamics, keyhole phenomena, and internal defects in LPB processes with a mini-operando LBP system. Nicholas P. Calta et al. published a paper in 2018, introducing a novel LBP system integrated with the X-ray facility at SSRL [48]. Meanwhile, Andrew M. Kiss et al. (2019) observed the depth and dynamic behavior of the vapor depression at different scanning speeds. Due to the low power of the X-ray facility, only the keyhole evolution was explored over time at varying scanning speeds [180]. In another study, Aiden A. Martin et al. (2019) considered the vapor depression and melt pool dynamics, along with the movement of pores in the LBP process for Aluminum alloy Al6061 (635 μm thick) and Titanium alloy Ti-6Al-4V (508 μm thick), using a laser power of 400 W and a scan speed of 800 mm/s under high vacuum. The results showed that pores with a size of around 20 μm were found in the case of aluminum [270]. In another publication, Nicholas P. Calta et al. (2020) conducted an LBP experiment for 316L steel, nickel alloy, aluminum alloy, and titanium alloy, with a change in scanning speed. They reported on the evolution of the keyhole and melt pool dynamics, discussing the changes in keyhole depth and width

with the change in melt pool size based on the variation in heat input and the control of the Marangoni force [271]. In another study, Aiden A. Martin et al. observed the movement of pores and melt pool dynamics during the LBP of Ti6Al4V materials [272]. Figure 30 shows the melt pool and keyhole dynamic in the LPB process. Experiments have been performed at the SSRL x-ray facility with a frame rate of 4000 fps.

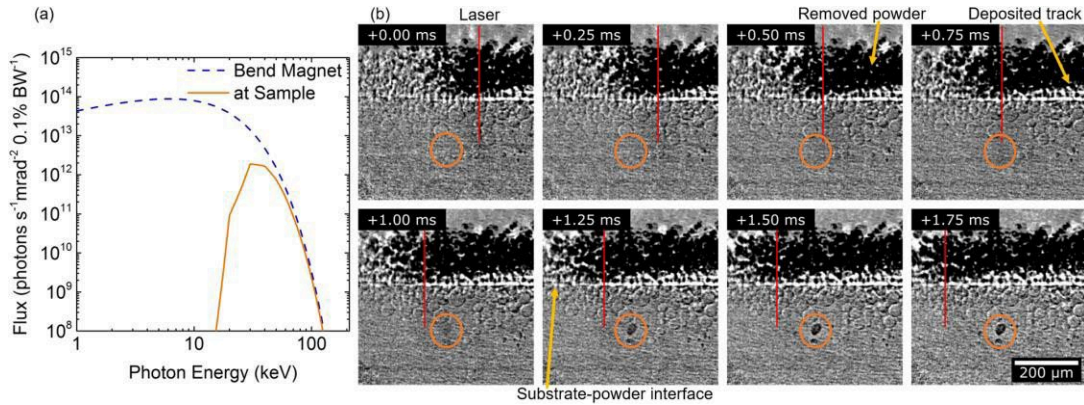


Figure 30. Melt pool dynamic in LPB process with SSRL X-ray facility [48]. X-ray imaging of a typical melt pool region. (a) Simulated X-ray spectra produced at SSRL beamline 2-2, used for imaging. Both the full emission from the bend magnet and the attenuated spectrum experienced at the sample are shown. (b) A series of frames collected at 4 kHz during a scan. Each frame shows the absorption difference $A(t) - A(t_0)$ such that darker regions represent decreases in absorption (or material) and lighter regions represent increases in absorption (or material). The t_0 frame was collected before +0.00 ms and is not shown. The laser moves from right to left, and the approximate location (within $\sim 50 \mu\text{m}$) is marked with a red line. A void, circled in orange, forms beginning in the +1.00 ms frame.

2.7. Thomas Graf group

A group led by Prof. Thomas Graf from the University of Stuttgart in Germany has conducted numerous experiments using X-ray images for welding processes, and more recently, for metal additive manufacturing processes [273,274,275,276,277]. Starting in 2011, they used a mini-focus X-ray facility, and from 2020 onward, they utilized the X-ray synchrotron facility at DESY for several recent papers. In a paper published in 2013, A. Heider et al. observed spatter in laser welding of copper material using a mini-focus X-ray radiography system, combined with high-speed camera images. They discussed the instability of this welding process due to keyhole formation [278]. In another publication, Florian Fetzer et al. (2018) examined pore formation in laser welding of AlMgSi alloy by varying beam oscillation [279]. In a separate study, Jonas Wagner et al. applied a high-power X-ray radiation facility at DESY to observe the keyhole and

melt pool during welding of several types of aluminum (see Figure 31) [280]. In another publication, Jonas Wagner et al. (2024) investigated the transition of the welding mode from partially melted to fully melted, from the start of welding to full penetration, using X-ray radiography images. This study is related to the absorption of X-rays when the keyhole forms. The absorption decreases suddenly when an open hole appears at the bottom of the metal pool [281].

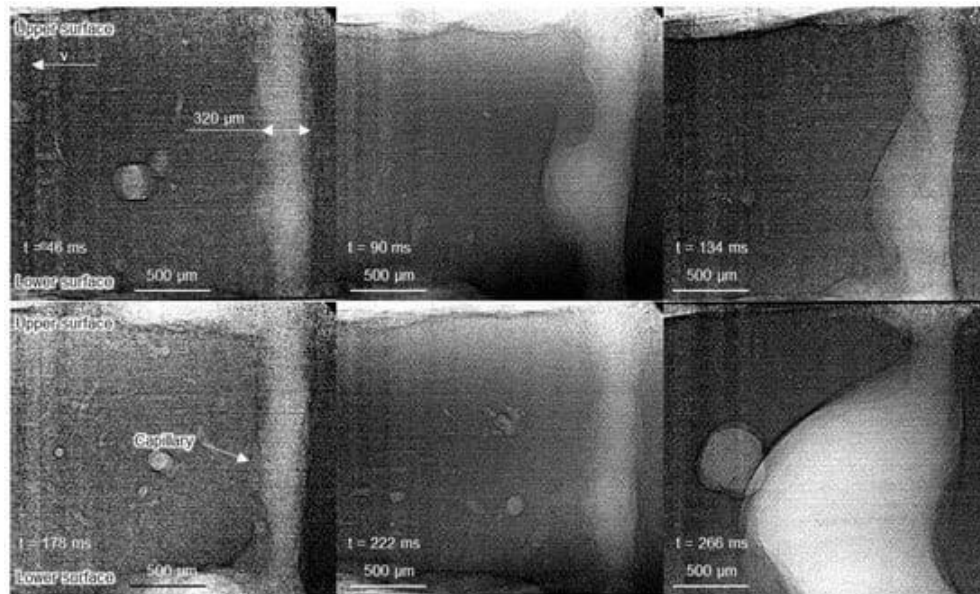


Figure 31. Single frames at different times from a high-speed X-ray video of laser beam welding of AA5754 with $P = 2.1$ kW, $df = 102$ μm , $ss = 2$ m [280].

2.8. Other groups

In addition, several other researchers have focused on the melt pool in TIG welding and other welding processes using “in-situ” X-ray images. Hongbiao Dong et al. (2020) studied the changes in melt pool morphology (size and dimensions) and fluid flow when oxygen is mixed with shielding gas in TIG welding (see Figure 32). The results in this paper were captured at the beginning of the process when the arc is started and the melt pool is progressing toward expansion. However, these results do not represent actual welding, as the dynamics correspond to a stationary case. Therefore, the phenomena observed in this case can be referenced as a research scenario rather than a real-world application [107]. In a similar TIG welding stationary case publication, Fan Wu et al. (2022) examined the melt pool width, depth, and volume. The movement of tungsten particles in the melt pool was also detected to estimate the velocity and acceleration of fluid flow. However, the results may not be entirely realistic because only one X-ray source was used, capturing a 2D projected melt pool [179]. In another study, Fan Wu et al. (2023) reported forming an interface in dissimilar aluminum and steel welding. They

also developed a simulation model to estimate fluid flow velocity in the melt pool [282]. In a different context, Chinese researchers used the Shanghai X-ray synchrotron radiation facility (SSRF) to observe fluid flow in underwater welding processes. Recently, several publications on welding processes from this facility have been published. One paper by Hang Xu et al. (2019) focused on the melt pool dynamics in underwater welding and compared the melt pool boundary between welding onshore and offshore, with and without the support of external ultrasonic waves [112]. The paper showed significant differences in melt pool morphology across these cases. Changsheng Xu et al. (2019) reported an investigation using X-ray images of the underwater welding process. They observed the melt pool dynamics and boundary flow over time, then applied an external ultrasonic source and compared it to the case without it. The stability of the melt pool was significantly improved [283]. In another publication, Shuya Zhang et al. (2024) reported on pore evolution in the DED process for high-entropy alloys. They discussed the Marangoni force as the main driving force controlling fluid flow, estimated the width and depth of the melt pool, and calculated the fluid flow velocity in the melt pool. The movement of the pores was also estimated [284]. Another publication on welding ultra-thin sheets for semiconductors by a group of researchers from Penn State University focused on dissimilar joints of aluminum and copper in manufacturing lithium batteries. They observed the melt pool dynamics using X-ray from the APS X-ray facility. Instead of relying on tracking technologies, they developed a simulation model to validate the experiment and estimate the flow velocity [285].

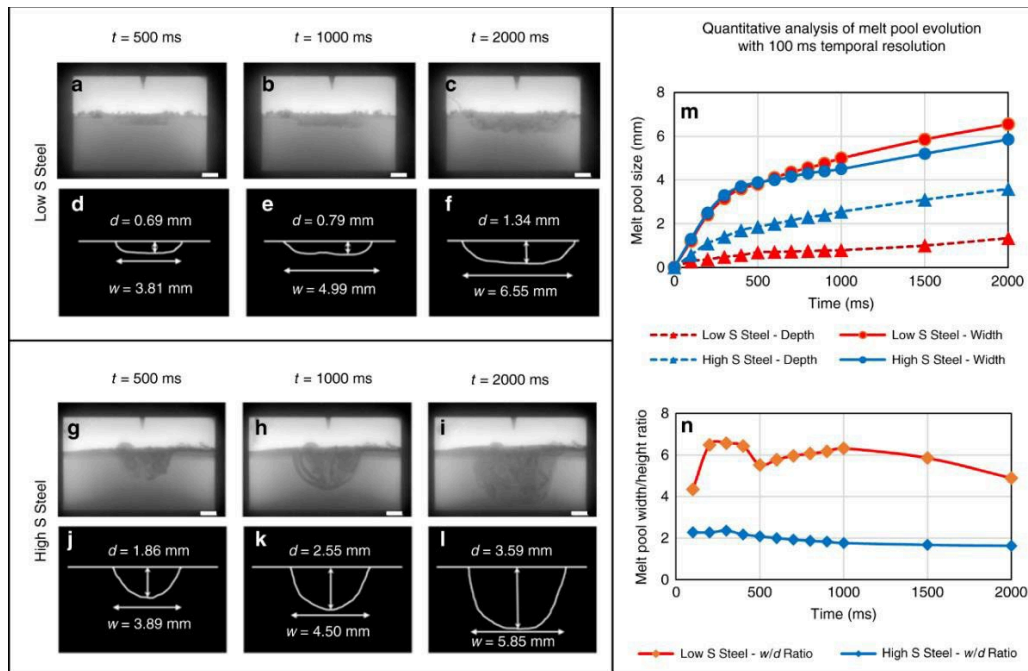


Figure 30. Melt pool dynamic in the case of stationary TIG welding additive manufacturing [107].

2.9. Other phenomena of melt pool, keyhole dynamic and heat transfer

In addition to investigating fundamental phenomena in traditional manufacturing processes, researchers have sought to eliminate the disadvantages and improve the final quality of conventional manufacturing processes by applying external support, such as ultrasonic vibration or electromagnetic fields. The use of external support is, therefore, an important and emerging topic. Several publications discuss the influence of external conditions on melt pool dynamics and boundaries. For instance, Changsheng Xu et al. (2019) investigated the influence of ultrasonic variation on the formation of melt pool boundaries [283]. Meanwhile, Sarah J. Wolff et al. (2020) discussed the impact of external electromagnetic force on the formation of melt pool sizes (depth and width) in laser welding of 4140 steel [286]. The results indicated that external electromagnetic force could alter the behavior of Marangoni flow and eliminate pore formation. Jared Gillespie et al. (2021) investigated the effect of ultrasonic vibration on the melt pool morphology in laser welding of Al6061 alloy [287]. Their results clearly demonstrated that external ultrasonic variation significantly affected the formation of the melt pool shape. This finding was further confirmed by another paper by Lovejoy Mutswatiwa et al. (2024) [29].

While there are numerous publications on melt pool dynamics and heat transfer in materials and manufacturing processes, most focus primarily on LPB processes. Moreover, no comprehensive studies have thoroughly examined the driving forces that control melt pool dynamics in detail. Understanding the mechanisms governing melt pool behavior and heat transfer—particularly the role of Marangoni forces and other dominant forces—is crucial, as these factors dictate cooling rates, solidification, and microstructure evolution through fluid flow dynamics. This knowledge is also essential for preventing defects by enabling the design of optimal convection patterns. Consequently, more attention should be directed toward investigating other physical phenomena and metallurgical processes in manufacturing methods such as DED-AM, casting, and furnace processes.

3. X-ray Imaging for flow velocity, convection patterns, and fluid eddies

The flow velocity of the melt pool is a critical factor in understanding the mechanisms behind the relationships among microstructure, properties, and processes [51]. Numerous studies have demonstrated that direct measurements of velocity provide more detailed insights into fluid flow and melt pool dynamics than simulations alone [288]. The flow velocity in the melt pool and droplet transfer during welding and additive manufacturing processes consists of two components. For surface flow velocity, a high-speed camera combined with laser illumination systems and tracking particles, such as zirconia particles, offers a practical approach [289,290,291]. However, surface velocity measurements are often influenced by external factors, including plasma gas, shielding gas, powder gas, and environmental conditions, which may lead to inaccuracies. In such cases, internal melt pool velocity becomes crucial for understanding the processes [117,64]. X-ray imaging provides a unique method for investigating internal flow and heat transfer due to its ability to penetrate metal. While simulation models are commonly developed to address challenges in using X-ray facilities, these models still require validation through experimental data. Thus, clarifying physical phenomena in metallurgy remains a significant research objective. Obtaining accurate fluid velocity and convection patterns from X-ray imaging poses challenges. A single X-ray source typically provides only 2D images or videos (projected images), which are insufficient for calculating velocity or estimating convection patterns and heat transfer [285]. Consequently, very few studies have successfully utilized X-ray imaging to calculate flow velocity and convection patterns in manufacturing processes, such as welding, casting, furnaces, and metal additive manufacturing (AM). The following sections analyze studies that calculated flow velocity using X-ray imaging, focusing on welding and metal additive manufacturing processes.

3.1 Welding Processes

As mentioned above, the flow velocity and melt pool dynamics are critical information as they reveal the solidification process and cooling rate, which are directly related to microstructure evolution, mechanical properties, and final quality. Researchers worldwide are intensively studying these aspects using X-ray imaging to calculate and predict flow velocity in welding processes.

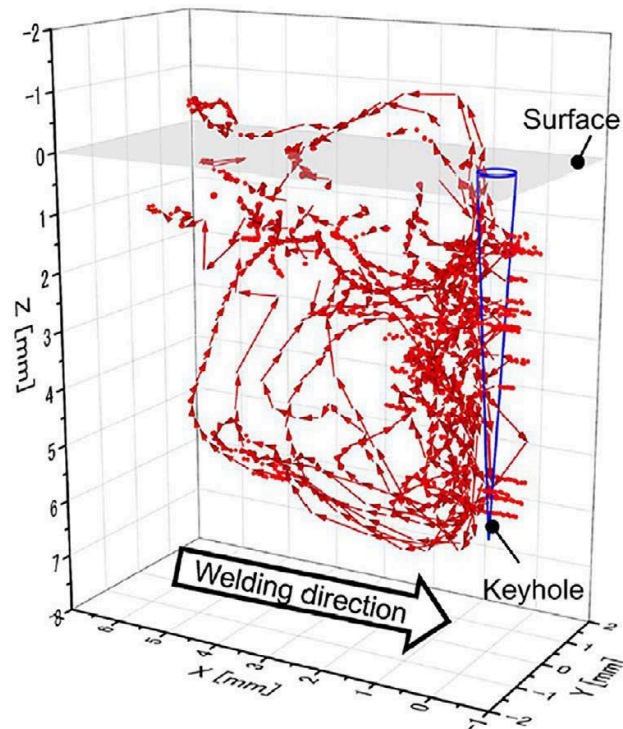
Prof. Katayama and his team focus on clarifying the formation mechanism of the melt pool in laser welding processes. Several papers have studied flow velocity in detail. Mizutani et al. (2004) conducted experiments on pure liquid zinc baths using a mini-focus X-ray facility. They observed that the velocity of bubbles moving downward in the pool was approximately 0.4–0.8 m/s, whereas their upward velocity was much smaller, at 0.001–0.04 m/s [113]. In another publication, Katayama et al. (2007)

reported the flow velocity of the melt pool during laser welding of SUS 304 for TIG welding processes using 0.11% Sn, which was 0.025–0.5 m/s [167].

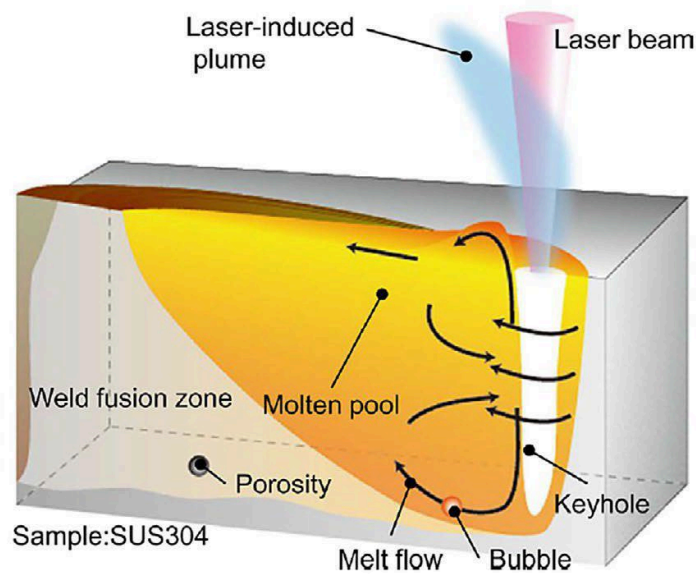
Gatzen et al. (2011) calculated fluid flow during laser welding of aluminum alloy with external magnetic stirring (see experimental setup in Figure 35) [116]. They observed varying velocities of W and Pt particles depending on the magnetic field, with a maximum velocity of about 0.45 m/s in the case of $B_0 = 120$ mT (Figure 36). Jin Peng et al. calculated the melt pool velocity during laser welding of aluminum and found it to be about 0.032–0.12 m/s at different welding speeds [28]. Similarly, Kawahito et al. (2017) measured the melt flow velocity along the keyhole wall in laser welding of SUS 304 at welding speeds of 25 to 250 mm/s, observing values between 0.24 m/s and 0.54 m/s. Notably, a novel X-ray facility with two synchronized X-ray sources was employed to capture 3D images of the melt pool and keyhole, as described in Figure 33 [263]. In a recent study, Miyagi et al. (2017) demonstrated that the melt flow velocity at the bottom surface of the keyhole wall in laser welding of aluminum alloy was higher (0.178 m/s) compared to the top surface (0.093 m/s) [264]. Kawahito et al. (2018) reported that the flow velocity, equated to bubble velocity, was 0.35 m/s at the real keyhole, 0.24 m/s at the front keyhole, and 0.11 m/s at the butted interface in aluminum butt-joints [265]. Additionally, Morisada et al. (2011) estimated the flow velocity by tracking tungsten particles during the friction stir welding process of aluminum alloy. They observed a maximal particle velocity of 0.35 m/s at a 5 mm distance from the probe's center [67].

Van Anh and Tanaka and his team from Osaka University in Japan investigated melt pool formation and its relationship to defects using in-situ X-ray imaging. Their comprehensive experiments, supported by X-ray facilities, high-speed cameras, and thermal cameras, used zirconia and W particles to track melt pool dynamics (size, width, length, depth), flow velocity (maximum velocity, velocity contours, etc.), eddy formation, and their linkage to defects and final quality in plasma keyhole arc welding. They found that the fluid flow velocity on the melt pool's surface, measured by high-speed cameras, was higher than the internal fluid flow. This discrepancy was attributed to shear forces and shielding gas effects on the surface, as zirconia particles are minimally in contact with the liquid surface while primarily interacting with the air. They also observed that the highest velocities occurred at the top or bottom surface along the keyhole wall due to strong shear forces. Additionally, they linked higher melt pool velocity and backward melt flow movement as primary causes of undercut phenomena in PKAW [64,198,199]. Figure 34 summarizes comprehensive and detailed results from the Van Anh and Tanaka group for the PKAW process. In another paper, Christian Hagenlocher et al. (2020) measured the movement speed of bubbles during the laser welding process of aluminum alloy AA6016 with surface-

contaminated lubricant. The results showed that the bubble speed could reach a maximum value of 0.048 m/s [325].



(a) Velocity of melt flows calculated from 30 tracers



(b) Schematic illustration of melt flows in molten pool at 50 mm/s welding speed

Figure 33. A result from papers of the Katayama group at Osaka University presented a typical example of the melt pool, fluid flow, flow velocity, and eddies in laser welding [263].

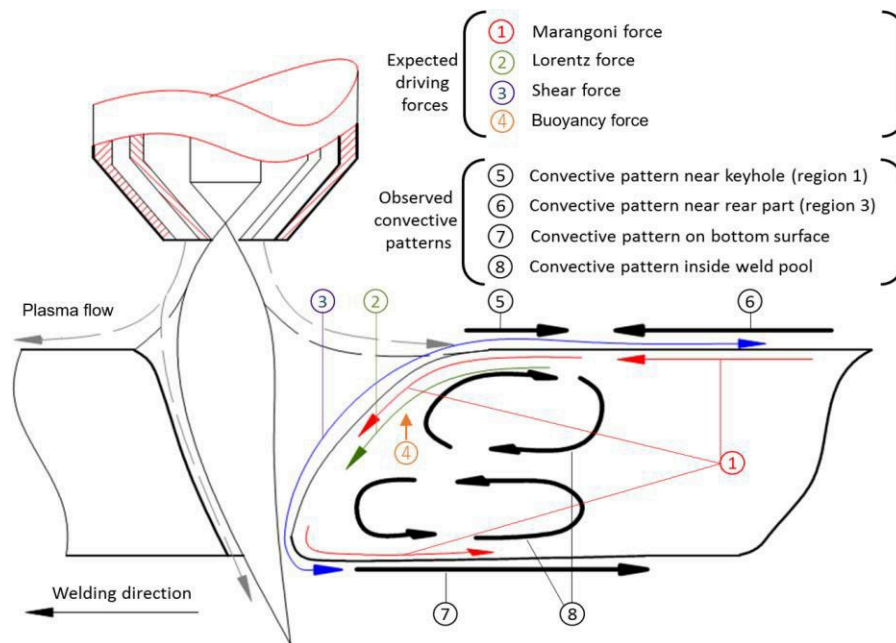


Figure 34. A typical summary of comprehensive physical phenomena of welding processes (including keyhole profile, driving forces, fluid flow, flow velocity, eddies and convection patterns) [64].

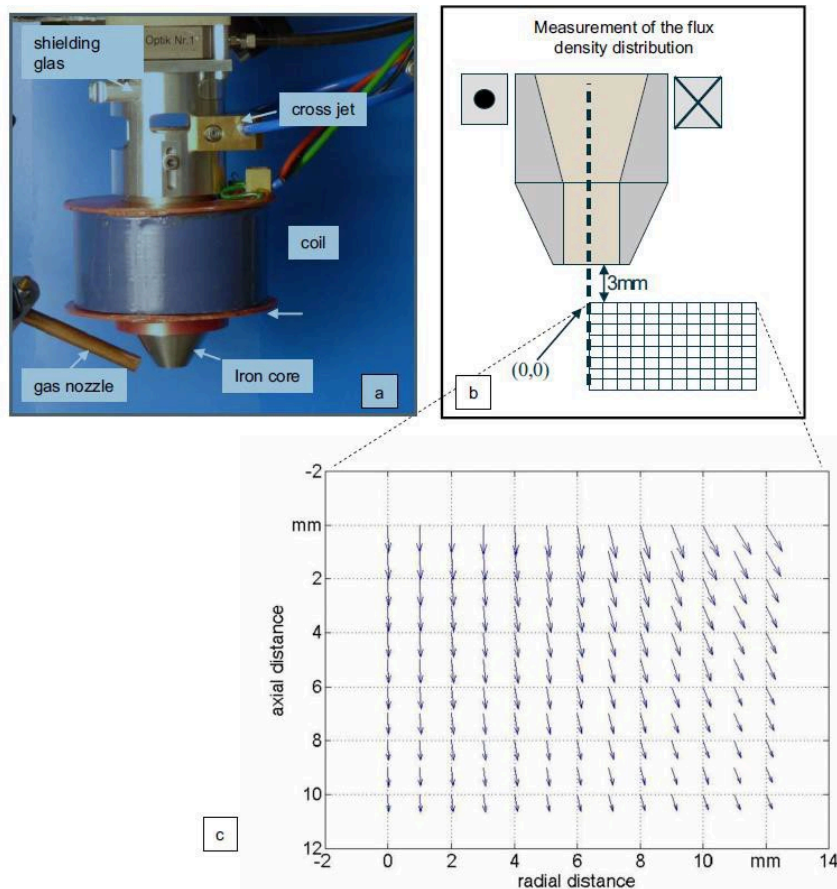
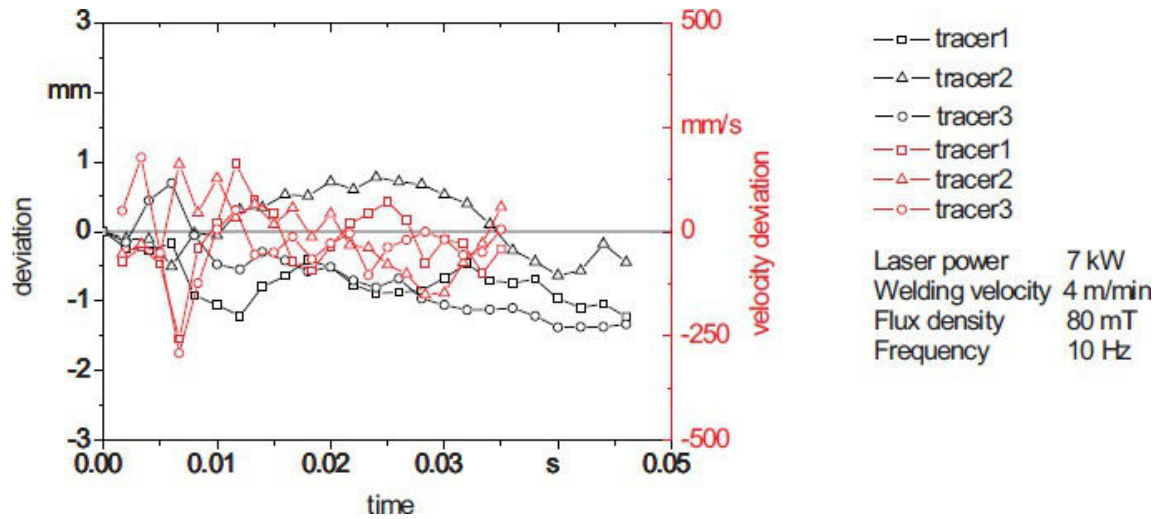
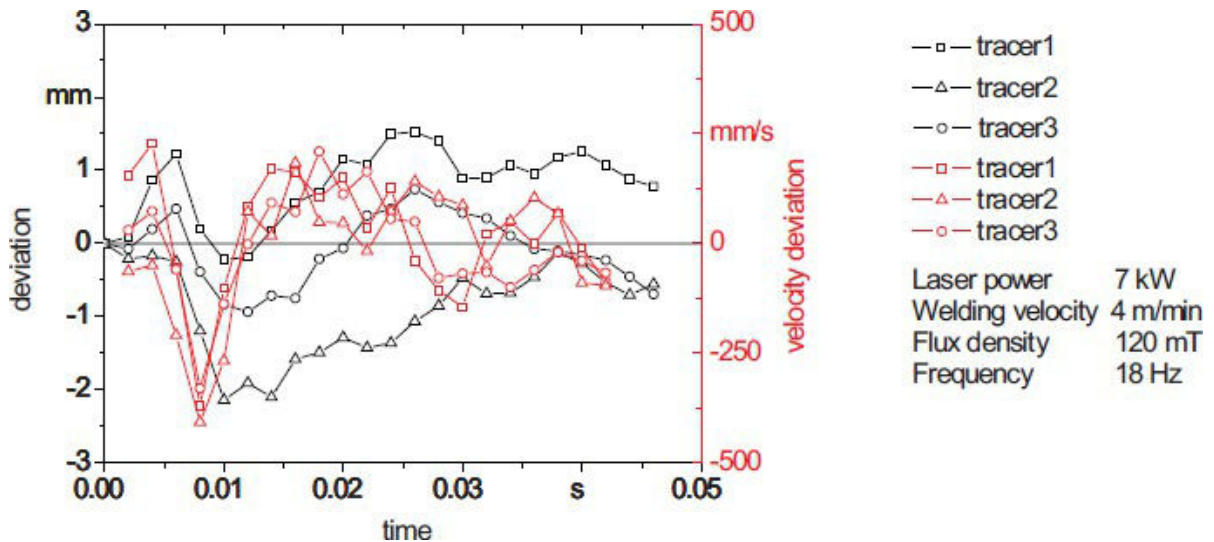


Figure 35. A schematic of external electromagnetic force in laser welding [116]. (a) Welding head prototype. (b) Principle of flux density measurement. (c) Radial and axial flux density distributions.



(a) alternating magnetic field with $B_0 = 80$ mT at a fixed frequency of 10 Hz.



(b) alternating magnetic field with $B_0 = 120$ mT at a fixed frequency of 18 Hz.

Figure 36. Flow velocity in laser welding melt pool with support of external electromagnetic force [116].

3.2 Powder Bed AM Processes

As discussed in Section 2, many publications have utilized X-ray imaging to study the melt pool dynamic behavior and heat transfer in LPB processes. However, only a few have considered melt flow velocity and convection patterns. Furthermore, all published papers on this topic have only measured projected velocity because they lack the

integration of two X-ray sources required to create three-dimensional images. Projected velocity refers to measurements in only two coordinates (X and Y), without information on the Z-axis. Researchers have estimated that the melt pool in LPB processes is extremely narrow—less than one millimeter in width—and hypothesized that melt flow oscillates only within the vertical plane (X-Y plane), with no horizontal oscillation in the Z-axis. Based on this hypothesis, they calculate velocity and convection patterns to predict heat transfer and other physical phenomena in LPB processes. However, in real-world applications, the melt pool may be wider, making this hypothesis unreliable. Additionally, no publications have yet addressed the flow velocity in EB powder bed AM processes. This may be attributed to the limited accessibility of EB powder bed systems. EB-PBF equipment is more complex and bulkier compared to LPB systems. Manufacturing an in-house EB powder bed AM system is also highly challenging, and its application is not as widespread as laser powder bed systems. Consequently, this process has received less research attention. Below, we summarize all publications addressing flow velocity and convection patterns in LPB processes.

Jian Yang et al. (2024) discussed the flow velocity in the melt pool of the LPB process for stainless steel powder and investigated the influence of flow velocity on keyhole formation and stability. As they pointed out, the velocity at a radius of 3 mm from the laser point can reach a maximum of 0.275 m/s [257]. In another paper, Jihui Ye et al. (2024) presented the velocity of particles during the spread process in LPB for Ti6Al4V powder. Three particles were tracked, revealing that the velocity of melted particles is much greater than that of unmelted particles. The velocity ranges from 0.15 to 0.2 m/s for unmelted particles and reaches 0.53 m/s for melted particles [292]. In his PhD thesis, Alex Chulun Leong discussed the velocity of spatter and pores. The velocity of the pores is about 0.42 m/s at maximum, whereas the spatter reaches a maximal velocity of about 1.0 m/s [49]. In another paper, Chulun Alex Leong et al. (2018) showed that the spatter's maximal velocity is approximately 0.27 m/s, which is significantly lower than the value reported in his PhD thesis [237]. In a paper by Qilin Guo et al. (2020), the flow velocity of Aluminum alloy AlSi10Mg and Al-6061 during the LPB process was estimated. The results showed that in conduction mode, the flow velocity can reach 2.9 m/s, while in depression mode, the velocity increases to 3.45 m/s. Meanwhile, in radiation from the depression center, the flow velocity decreases from 1.6 m/s to 0.15 m/s over a distance of 1.2 mm. Additionally, they estimated the movement of the tungsten tracer along the front depression wall of the melt pool, where the maximal velocity was observed to reach 4.5 m/s [219]. Cang Zhao et al. (2017) discussed the powder ejection velocity in LPB for Ti6Al4V powder at two laser power levels. The results indicate that the powder ejection velocity increases significantly with higher power. The maximal velocity in the high-power case reaches 13.5 m/s, whereas it is about 11.5 m/s in the low-power case [46]. In another paper, Luis I. Escano et al. (2018) presented three types of velocities: the slope surface velocity of two powder sizes, the

velocity of powder clusters, and the velocity of individual particles. For individual particles, the maximal velocity was approximately 0.12 m/s for smaller powder and 0.08 m/s for larger powder. The maximal velocity for powder clusters was about 0.073 m/s, while the slope surface velocity reached a maximum of 0.1 m/s [47].

Figure 37 presents a schematic for observing flow velocity in the LPB process using tungsten particles as trackers with a single X-ray synchrotron source. In this setup, only a 2D image of the melt pool can be captured, making it highly challenging to calculate the fluid flow velocity due to missing information about the horizontal direction. Figure 38 illustrates the fluid flow by tracking particle movement in the melt pool based on the projected image. However, this approach provides limited information, and the reliability of the velocity measurements remains a significant concern.

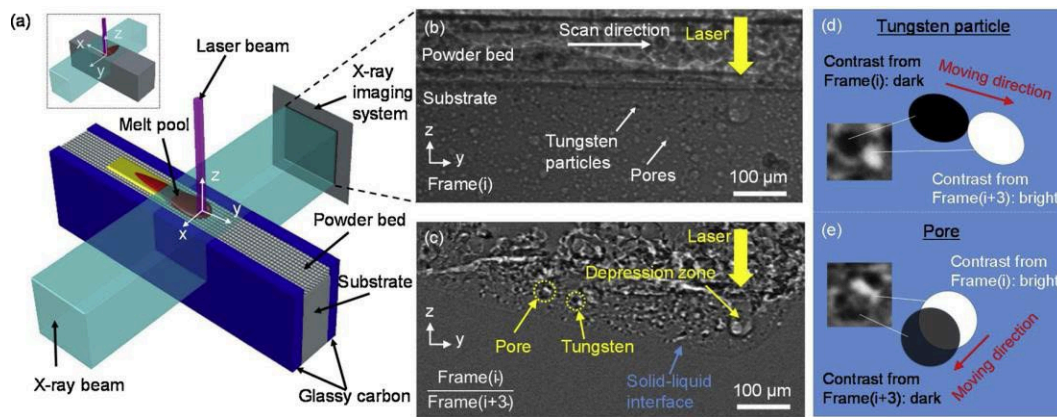


Figure 37. Method for “in-situ” observation of melt flow dynamics [219]. (a) Schematic illustration showing the in-situ x-ray imaging setup for laser powder bed fusion process. The high-speed high-resolution x-ray imaging system was used to capture the movement of tracing particles within the melt pool in the longitudinal view, as well as the transverse view (as illustrated by the simplified drawing in the inset). The x–y–z coordinate system used in this paper is indicated on the powder bed, where z is the normal direction of powder bed, y is the laser scan direction, and x is the normal direction of y–z plane, following the right-hand rule. (b) Representative x-ray image obtained at Frame(i). Uniformly dispersed populous micro-tracers (tungsten particles and pores) for melt flow tracing can be clearly identified from the x-ray image. (c) Representative x-ray image after image processing to show tracer movement and melt pool boundary. To obtain enhanced contrast, the image intensity at each pixel of Frame(i) is divided by the intensity of corresponding pixel in Frame(i+3). (d, e) Schematics showing different contrast of two types of tracers after image processing. For tungsten particle, the dark contrast comes from Frame(i) while the bright contrast comes from Frame(i+3). On the contrary, for pore, the bright contrast comes from Frame(i) and the dark contrast is from Frame(i+3). The insets in (d) and (e) are zoom-in views of the circled areas in (c).

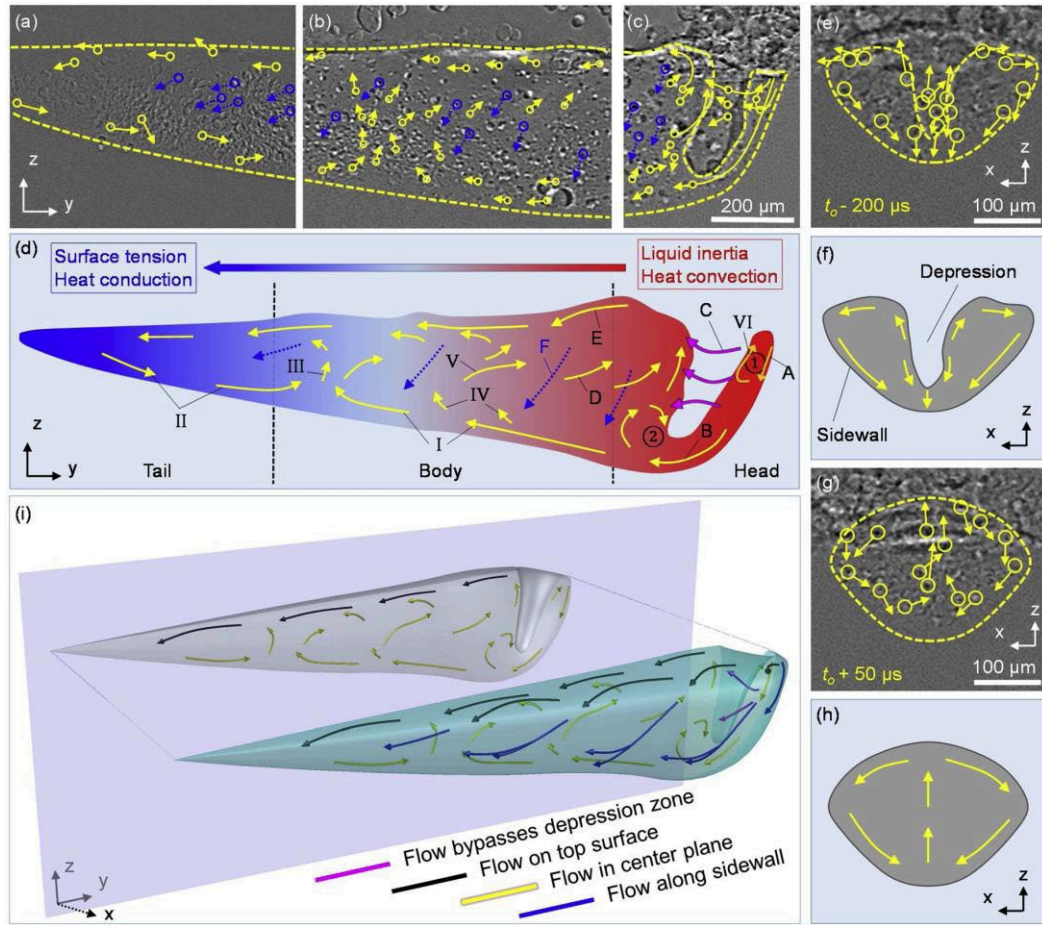


Figure 38. A typical example of observing the melt pool and flow velocity by tungsten particle [219]. Melt flow behavior under conduction mode. (a) X-ray image showing the instantaneous liquid flow direction in y - z projection plane (longitudinal view). (b) Schematic summarizing the melt flow pattern in y - z projection plane. (c) X-ray image showing the instantaneous liquid flow pattern in x - z plane (transverse view). (d) Schematic summarizing the melt flow pattern in x - z projection plane. (e) Reconstruction of three-dimensional melt flow pattern. All the tests were carried out on AlSi10Mg powder bed with a laser power of 260 W and a laser scan speed of 0.6 m/s. The laser D4 σ diameter is around 80 μm .

As discussed in this subsection, all publications on “in-situ” X-ray imaging of melt flow and convection patterns in the melt pool have focused exclusively on LPB processes. To date, no studies have been published on electron beam additive manufacturing processes.

3.3 DED Processes

Although it is well established that the dynamics of the melt pool and flow velocity are critical in controlling the final quality and mechanical properties of printed parts or welded structures, most research has focused exclusively on LPB processes. In contrast, very few studies have investigated powder-blown DED processes utilizing laser or EB heat sources.

Hui Wang et al. (2022) estimated the velocity of the melt pool and powder flow in the laser-blown DED process for various powders, including Mo, Nb, V, and Ti particles. The results indicated that the maximal velocity of the melt pool can reach 0.91 m/s during the initial phase of the process when the powder is spread and melted simultaneously. This velocity decreases to less than 0.5 m/s once the process stabilizes [146]. Suyu Zhang et al. (2024) used the X-ray radiation facility at SSRF to observe pore movement in the laser DED process for high-entropy alloys. They demonstrated that pore movement occurs in both the laser interaction zone and the circulation zone of the melt pool, with a maximal velocity of 0.5 m/s [284]. In a study by Sarah J. Wolff et al. (2021), a laser-blown DED process was applied to Ti6Al4V powder. The researchers calculated powder flow velocities under both high and low gas flow conditions, reporting values of approximately 10 m/s and 1.5 m/s, respectively [226]. Xianquang Fan et al. (2023) investigated the influence of an external electromagnetic field on melt pool flow in laser DED processes. Their findings revealed that higher laser power increases melt pool velocity; however, when an external electromagnetic force is applied, the velocity decreases. The maximum velocity exceeds 0.2 m/s in the absence of the electromagnetic field, which can be explained by the effect of Marangoni flow (see Figure 39) [293]. In another study, Kai Zhang et al. (2024) estimated bubble velocities in the circulation zone of the laser DED process and developed simulation models to predict these velocities, which were validated through experiments. The results showed that the maximal velocity of bubbles was approximately 0.12 m/s in experiments and 0.15 m/s in simulations [251]. Among DED processes, wire-arc additive manufacturing (WAAM), or wire-arc DED, with variations such as Plasma-WAAM, TIG-WAAM, MIG/MAG-WAAM, SAW-WAAM, and hybrid-WAAM, plays a crucial role [294,295,296,297]. However, no studies have been published on fluid flow or other physical phenomena in WAAM processes using X-ray imaging. This gap is attributed to the challenges of developing compact, in-house WAAM systems compatible with X-ray facilities. Furthermore, WAAM process samples are generally thicker, measuring several millimeters, making them difficult to observe with low-power X-ray systems.

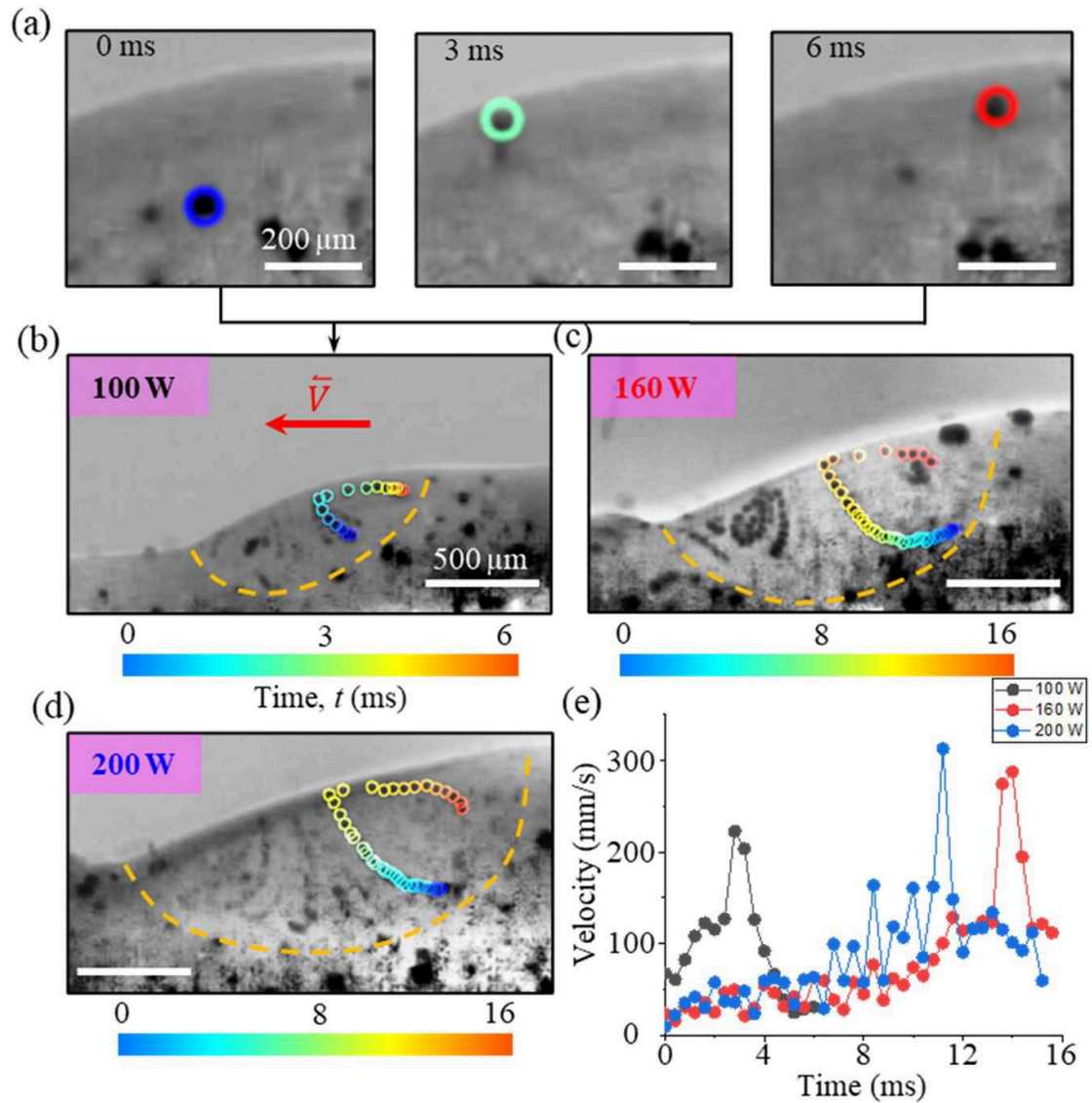


Figure 39. Velocity of fluid flow in Laser-blown powder DED process [293]. Flow behaviour without magnetic field. (a) Three successive radiographs showing a tungsten (W) particle's trajectory, coloured by time. (b-d) Time-integrated radiographs showing W particles trajectories under no B case at various laser powers: (b) 100 W; (c) 160 W; (d) 200 W. (e) W particle velocity versus time with three laser powers, corresponding to the coloured trajectories in (b-d). The sample traverse speed is 1 mm/s for all the cases.

3.4 Other phenomena

“In-situ” X-ray imaging can also observe the velocities of various physical phenomena in manufacturing processes. Figure 40 highlights additional capabilities, such as the powder spreading process and spatter velocity in LPB process. In a study by Qilin Guo et al. (2018), the velocity of powder spattering in the LPB process was calculated. The materials used included 316L stainless steel for stationary laser beam melting and AlSi10Mg for laser single-track scanning. In the case of a stationary laser beam, the

velocity reached 1.7 m/s in a vacuum environment, about 0.39 m/s in an Ar chamber with 0.1 atm pressure, and 0.32 m/s in an Ar environment with 0.05 atm pressure. For the moving laser heat source, the maximal velocity was approximately 2.25 m/s in a vacuum environment and 0.53 m/s in an Ar environment [204]. Cang Zhao et al. (2019) estimated spatter ejection velocities in the LPB process for Ti6Al4V at pressures of 0.1 atm and 0.05 atm. At 0.1 atm, the spatter velocity was significantly higher than at 0.05 atm, decreasing from 0.035 m/s to 0.005 m/s. In contrast, at 0.05 atm, the velocity dropped from 0.01 m/s to 0.004 m/s [207]. S. Mohammad H. Hojjatzadeh et al. (2019) investigated pore formation and movement in the LPB process for AlSi10Mg rectangular bars using two types of powder: AlSi10Mg powder (15–45 μm , LPW Technology, Ltd, UK) and Ti6Al4V powder (53–106 μm , PRAXAIR, USA). Their results showed that pore movement could reach a maximum velocity of 3.1 m/s [209]. In another study, Xuxiao Li et al. calculated the projected ejection velocity of powder in the LPB process for Ti6Al4V powder, reporting a maximal velocity exceeding 10 m/s [221]. Zachary A. Young et al. (2020) analyzed the velocities of single powder particles, powder agglomerations, and entrainment melting in the LPB process. The maximal velocity for single particles was 2.2 m/s, while powder agglomerations reached about 0.57 m/s, and entrainment melting was approximately 0.98 m/s [222]. Nicholas Derimow et al. (2024) investigated powder velocity in the LPB process for Ti6Al4V powder. The results showed a maximum powder velocity of 1.75 m/s in certain cases, with an average velocity around 1.2 m/s [183]. Chulun Alex Leong et al. (2018) presented results on spatter velocity and pore movement velocities consistent with findings reported in his PhD thesis [49,237]. Da Guo et al. (2024) examined spatter and vapor pressure in the LPB process. They determined that the average velocity of solid spatter reached a maximum value of approximately 1.25 m/s [250].

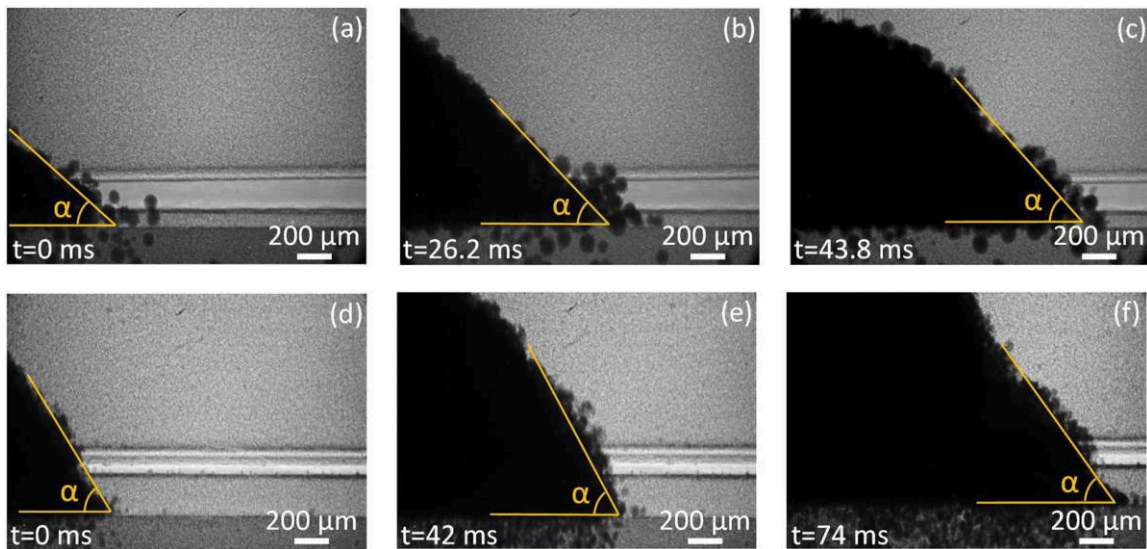


Figure 40. (a) the powder spreading process in LPB [47]. Dynamic x-ray images showing the evolution of dynamic repose angle “ α ” during the spreading of 316 L stainless steel powders with two different average powder diameters. (a–c) 316 L stainless steel powder with an average diameter of 67 μm . (d–f) 316 L stainless steel powder with an average diameter of 23 μm . The two powders were spread with a constant spreading speed of 11.5mm/s from left to right. A rigid aluminum blade with a fat front (perpendicular to the building platform), was used as the wiper. The powder was spread under an ambient pressure of 1 atm within a stainless steel chamber. The dynamic repose angle “ α ” of the powder is indicated by the yellow line on each picture.

4. X-ray Images for Phase Transformation, Solidification, and Microstructure Evolution

4.1 Casting and Furnace Processes

The application of “in-situ” X-ray imaging for material processes began much earlier in casting and furnace processes compared to other manufacturing methods such as welding and AM. On this topic, a comprehensive review by D.G. Eskin et al. (2004) summarized and discussed publications on solidification and the growth of dendritic, eutectic, and cellular structures, as well as defects like porosity in aluminum alloys [298]. Similarly, a review paper by Hen Thi-Nguyen et al. (2012) emphasized the importance of X-ray radiography and tomography in observing microstructure evolution and solidification of metal alloys during furnace or casting processes [299]. R.H. Mathiesen et al. (1999) studied cellular and dendritic solidification during the crystallization of Sn-Pb alloy at temporal and spatial resolutions down to 0.7 s and 2.5 mm, respectively. Their results indicated that segregation occurred during crystallization. In the cellular process, continuous nucleation was observed, crystal growth was equiaxed, and dendrite arms aligned parallel to the heat flow [300]. In another study, Ragnvald H. Mathiesen et al. (2002) used “in-situ” X-ray imaging at the ESRF in France to observe dendritic solidification, eutectic growth, and porosity in Al-Cu alloy [301]. Hideyuki Yasuda et al. (2004) reported on crystal formation in Sn-Bi alloy using the Spring-8 X-ray facility. They employed a 1024x1024 pixel camera with a 10x10 mm observation area, 10 μ m spatial resolution, and 30 fps recording. Their findings revealed that during unidirectional solidification, a morphological transition from planar interface to dendrite occurred, with some dendrite arms detaching from the mushy zone. This detachment happened in an enlarged region after the dendrites passed through the re-entrant channel [302]. H. Nguyen-Thi et al. (2007) observed solidification dynamics in Al-Ni alloy during furnace processes. For the first time, the transition from columnar to equiaxed microstructures was visualized using X-ray imaging. Additionally, variations in columnar growth velocity during this transition were measured and discussed [303]. In a subsequent study by H. Nguyen-Thi et al. (2008), the dynamics of the mushy zone's solidification in Al-Ni 3.5% and Al-Si7.0% alloys were investigated. The microstructure evolution during solidification was directly observed in both materials, providing critical insights. Results indicated that solidification velocity plays a crucial role in microstructure formation [304]. S. Boden et al. examined the melt flow during the solidification of Ga-30 Wt% In alloy using “in-situ” X-ray imaging. They estimated melt velocity, concentration distribution, and the growth velocity of dendritic arms. Their findings demonstrated that unstable density stratification in the melt, caused by a positive density gradient, drives plume-like convection [305]. Adeline Buffet et al. (2010) investigated the metallurgy process of Al-Cu alloy and observed the effects of varying cooling rates on melt flow and microstructure during solidification. Their results highlighted the role of solute poisoning by fluid flow in influencing primary dendrite arm growth during the early

stages of equiaxed solidification, with equiaxed grains being the primary cause of solidification cessation [306]. In a study by R.H. Mathiesen et al. (2010), the solidification and microstructure evolution of eutectic Al-Si and Al-Si-Cu alloys were examined [307]. Similarly, A. Bogno et al. (2012) observed equiaxed grain growth and interactions in Al-Cu alloy under isothermal conditions, measuring dendrite arm velocities during the process [308]. A.G. Murphy et al. (2013) utilized mini-focus X-ray radiography to study microstructure evolution during the eutectic transformation of Al-Cu alloy at solidification rates of 0.025 K/s (first stage) and 1 K/s (second stage). This created large equiaxed dendritic microstructures and fine eutectic spacings [309]. W.U. Mirihanage et al. (2014) observed columnar dendritic growth in Al-15Cu-9Si-0.0015Sr alloy with temporal and spatial resolutions of 100 ms and 0.65 μm , respectively. Their findings revealed that gravity-driven natural convection and solute sedimentation significantly affected mushy zone permeability, deviating from predictions by Scheil and Lever-rule-based models [310]. H. Nguyen-Thi et al. (2014) explored microstructure evolution during solidification under microgravity conditions for the first time, demonstrating that the elimination of buoyancy-driven convection leads to distinct outcomes compared to Earth-based solidification [311]. B. Cai et al. (2015) observed α -Al grains in Al-Cu alloy during extrusion, quantifying inhomogeneous compression of grains, interdimeric channel closure, and the formation of liquid extrudates [312]. A.G. Murphy et al. (2015) used X-ray imaging to study equiaxed solidification in Al-Cu alloy. The results showed the effects of buoyancy force on grain motion, nucleation density, and average grain size, along with measurements of dendrite growth velocities and nucleation density under varying cooling rates and alloy compositions as depicted in Figure 41 [313]. In 2016, Murphy et al., extended this work to experiments conducted in microgravity aboard the MASER 13 rocket, comparing results to Earth-based experiments [314]. M.A. Azeem et al. (2018) focused on graphite evolution in cast iron during solidification, revealing that graphite nodules remain anchored and grow from spherical to degenerate morphologies through burst growth, forming polyp-like features [315]. Hideyuki Yasuda et al. (2019) studied dendrite fragmentation in Fe-C alloy during solidification. Their findings showed a massive transformation from ferrite to austenite rather than a peritectic reaction, refining the austenite grains [316]. B. Cai et al. (2016) used “in-situ” X-ray imaging to observe Al-Cu alloy solidification, capturing cellular growth, dendrite fragmentation, and Mullins-Sekerka morphological instabilities [317]. Shikang Feng et al.'s review comprehensively addressed crystallization, solidification, and defects in aluminum alloys, including porosity, hot tears, and cracking [318]. In a review by Wen-quan Lu et al. (2022), the progressive observation of alloy solidification via X-ray imaging was discussed in detail, covering phenomena such as dendrite coarsening, fragmentation, columnar-to-equiaxed transitions, and solid-liquid interface evolution [319]. G. Reinhart et al. (2023) examined metal alloy solidification processes in microgravity, discussing metallic foam formation and diffusion in melts during space-based experiments. The results showed

that fragmentation density in the top (0–200 μm from the solidification front) and bottom (200–4800 μm from the solidification front) of the mushy zone can be seen (Figure 42) [320]. Most recently, Sarah de Albuquerque et al. (2024) investigated the solidification of Al-Cu alloy with Sn addition. Using the CALPHAD method via thermal-calc software, they identified transformation sequences from initial α -Al dendrite formation to the final eutectic reaction. These phenomena were subsequently observed using an X-ray radiation facility for comparison [321].

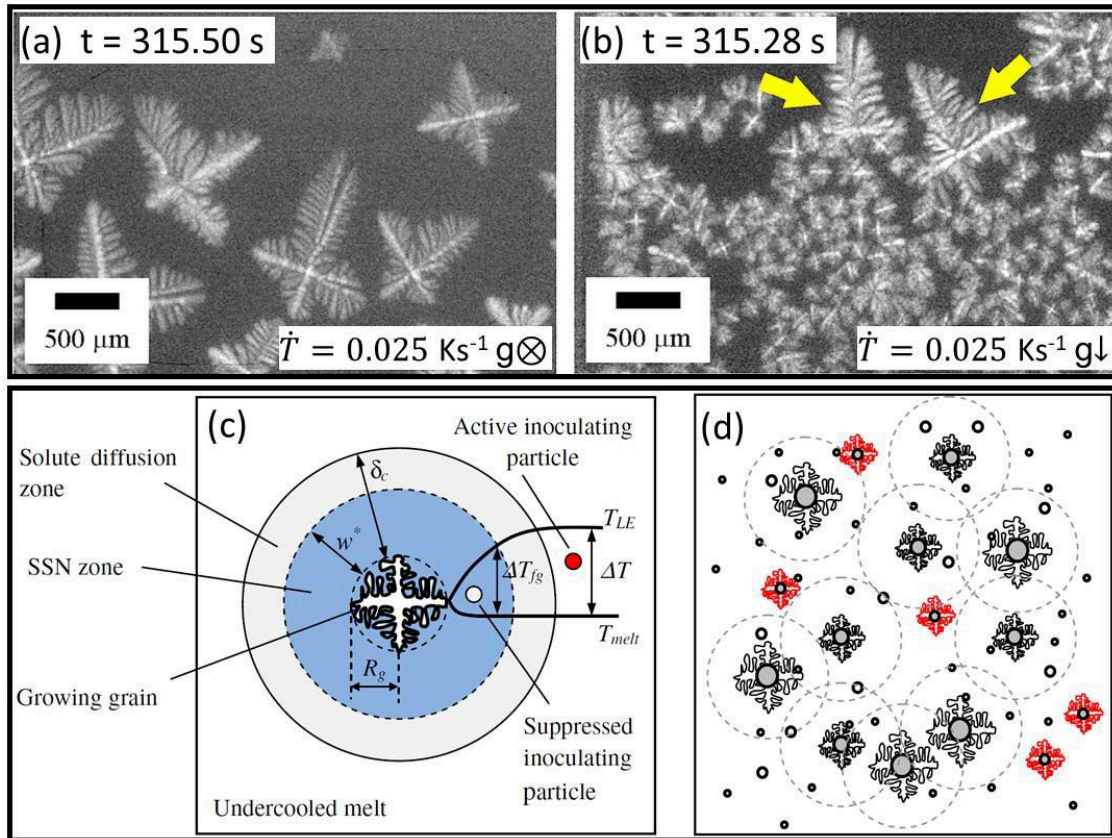


Figure 41. Solidification process and phase crystallization in Al-20wt%Cu alloy inoculated with TiB₂. [313]. Al-20 wt.%Cu-0.1 wt.%GR alloy solidifying in the (a) horizontal orientation (g), and in the (b) vertical orientation (g), respectively, at a constant cooling rate of - 0.025 K/s. The arrows highlight equiaxed grains that nucleated on a stationary particle trapped in the sample wall. Both images were recorded at an undercooling of $\Delta T = 8 \text{ K}$.

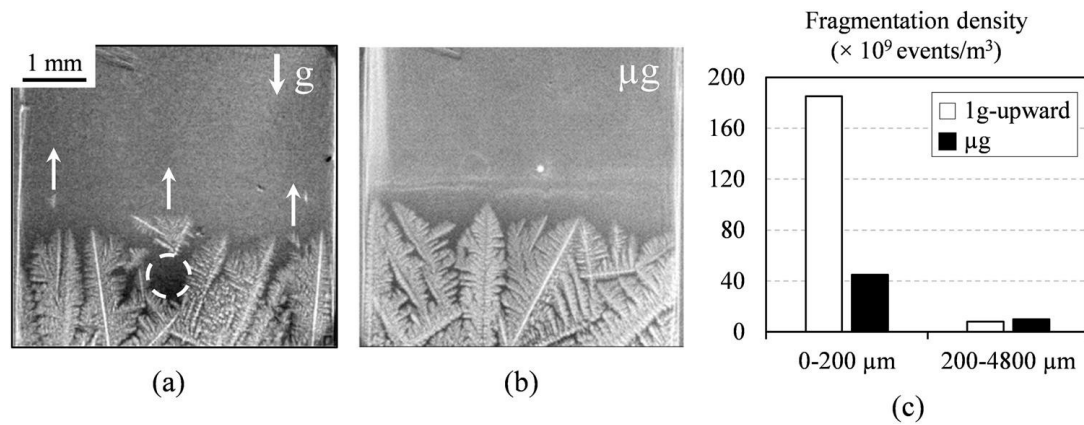


Figure 42. Columnar growth and fragmentation in Al-20wt.%Cu [320]. Investigation of columnar growth and fragmentation in Al-20wt.%Cu. Radiographs showing the columnar growth of an Al-20wt.% Cu alloy (a) with the sample in vertical position and (b) in microgravity. c Fragmentation density in the top (0–200 μm from the solidification front) and bottom (200–4800 μm from the solidification front) of the mushy zone.

4.2. Welding and Additive Manufacturing

Welding and AM are key manufacturing processes, alongside casting and furnace. As mentioned, X-ray images for phase transformation and microstructure evolution have been significantly explored in casting and furnace processes [318]. However, unlike casting and furnace processes, there are far fewer publications using X-ray images for welding and AM processes for solidification and phase transformation. Most studies have focused on melt pool dynamics, heat transfer, and typical internal defects. Therefore, it is crucial to place more emphasis on applying X-ray images to investigate metallurgy processes such as phase transfer, microstructure evolution, and other phenomena during solidification, and ultimately to control them effectively. Among the publications on this topic for welding and AM processes, only a few address solidification in the LPB process. Cai et al., 2016, calculated the dendritic tip evolution and demonstrated the velocity using X-ray synchrotron images. The velocity was observed to be approximately ten micrometers per second, which is the maximum [312]. In another study, Cang Zhao et al., 2017, investigated powder movement, phase transfer, and the solidification rate in the LPB process [46]. Figure 41 illustrates the melt pool dynamics and solidification process in LPB [189]. Figure 41 (a) shows the keyhole dynamics during formation and instability over time. Figure 41 (b) shows the solidification process with phase changes. The angle of solidification and crystallization can be predicted with the support of “in-situ” X-ray images. In a recent paper by Lianghua Xiong et al., 2024, the authors discussed the phase transfer in the LPB process for 304L SS powder. The findings revealed the mechanism of coupled peritectic growth and local remelting in a three-phase region. This represents an important milestone in

using X-ray images to explore phase transformation dynamics and the precise design of phase structures for metal additive manufacturing (see Figure 44) [322].

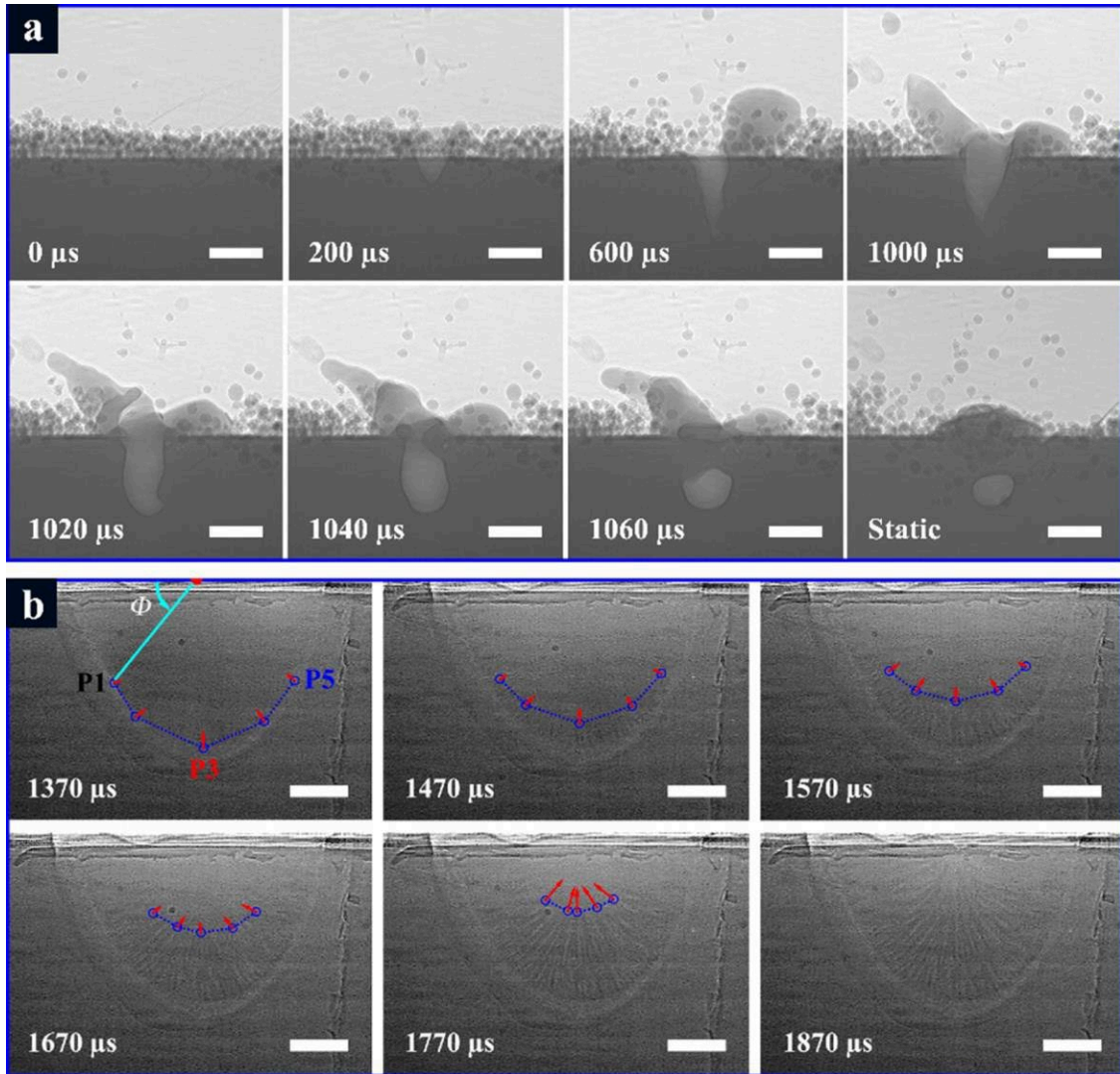


Figure 43. Solidification process in LPB process [189]. High-speed synchrotron x-ray imaging of Ti-6Al-4V in laser melting and solidification. (a) Formation of a keyhole pore. (b) Growth of columnar grains.

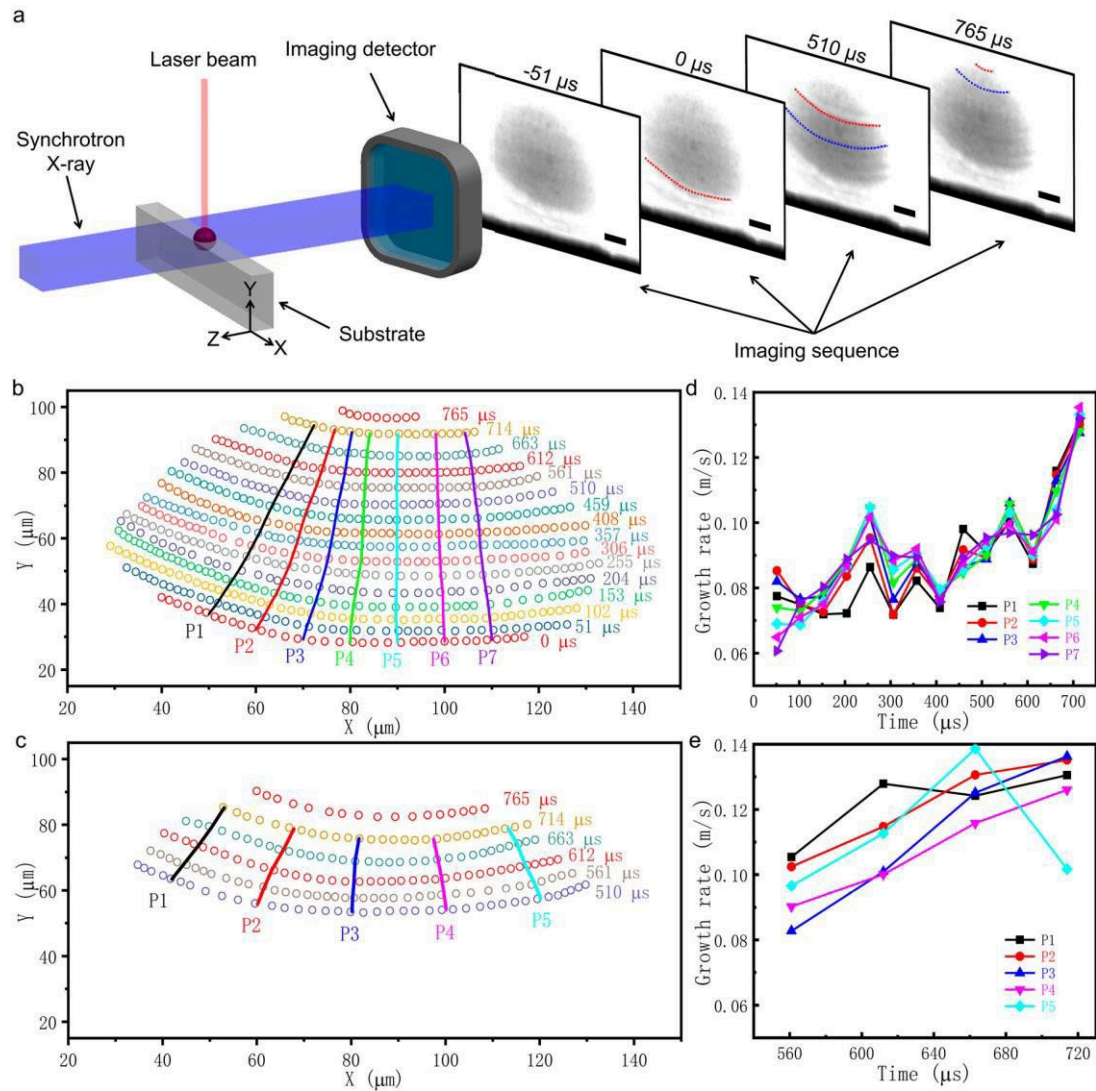


Figure 44. The solidification process in LPB for 304L SS powder [322]. High-speed synchrotron X-ray imaging quantification of double solid–liquid interfaces during rapid solidification of 304L SS droplet. (a) Schematic of high-speed synchrotron X-ray imaging during rapid solidification of a fully liquid spherical droplet. Representative X-ray images show the evolution of double solid–liquid interfaces of a laser melted droplet. (b) Evolution of primary solid–liquid interface upon cooling of the spherical droplet. The appearance of detectable solidification front is set as reference point. Seven spots are tracked for the entire solidification lifetime by calculating the moving trajectories according to normal direction of growth at the solidification front. (c) Evolution of second moving boundary following the first solidification front. Five spots are tracked to quantify the moving trajectories. (d) Growth rate of seven tracked locations as function of time at primary solid–liquid interface. (e) Growth rate of five tracked locations as function of time at second moving solid–liquid interface.

5. X-ray imaging for defects

During casting, furnace, welding, and AM processes, the melt pool solidification process and crystallization behavior lead to changes in microstructure, the formation of defects, and, ultimately, the failure of mechanical properties and quality. Among these defects, pores, and porosity primarily occur in welding or AM processes for oxidation-prone materials such as titanium and aluminum alloys. Meanwhile, cracking mainly occurs in materials sensitive to heat and thermal gradients, such as those with a high percentage of sulfur, oxygen, or other elements.

Many authors have applied “in-situ” X-ray imaging to furnace processes for this topic. For example, Henri-Thi Nguyen and his team studied the formation of porosity in casting under low-gravity environmental conditions in a project funded by the European Research Council [320]. In this project, researchers used the X-ray synchrotron beamline ID19 at ESRF to observe and clarify porosity formation and its impact on mechanical properties in low-gravity environments. However, this approach is rarely applied to welding, particularly in metal additive manufacturing processes. Only a few publications on this topic exist.

5.1. Porosity and Pores

Porosity and pores are among the most common and typical defects in manufacturing processes of welding, AM and casting, particularly for sensitive materials like aluminum and titanium. These defects lead to structural destruction and failure. Pores and porosity form when gas bubbles trapped in the melt pool persist even after solidification. Understanding the evolution and mechanisms of this phenomenon is essential for more efficient process control. However, since these phenomena primarily occur within the melt pool, traditional inspection methods like high-speed cameras or sensors face limitations. Meanwhile, X-ray imaging, with its ability to penetrate materials, presents an ideal solution. Due to the significant challenge and the demand for defect-free manufactured structures, numerous studies have addressed this issue. Researchers have utilized “in-situ” X-ray imaging to observe the formation and evolution of pores and porosity in welding and AM, particularly in laser welding and laser AM processes.

For welding processes: One of the pioneering papers discussing internal defects in the welding process using X-ray imaging was published by Qiaofeng Zhou et al., 2015 [323]. This study linked bubble phenomena in the laser welding of aluminum to melt flow dynamics and developed a simulation model to validate the experimental results. The key mechanism identified was the transition of melt flow from outward to inward directions, which generates bubbles and porosity. In another study, Masanori Miyagi et al., 2017, analyzed the formation mechanism of porosity in laser welding for aluminum [324]. They reported that porosity could reach around 6% under stable keyhole

conditions but increase to 18% if the keyhole becomes unstable. Among the series of studies on porosity, most focused on aluminum alloys. For example, Florian Fetzner et al. and Christian Hagenlocher et al. explored strategies to prevent porosity in aluminum laser welding by modifying laser beam oscillation [325,326]. Their findings showed that increasing the beam oscillation frequency to 200 Hz effectively eliminated porosity. Using SSRF, Hao Chen et al. investigated bubble formation in the arc welding process (GTAW) of H40 steel under varying water pressures in a submerged environment [112]. Additionally, another study on dissimilar joints of Al-Cu observed bubble formation when Al and Cu plates were prepared and welded in an overlap configuration [327]. More recently, Fan Wu et al., 2023, examined pore formation in the TIG welding process [108].

For DED AM processes: Samantha Webster et al. published the first paper on laser powder-blown DED AM for Ti6Al4V material to detect porosity in 2019 [214]. Meanwhile, Yuhui Chen et al., 2020, presented the formation of porosity in titanium alloys using the laser powder-blown DED process. They also hypothesized that porosity in the DED process is closely linked to melt flow and solidification processes [239]. These findings align with those of Sarah J. Wolff et al., 2021 [328], and Hui Wang et al., 2021 [329]. In another recent publication, Kai Zhang et al., 2024, identified five mechanisms for porosity formation in the DED process, corresponding to five stages during the printing process. They emphasized that the key factors to control are Marangoni flow and melt pool solidification. The formation and movement of pores and porosity have been tracked; the velocity has been estimated (see Figure 47) [251]. Additionally, for the first time, Shuya Zhang et al., 2024, explored porosity observation in high-entropy alloys, identifying three mechanisms corresponding to the formation process during printing [284]. In another publication, Sarah J. Wolff et al. (2019) explored the formation of porosity in the laser powder-blown Directed Energy Deposition (DED) additive manufacturing process for Ti-6Al-4V powder. The results, presented in Figure 45, depict a keyhole mode experiment conducted with a laser power of 250 W and a scan speed of 100 mm/s, highlighting the impact of mass addition on porosity and cavity geometry. Keyhole mode occurs when the laser's power density on the substrate is sufficiently high to create a cavity filled with ionized vapor and ambient gas [215].

For LPB processes: Most studies on the topic of porosity and pore have focused on porosity formation and mechanisms in LBP processes. The first paper to address this issue was by Andrew M. Kis et al., 2019 [180], who highlighted that keyhole formation is the primary cause of porosity. They proposed reducing laser scanning speed as a means to mitigate and prevent this issue. In another publication, S. Mohammad H. Hojjatzadeh et al. discussed how a higher temperature gradient (thermocapillary force) could eliminate porosity formation [209]. This result was further confirmed by [218]

and [330]. Jean-Baptiste Forien et al., 2020, observed porosity in stainless steel with variations in laser power and laser scanning speed. Similar to other studies, they confirmed that increasing laser power and decreasing laser scanning speed can eliminate porosity formation [331]. In another publication, Yunhui Chen et al. confirmed that porosity in LBP processes forms during keyhole instability and keyhole progression stages [239]. With changes in laser wave, S. Mohammad H. Hojjatzadeh et al., 2021, discovered that vapor depression collapse occurs when laser irradiation stops within a single pulse, and rapid melt pool solidification leads to occasional pore formation during this process [332]. This phenomenon was also confirmed by Jiandong Yuan et al., 2024 [333]. By adjusting laser power and scanning speed, Chenxi Tian et al. (2024) proposed that the number of pores is related to laser power, and that increasing laser power or decreasing laser scanning speed can prevent porosity, as supported by previous publications [334]. Cang Zhao et al., 2020 discussed the keyhole porosity boundary separating the keyhole porosity regime from the stable melting regime with or without the presence of powder (Figure 46 (a)). Across the boundary toward higher energy density, discernable pores were released into the liquid from the keyhole bottom (Figure 46 (b)). The maximum pore size (among all observed in any given experiment) trended up with decreasing scan speed at a constant laser power.

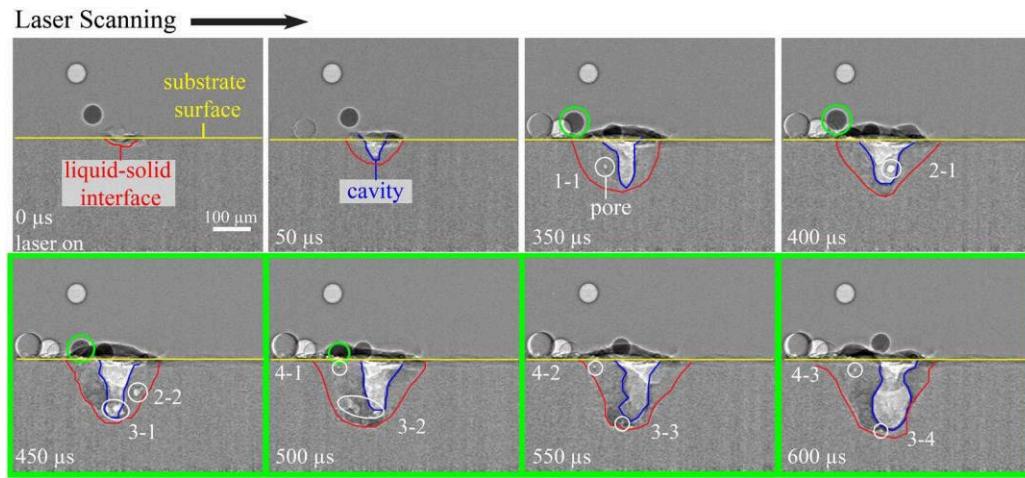


Figure 45. Formation of porosity in the DED process [215]. Cavity, melt pool, and porosity evolution as mass is added due to surface tension in an experiment with a laser power of 250W and a scan speed of 100mm/s.

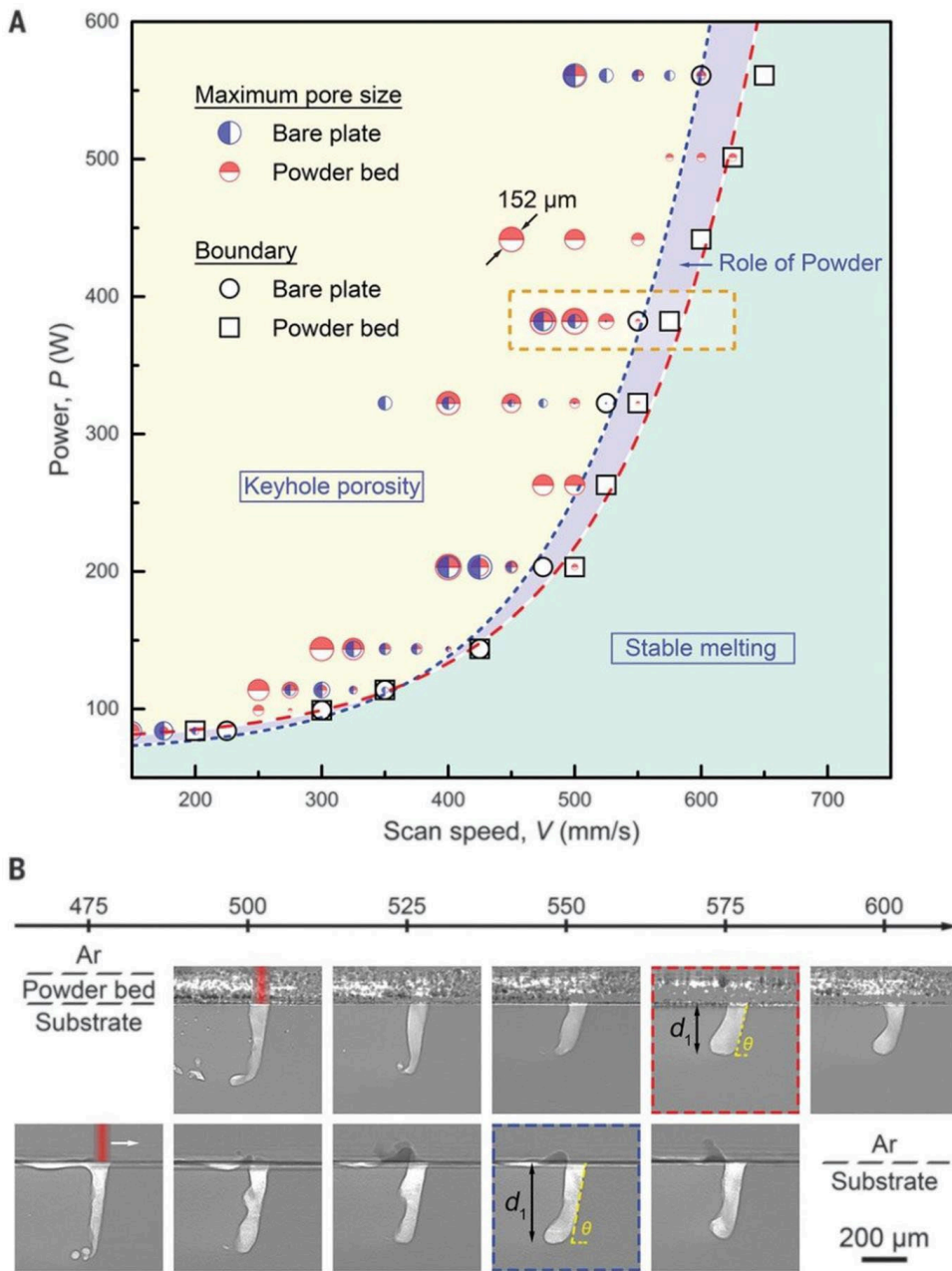


Figure 46. Porosity formation in LPB process of aluminum [217]. A) P-V space, which is divided into a stable melting regime (light green shaded area, consisting of stable keyhole, transition, and conduction regimes) and a keyhole porosity regime (light yellow area), indicated by open circles and a blueshort-dashed line for the case of bare plate and by open squares and a red long-dashed line for samples with a ~ 105 -mm powder layer on top. The extent to which adding powder increases the instability and widens the porosity regime is indicated by the light purple shaded regions and a blue arrow identifying the role of powder. In the keyhole porosity regime, the diameters of the blue and red half solid circles indicate the measured maximum equivalent pore size for each specific P-V combination. The dashed lines are to guide the eye. B) Tableau of representative x-ray

images at constant $P = 382$ W and varying scan speed across the keyhole porosity boundary indicated by the orange dashed rectangle in (A). (Top) Powder bed samples. (Bottom) Bare plate samples. The red and blue dashed framed images correspond to the respective boundaries in scan speed, below which pores are trapped in the resolidified metal. The overall keyhole depth, d_1 , and front keyhole wall angle, q , are labeled. All images were background corrected by the images collected before laser melting. The laser spot size is ~ 100 μm .

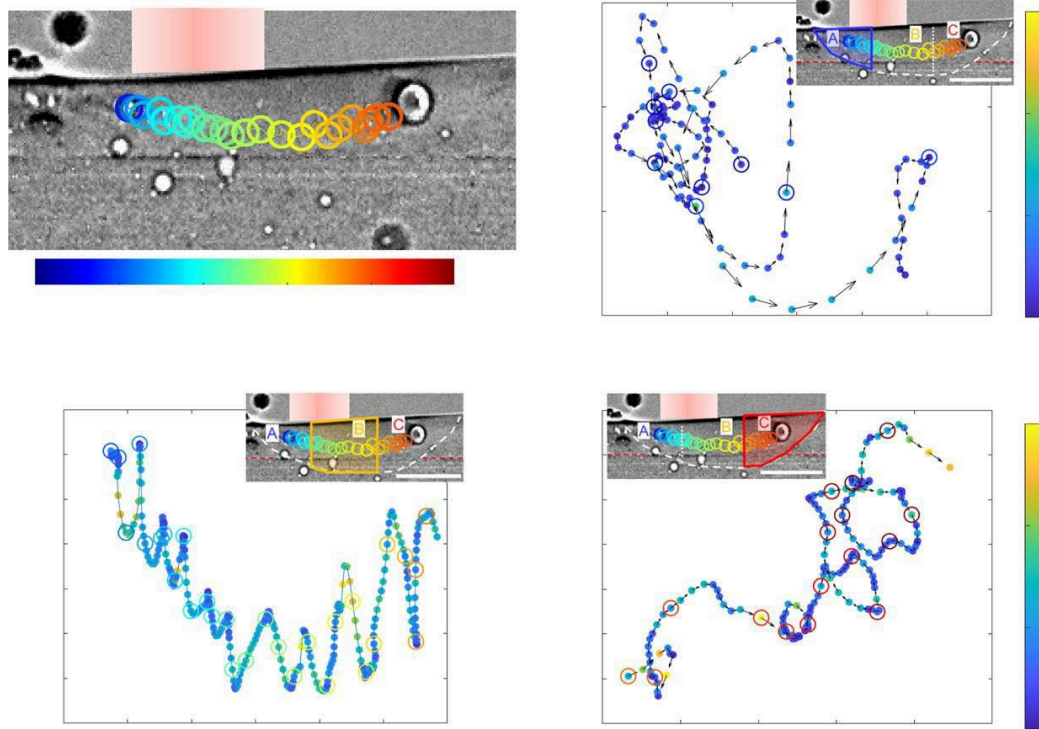


Figure 47. The pore evolution and its movement in the Laser-powder blown DED process [251]. Flow behavior without magnetic field. (a) Three successive radiographs showing a tungsten (W) particle's trajectory, colored by time. (b-d) Time-integrated radiographs showing W particle trajectories under no B case at various laser powers: (b) 100 W; (c) 160 W; (d) 200 W. (e) W particle velocity versus time with three laser powers, corresponding to the colored trajectories in (b-d). The sample traverse speed is 1 mm/s for all the cases.

As seen above, most studies have focused on clarifying and discussing porosity and pores in LPB and DED processes for Ti6Al4V and aluminum alloys. In contrast, several other papers have addressed the issue of laser welding processes for aluminum alloys. This highlights the need for more attention to clarifying porosity and pore formation in LPB and DED processes to develop "defect-free" processes and enhance their applicability in industrial settings for various other materials rather than only the above-mentioned materials. Also, more attention of X-ray images for furnace and casting

processes are indispensable to discuss the physical and metallurgical mechanisms behind the quality of these processes.

5.2. Cracking

Cracking is a typical defect in sensitive materials such as aluminum and high-carbon steels, which contain high levels of sulfur and other critical elements. X-ray images can detect these phenomena and explore their mechanisms and evolution. This provides valuable data for developing novel simulation models and deep-learning models to predict defects and fluid flow dynamics in the manufacturing science.

Masanori Miyagi et al.'s first paper on this topic discussed crack formation in laser welding by observing the propagation of cracks during aluminum alloy welding. Hot cracking was initially observed as it developed from the bottom surface toward the top surface [335]. In a study on the TIG welding process, Tomoya Nagira et al., 2021, observed crack propagation during TIG welding of 310S and 316L steels [336]. They found that solidification cracking initiation began when welding started and progressed along the welding direction. They also predicted the velocity at the tip of crack propagation and verified that cracks developed faster at lower solidification temperatures than higher temperatures. In another publication, Nadia Kouraytem et al., 2021, discussed that cracking in LBP processes began at locations where pores and porosity were present. They identified two types of cracking: keyhole porosity and cracking-melting porosity [337]. David T. Rees et al., 2023, explored the development of hot cracking in aluminum. They confirmed that the solidification process is a key factor in controlling this phenomenon. Additionally, they found that adding TiB₂ powder to the process could significantly reduce cracking [338]. Tristan G. Fleming et al., 2023, observed crack formation using novel equipment integrated with coherent imaging (ICI) in an X-ray facility. However, this publication did not provide more detailed information or discussion on the mechanism of this phenomenon [339]. Yunhui Chen et al., 2023, utilized an X-ray facility with 200,000 pfs to observe hot cracking formation during the LBP process for aluminum alloy. They confirmed that heat input (laser pulse power) could eliminate hot cracking formation and concluded that melt pool behavior and the solidification process are key factors in controlling this issue [340]. In a paper on the casting process, Insung Han et al., 2024, presented that hot tears during the solidification of Al-Cu alloy are caused by the intermetallic component (IMCs) layers. Based on this observation, they discussed the role of Fe-rich IMCs in forming this issue [341]. Figure 48 provides a real-time X-ray radiography imaging of cracking in the LPB process. The cracking is evolve with the increase of time frames [254].

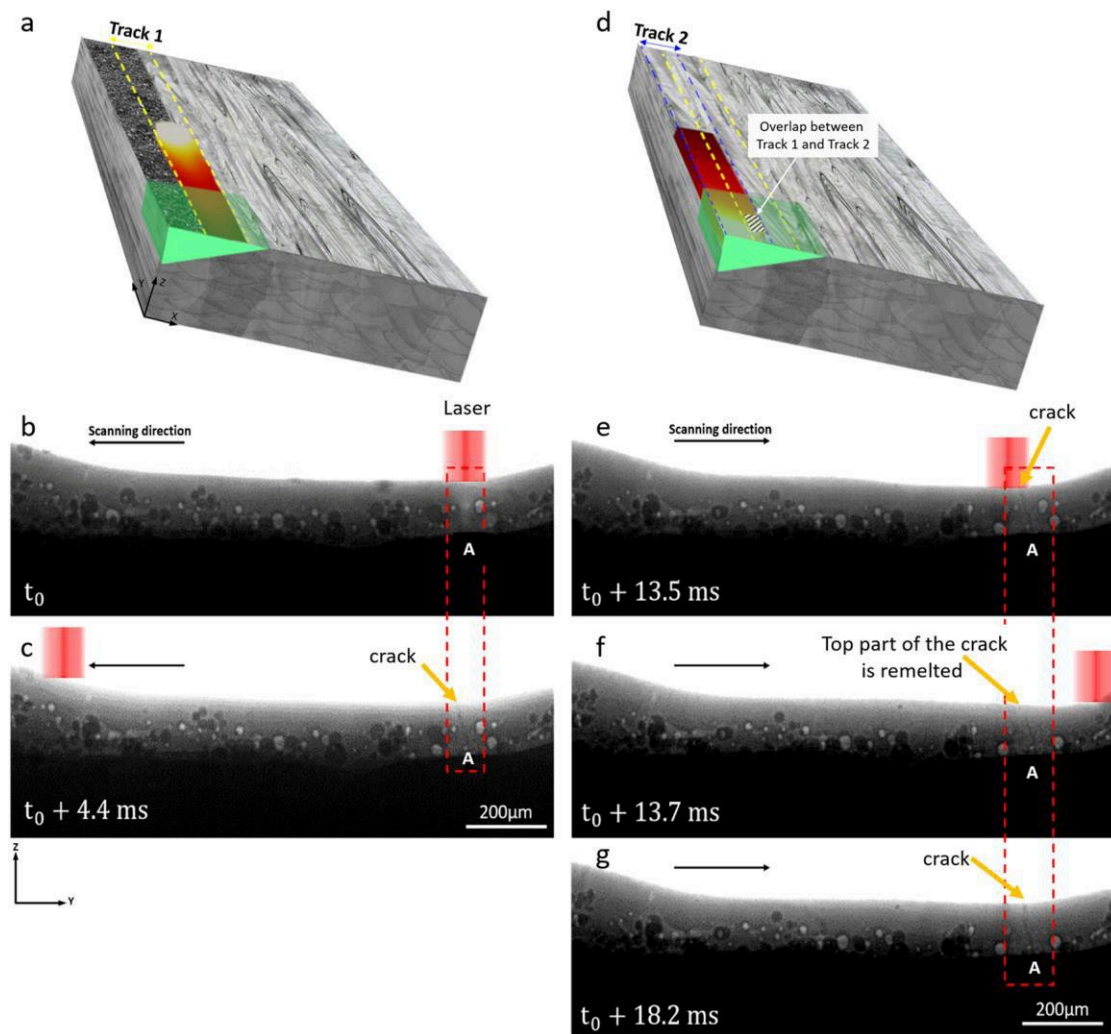


Figure 48. Direct observation of cracking in LPB by X-ray images [254]. Radiographs acquired during L-PBF of CM247LC. a) The position of the track (Track 1) observed in b) and c) is shown schematically. b) At $t = t_0$, the laser reaches point A. The crack starts appearing at the same location 2.7 ms later. c) The crack is visible at $t = t_0 + 4.4$ ms. d) The position of the track (Track 2) observed in e), f), and g) is shown schematically. e), f) During printing of the next line scan, the crack is partially remelted. Track 2 remelts the top part of the crack. Considering the overlap between two adjacent tracks, the striped part in d) indicates the zone in which the crack formed. The crack starts growing again towards the surface with a 2.9 ms delay. g) A radiograph at $t = t_0 + 18.2$ ms clearly shows the fully regrown crack.

5.3. Spatter

Spatter is a key defect that significantly affects surface accuracy and post-processing in manufacturing processes typically such as welding and AM processes. It can be a tiny melt droplet from the melt pool in the welding process or a small powder particle that melts in the AM process. Spatter forms when strong gas pressure or inappropriate parameter settings are applied. It can affect the final product's surface, leading to post-

processing that incurs additional costs and time. In some cases, it is the primary cause of low surface accuracy and high surface roughness. There are several ways to study this defect, including high-speed cameras, synchrotron imaging, and X-ray radiography. Among these, using X-ray radiography images is advantageous because it can observe the mechanism and evolution of the interaction between matter and laser during the process.

In a recent publication, Heider et al., 2013, discussed the formation of defects, including spatter, in laser keyhole welding mode. They indicated that keyhole instability is the main reason for bubble formation and spatter [342]. In another study, Chu Lun Alex Leung et al., 2018, proposed that the low viscosity of the melt pool in SS316 material during LPB processes is strongly driven by Marangoni flow [50]. This result was confirmed by Cang Zhao et al., 2019 [207]. In another publication, Qilin Guo et al., 2018, discussed and established mathematical functions to represent the relationship between powder spatter and pressure in the printing chamber. The dynamics of powder flow over time are illustrated in Figure 49 [204]. Meanwhile, Da Guo et al. considered spatter a mathematical function of the vapor depression shape. They also attempted to estimate the velocity, angle, and number of spatters during LBP [250]. This paper classified spatter in LPB into five types: solid spatter, metallic jet, powder agglomeration spatter, entrained melt spatter, and defect-induced spatter. They also conducted a series of investigations on laser scanning power and scanning speed to explore regions where spatters can form, re-confirming the results of [222].

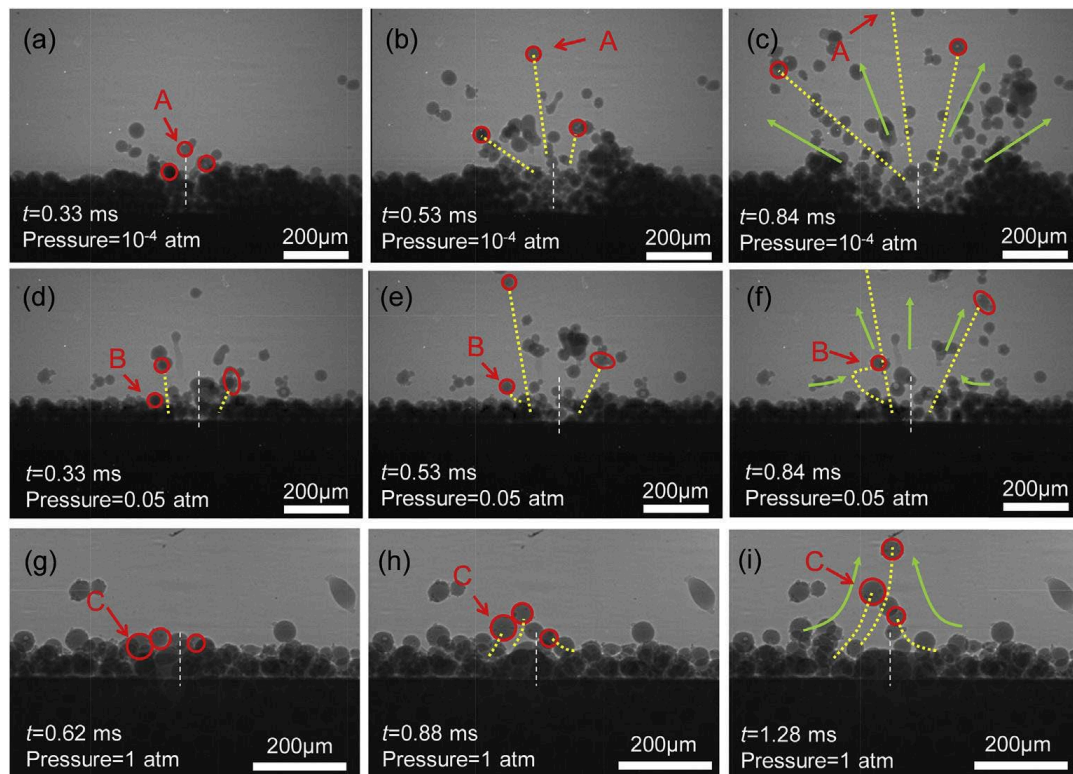


Figure 49. Spatter in LPB process along the printing time. [204]. Dynamic x-ray images show powder motion at different moments and under different environmental pressures. The powder bed was exposed to a stationary laser beam with a D4s beam diameter of 200 μ m, laser power of 312 W, and duration time of 1 ms. The environment is filled with argon. The material is 316 L stainless steel. The time elapsed from initial laser exposure is shown on the left bottom of each image. (a-e-c), powder motion under 10^{-4} atm. Powder A was ejected out of view in (c). (d-e-f), powder motion under 0.05 atm. (g-e-i), powder motion under 1 atm. White dashed lines highlight the position of the laser. Red circles indicate the representative powders traced. Yellow dashed lines mark the trajectories of powders. Green arrows represent powder-moving trends.

5.4. Other defects

Other defects, including surface roughness, undercut, burn-through, and so on, can also be directly detected by “in-situ” X-ray images. A series of papers published by Van Anh et al. discussed how X-ray images can reveal the formation of burn-through, undercut, reinforcement, and other defects by observing changes in eddies and convection flow in arc welding processes [171,199]. In another approach, the formation of surface roughness by checking the spatter through X-ray images has been studied by Alisha Bhatt et al., 2023 [343] and Gowtham Soundarapandiyan et al., 2023 [248] for AM processes. As seen from the discussion above, there are fewer publications on this topic than melt pool dynamics and heat transfer. Still, many fundamental phenomena and mechanisms remain unclear, particularly how surface roughness forms and how it links to fluid flow and other physical phenomena. Therefore, more attention should be directed toward developing and enhancing efficiency for manufacturing processes. This is especially important for DED AM processes, both wire-based (laser and arc) and powder-based (laser and electron beam) additive manufacturing (AM) processes, where these defects are still not fully understood.

6. X-ray Imaging for Novel Materials and Manufacturing Processes

Currently, "in-situ" X-ray images are primarily used in manufacturing processes focused on Titanium and its alloys, with limited aluminum and stainless steel applications. However, with advancements in material and manufacturing sciences, many researchers are developing novel material classes, rapidly becoming emerging fields and the future of manufacturing science. Most studies rely on "ex-situ" observations using metallographic analysis techniques such as SEM, TEM, and EBSD to investigate these materials. These methods explore phenomena and mechanisms but are limited in studying "in-process" phenomena. Specifically, the melt pool dynamics and other factors during manufacturing that influence phase formation, microstructure, and final properties are difficult to analyze. On the other hand, as mentioned earlier, "in-situ" X-ray imaging is a more advanced and unique approach that offers numerous benefits over conventional "ex-situ" methods like metallographic imaging. Despite these advantages, there is still a lack of publications exploring the physical phenomena of novel materials using X-ray imaging. This section explores the potential of X-ray imaging to investigate the fundamental physical mechanisms of several key novel material classes, including high-entropy alloys, functionally graded materials, and refractory materials. Furthermore, as discussed earlier, "in-situ" X-ray images have been applied to understand the fundamental mechanisms of developing various manufacturing processes. However, there is a gap in research regarding novel manufacturing processes, such as the WAAM for micro-scale components, hybrid Plasma-Laser DED AM processes, or other DED AM processes that use heat sources like TIG or MIG/MAG. These areas have yet to be explored using X-ray imaging, highlighting the need for further research in future studies.

6.1 High-Entropy Alloys (HEAs)

High-entropy Alloys (HEAs), a novel class of materials first introduced in 2004 by Brian Cantor and Jien-Wei Yeh [344,345,346,347], are characterized by a primary composition of at least four elements. These materials offer numerous advantages for novel applications, making them an area of growing interest in material science. Their anisotropic microstructure, resulting from the mixture of four or more elements, provides superior properties over conventional materials.

As this material class develops, understanding the behavior of fundamental physical phenomena and the mechanisms behind them is crucial. Using X-ray images to explore fluid dynamics, fluid flow, metallurgical processes, and phase transfer within HEAs should be a priority for researchers in material science. Only three publications that use X-ray images to study high-entropy materials can be found [146,284,348]. This limited use of X-ray imaging in HEAs is likely because much of the research focus is still on conventional materials and manufacturing processes, with researchers extending X-ray applications to advanced materials as they become more established. The complexity of

X-ray facilities and the time and cost required for experiments also contribute to this limited application.

6.2 Functionally Graded Materials (FGMs)

Functionally graded materials (FGMs) are a novel material class characterized by a gradual change in composition and properties along one or multiple directions. This enables FGMs to enhance performance for specific applications, such as aerospace, medicine, and other industries [349,350]. The development of FGMs, particularly through additive manufacturing (AM), has gained significant traction due to the reduction in time required to achieve sustainable manufacturing advancements. AM offers several advantages in producing higher-quality FGMs, allowing for tailored material properties and complex structures [351,352].

However, to ensure the quality of FGMs and their successful application, it is essential to thoroughly understand the fundamental physical phenomena and mechanisms behind the changes in their properties. X-ray synchrotron facilities could play a key role in this investigation, offering a powerful tool for studying these complex materials. Since FGMs are a relatively new class, they likely exhibit novel solidification mechanisms, microstructure evolution, and phase formation. Despite their potential, no publications currently utilize X-ray images to explore these phenomena in FGMs. Thus, one of the key applications for X-ray images in material science is to focus on understanding the fundamental phenomena and mechanisms within FGMs.

As highlighted earlier, X-ray imaging has been applied to investigate the fundamental phenomena and mechanisms in additive manufacturing and welding of functionally graded materials and high-entropy alloys. However, more attention should be given to exploring these novel material classes by clarifying the physical phenomena and metallurgical processes behind these materials, which is a crucial area of study. This could accelerate their development and applications, as these materials have the potential to replace conventional materials and open up numerous new possibilities.

6.3 Refractory Materials

Refractory materials are a novel class of materials designed to withstand high-temperature environments [353]. One key feature of refractory materials is their high content of carbides, making them ideal candidates for extreme conditions such as rocket exhaust tubes and aircraft components. These materials are often used in manufacturing welding and AM processes, with powder metallurgy being the predominant technique.

However, research on refractory materials is still limited, and much of it relies on “ex-situ” observations. The behavior of phases transition, crystallization, and microstructure evolution is crucial for understanding the performance of these materials in extreme conditions. “In-situ” X-ray imaging should be an ideal technique for investigating these

phenomena, offering valuable insights into the material behavior during manufacturing and under real working conditions. Using X-ray images to study refractory materials could help address gaps in understanding their behavior and improve manufacturing processes.

6.4 Novel AM Processes

External support, such as electromagnetic forces or ultrasonic waves, has led to the development of novel additive manufacturing (AM) processes capable of producing fine-grain structures [112,220]. These processes improve the mechanical properties of AM components and reduce defects. Using "in-situ" X-ray imaging can help explore the mechanisms that contribute to their advantages over traditional manufacturing processes. However, to date, only a few publications have addressed this challenge. To fully understand these processes, it is essential to observe the transition of nuclei, grain growth, and the dynamics of the melting-solidification process. "In-situ" X-ray imaging is invaluable for examining these processes and clarifying the underlying mechanisms that make them superior to conventional AM techniques. Although X-ray imaging has been applied to some novel AM processes, more research and publications are needed in this area, particularly due to the complexity of integrating external systems.

One recent development from Cranfield University in the United Kingdom introduced a novel hybrid laser-plasma wire AM process. This hybrid process uses a plasma heat source to create a large and deep melt pool, which a laser scanning trailer reshapes to increase the melt pool's width. This approach significantly increases the deposition rate and allows independent control of the melt pool's width, without being limited by depth or other factors [354]. Experiments and simulations showed that, with a high wire feeding speed, the process could alter crystallization and promote the transition from columnar to equiaxial grain structure (CET), leading to a finer grain structure and improved final quality in WAAM components compared to conventional methods [355]. However, further investigation is needed to understand the internal fluid flow, melt pool morphology, and heat transfer in this process. "In-situ" X-ray imaging could provide valuable insights into these phenomena [348].

Another area of innovation is the development of WAAM for miniature components, which holds significant potential for applications in medicine, electronics, and other fields. Unlike LPB processes, which are typically used for small-scale parts with high complexity but lower reliability, WAAM offers a solution for manufacturing larger components with less complexity, lower surface accuracy, and reduced costs, while maintaining more reliable capabilities. Recently, researchers from Dreamweldtech in the United Kingdom developed a novel WAAM process, introducing an innovative printing head and wire feeding system capable of printing ultra-thin walls at the microscale with reasonable surface accuracy, using extremely low current (10-20 A) and tiny wire (0.15-0.3 mm diameter). This development, called "mobile i-WAAM" for microscale components [356], promises competition between WAAM and LPB processes for manufacturing miniature parts. However, WAAM for microscale components is still in its early stages and faces challenges in controlling heat input, wire transfer, and droplet dynamics. These challenges result in low repeatability and instability. This presents a unique opportunity for X-ray imaging technologies to

explore the fundamental mechanisms behind these challenges and help accelerate the development of WAAM for miniature components.

6.5 Cladding Processes

Cladding manufacturing, which utilizes laser or arc heat sources in combination with powder or wire feedstock, represents a novel application within manufacturing processes [357]. This technique forms a thin carbide layer on a substrate, enhancing resistance to corrosion, erosion, and high temperatures, while also improving mechanical properties. Like welding and additive manufacturing (AM) processes, cladding requires a thorough investigation of the physical mechanisms behind melt pool formation and heat transfer. Despite the potential benefits of "in-situ" X-ray imaging in these applications, it has not yet been applied to cladding processes. One major challenge in using X-ray synchrotron imaging for cladding is the process's significant differences from powder bed fusion (PBF) and other AM methods, which necessitates new designs and potentially in-house facilities. Cladding experiments also require larger spaces and higher-powered X-ray sources, which may not be readily available at current synchrotron facilities. Nevertheless, the potential for using X-ray imaging to explore physical phenomena in cladding processes remains a promising avenue for future research.

6.6 Electron beam powder bed fusion (EBPBF) processes

Electron beam powder bed fusion (EBPBF) is a key metal additive manufacturing (AM) process with a wide range of applications in advanced manufacturing [34, 124, 230, 292]. Despite its importance, EBPBF equipment is highly complex, and integrating it with an X-ray beamline presents significant challenges. However, recent advancements in EBPBF technology have led to the development of portable, compact in-house systems that may facilitate integration into X-ray synchrotron facilities for real-time observation of physical phenomena during the process [292]. Only a limited number of publications have addressed the integration of X-ray imaging with EBPBF processes. Notably, researchers at the University of Wisconsin-Madison developed an in-house EBPBF system designed to integrate with beamline B-32D at the Advanced Photon Source (APS) [230] (see Figure 50). Similarly, teams from Sweden and Germany have created another in-house EBPBF system for integration with the X-ray synchrotron radiation facility at DESY in Germany [358]. These experiments are particularly challenging due to the need to manufacture and integrate a portable EBPBF system with an X-ray synchrotron facility. Most existing studies from these groups have focused on the development and integration of EBPBF systems with X-ray synchrotron facilities, rather than investigating specific physical phenomena. Looking ahead, further advancements in simplified EBPBF systems and enhanced X-ray synchrotron facilities could enable a deeper exploration of the physical mechanisms underlying this promising powder bed fusion process.

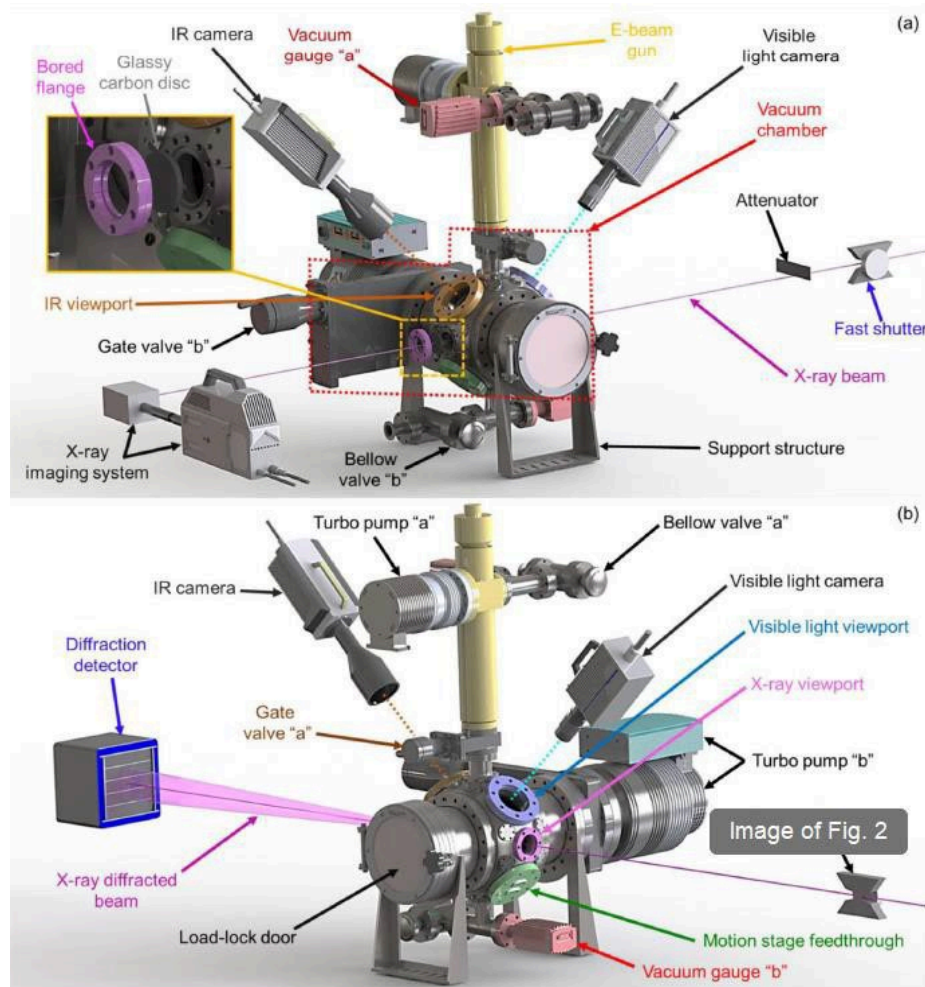


Figure 50. An X-ray facility is set up to observe the physical phenomena in the electron beam metal AM process [230]. Design of the in-situ characterization system. (a) Rendering of the perspective view of the experimental setup for X-ray imaging. (b) Rendering of the perspective view of the experimental setup for X-ray diffraction. The main components of the setup are a vacuum chamber with specially designed X-ray viewports, an electron beam gun, an X-ray imaging system, an X-ray diffraction detector, a visible light camera, and an IR camera. A fast shutter is used to control the exposure of the sample environment and imaging apparatus to the X-ray beam and synchronize it with the electron beam. The X-ray beam trajectory, X-ray imaging system, and diffraction detector are arranged so that the beam penetrates through one X-ray viewport of the chamber, hits the sample, and exits out the opposite X-ray viewport to get recorded by the X-ray imaging system or diffraction system. Customized viewports based on a glassy carbon disc let the X-ray beam penetrate and exit the chamber with sufficient transparency while maintaining a high vacuum. For X-ray imaging experiments, an attenuator is used to reduce the incoming X-ray flux above the substrate surface to prevent damage/saturation of the X-ray imaging system. The visible

light camera and IR camera are tilted, aiming toward the sample through the visible light viewport and the IR viewport, respectively.

7. Outlook for the Future

7.1. 3D X-ray Imaging with the integration of multiple X-ray sources

As discussed earlier, understanding fluid velocity, melt pool dynamics, the formation of eddies, and heat distribution in manufacturing processes is crucial. While developing brighter X-ray facilities improves image clarity, it is equally important to focus on advancing X-ray synchrotron facilities that integrate two X-ray sources to capture 3D images of the melt pool. This integration would enable a comprehensive and detailed analysis of complex physical phenomena and metallurgical processes that cannot be explored with 2D X-ray imaging.

Currently, X-ray techniques for in-situ monitoring are innovative, but all existing X-ray synchrotron facilities worldwide typically operate with a single X-ray source and detector, using only one high-speed camera. While these systems capture high-quality videos and provide valuable data, the resulting images are 2D and captured from a single perspective. Typically, the X-ray synchrotron sources are positioned perpendicular to the weld bead, with images projected onto the X-Z or X-Y planes. To overcome this limitation, novel X-ray synchrotron facilities need to be developed. In 2011, Osaka University in Japan developed an X-ray radiography system to address this challenge. This system uses two X-ray sources, two detectors, and two high-speed cameras, all synchronized to intersect at a central point in the field of view (POV). By simultaneously capturing two videos, the system allows for the extraction of three-dimensional information and images of the melt pool, enabling more accurate measurements of fluid flow velocity, acceleration, and other dynamics that a single X-ray source cannot detect. However, this mini-focused X-ray facility still has fundamental limitations. It lacks the beam flux and power of X-ray synchrotron facilities, making it difficult to observe the boundary between solidification and liquid phases, as well as complex dynamics such as cracking, solidification, or internal defect formation.

Developing next-generation X-ray synchrotron facilities with higher beam flux and multiple synchronized X-ray sources is compulsory to address these limitations. Such advancements will enable scientists to capture 3D images, revealing hidden physical phenomena and mechanisms that are otherwise impossible to observe. The challenge of X-ray facility experimentation in material science is significant, and few facilities are currently equipped. Therefore, advancing X-ray synchrotron technology to include high-performance, efficient, and easy-to-use systems with multiple synchronized X-ray sources should be another top priority for scientists, governments, and scientific committees in the coming years.

7.2. Using X-ray Imaging for WAAM and DED Processes with Higher X-ray Power (Higher Spatial Resolution and Temporal Resolution)

DED processes are crucial in AM processes. DED includes various techniques, such as Laser DED, Electron Beam DED, wire-arc DED, powder-blown DED (including Laser Blow DED), and a newer hybrid wire-powder DED process using an arc heat source. DED processes are characterized by much larger melt pools and sample sizes than LPBF processes. While the surface accuracy of printed parts in DED is lower than that of powder bed AM, DED offers a much higher deposition rate and superior metallurgical properties, making it ideal for manufacturing low-to-mid-complex and large-scale components. Given these advantages, DED processes are receiving increasing attention from researchers, with a growing number of publications in the field. However, most existing AM X-ray imaging publications focus on LPBF processes, which involve smaller melt pools. LPBF systems typically use micrometer-sized powders and relatively low laser powers (100-400 W), making them easier to integrate with X-ray beamlines. These small samples in LPBF processes also represent research-scale printing rather than real industrial applications.

In contrast, DED processes with larger melt pools and samples require higher X-ray power and flux for effective observation. Currently, most X-ray synchrotron systems have insufficient power to clearly observe the melt pool dynamics, droplet transfer, and other phenomena in DED processes. A recent review by Chrysoula et al. [124] suggested that the future of X-ray imaging in AM should focus on EBPBF due to its high-quality results with fewer defects. However, as noted in this subsection, the future of X-ray imaging may benefit from focusing on EBPBF and DED processes, which have seen rapid growth in market share in recent years. While many publications on “in-situ” X-ray imaging have focused on melt pool dynamics in PBF AM processes, few studies use X-ray imaging to investigate melt pool behavior and other physical phenomena in DED processes, particularly in laser-blown powder DED. Furthermore, no publications focused on melt pool and droplet transfer in wire DED processes such as EB-wire DED, Wire-arc DED, or newer hybrid processes. As such, focusing X-ray imaging efforts on DED processes is crucial for better understanding and controlling the physical phenomena. This is an important research topic that deserves more attention in the future. Therefore, new or innovative current X-ray facilities are indispensable to respond to this aim.

7.3 Develop deep-learning models using X-ray images

Developing deep-learning models to predict defects, melt pool dynamics, and microstructure evolution from X-ray images is crucial for gaining deeper insights and improving process control. High-speed X-ray observation systems can capture thousands, or even tens of thousands, of images per second. However, most of these images are not utilized efficiently. Among the vast number of frames captured, only a few are valuable for analyzing key phenomena, while many are redundant or contain

overlapping information. This leads to wasted computational resources and increases the complexity of data processing and selection.

Deep-learning models rely on extensive databases to generate highly accurate predictions. Maximizing the use of frames from X-ray video captures is crucial for advancing these models. However, a key challenge is the low resolution and poor quality of X-ray images compared to process cameras and other imaging systems. Enhancing image resolution and quality is essential for improving model accuracy. Post-processing techniques such as MATLAB, ImageJ, or internal algorithms [152,149] can enhance image quality but cannot fully overcome the fundamental limitations of X-ray imaging. Consequently, current image acquisition remains inadequate for “direct” input in deep-learning models. Addressing this challenge requires next-generation X-ray facilities or improvements to existing systems, such as optimizing process parameters or developing advanced detectors with novel scintillator materials [147,148]. Higher-resolution X-ray imaging would enable deep-learning models to more accurately predict fundamental physical phenomena. This advancement would significantly reduce reliance on trial-and-error methods, saving time and costs in developing novel materials and manufacturing processes.

So far, only a few publications have developed deep-learning models using X-ray image databases to predict melt pool dynamics. However, creating deep-learning models to predict factors like velocity, porosity, phase transition, and microstructure evolution remains a significant challenge for scientists and engineers. In 2024, the APS at Argonne National Laboratory [359] made significant progress, while the ESRF upgraded its beamlines in 2020 to achieve extreme brightness and power [360]. Similarly, DESY in Germany plans to upgrade its beamline in 2026 [361]. These advancements in X-ray imaging systems are promising, enabling the use of high-speed cameras and measurement systems in the development of deep-learning models. Currently, most studies in this field rely on external thermal cameras and equipment to capture signal noise or voltage, which are then compared to X-ray images to predict defect formation, such as porosity [362,363]. However, directly using X-ray images to build deep-learning models is crucial, as it avoids unnecessary resource consumption for capturing X-ray images and improves their efficient utilization, rather than relying on integration with external cameras. Given the importance of efficiently capturing images with high-speed cameras, researchers have recently focused on exploring this capability. In one of the earliest studies, Zhongshu Ren et al. developed a novel deep-learning algorithm based on data from “in-situ” X-ray synchrotron and “ex-situ” X-ray computed tomography, among other post-processing techniques. They compared the accuracy of various algorithms and found that “in-situ” X-ray images were more accurate than “ex-situ” X-ray images, as they allowed for detecting physical phenomena during the process [362]. In 2023, V. Notley et al. became the first group to utilize X-ray imaging to build a machine-learning model for the laser powder blown DED process of IN718 powder, focusing on predicting and detecting the melt pool boundary [364]. Continuing this progress, Wei Le et al. in 2024 developed a new segmentation machine learning model using X-ray imaging to detect and predict the formation of melt pool boundaries [365]. Additionally, Zhongshu Ren et al., in 2023, integrated an infrared (IR) camera with a high-speed X-ray imaging system to observe signal noise during

keyhole transitions. They used the dataset from this experiment to develop a machine-learning model to detect and predict the keyhole pore process [366]. In publications by Kilian Wasmer and his team, they predicted porosity formation in the laser welding process for aluminum alloy AA5005. They integrated a sensor to monitor the laser back-reflected (LBR) and acoustic emission (AE) signals, which were synchronized with X-ray imaging signals. Subsequently, they analyzed the changes in signals, melt pool dynamics, and the physical phenomena occurring during the laser welding process [367,368].

7.4. Development of simulation models

Simulation is a powerful tool for predicting fundamental phenomena and validating experiments. In the context of X-ray imaging, effectively utilizing these images to develop simulation models for predicting fluid flow dynamics, velocity fields, temperature distribution, and other physical phenomena in welding and additive manufacturing (AM) should be a key focus for the next generation. Enhanced imaging capabilities—such as higher power, brightness, and resolution—can provide more accurate inputs for these models. By analyzing fluid flow, velocity, and temperature fields, simulations can predict critical factors like cooling rates, solidification processes, and microstructure evolution, which are essential for controlling the properties and performance of final products. While simulation has traditionally been used to support and validate experiments, the integration of X-ray imaging into simulation models remains limited. This may be due to restricted access to X-ray facilities and the challenges associated with low imaging quality, as discussed in subsection 7.3.

As a result, only a few publications exist that combine X-ray experiments with simulation models as validated tools. However, these models are still in development and primarily focus on validating the fluid flow of the melt pool rather than other fundamental physical phenomena [28,161]. Therefore, developing simulation models to predict the underlying physical mechanisms behind defects and instability in manufacturing and metallurgy processes is paramount. Along with developing deep-learning models, as discussed above, this approach can lead to a new era of using X-ray images for analyzing physical phenomena and predicting and developing processes and materials.

One of the earliest papers on this topic was published by Jin Peng et al., in 2016 [28], where they combined X-ray images with a simulation model to predict the melt pool boundary. In another study, Nadia Kouraytem et al., in 2019, developed a simulation model for melt pool flow and keyhole dynamics in a laser process without powder [161]. Xuxiao Li et al., in 2020, established a multiphysics model to predict gas-liquid flow and powder movement under gas flow [221]. Meanwhile, Jürgen Jakumeit et al., in 2021, developed a Eulerian multiphase model to validate the melting, evaporation, and solidification processes in the LBP process. They considered the pressure and temperature distribution and compared them with real experiments using X-ray images [369]. Leander Schmidt et al., in 2024, simulated the temperature and flow velocity of

laser welding for high-alloy steels [370]. Mehdi Abdi et al., in 2024, proposed a novel approach to re-use X-ray images from publications by other groups and developed a simulation model for keyhole dynamics and melt pool formation [371]. In the most recent publication, T. Florian et al., in 2024, combined X-ray images with multiphysics simulation to reveal pore formation dynamics in laser welding of copper. They discussed the importance of considering the Marangoni force in forming defects [372].

However, recent publications indicate that scientists rely on external equipment and facilities to capture noise signals, which are compared with data from X-ray images in developing simulation models. This approach remains “indirect”. To address this limitation, another approach, “directly” utilizing high-speed X-ray images for simulation models, would be a more effective solution. This approach can significantly enhance the ability to predict and analyze mechanisms and phenomena in materials and manufacturing processes with greater accuracy and depth. Achieving this, however, requires advancements in X-ray facilities, as discussed in subsection 7.3, to obtain clearer and higher-resolution images.

7.5. Develop X-ray facilities and increase global collaboration to enhance research opportunities for scientists and engineers

As mentioned earlier, there are 26 X-ray synchrotrons worldwide, but only a few possess the high productivity required for studying physical phenomena in manufacturing, particularly in welding, additive manufacturing, and casting. Moreover, access to these facilities remains limited to a small number of research groups globally due to the complexity of the systems, the high cost of experiments, and operational challenges. Many X-ray facilities are also heavily utilized for research in other critical fields, such as astronautics, particle physics, medicine, and life sciences.

To address these limitations, investing in new X-ray facilities or enhancing existing ones is essential to improve accessibility, reduce operating costs, and simplify usage. Such advancements would increase efficiency and create more opportunities for scientists, engineers, and related industries. Ultimately, these improvements could accelerate and expand the capabilities of X-ray imaging for new applications, such as additive manufacturing for plastics, and enable the integration of external factors—such as ultrasonic waves—to enhance print quality [373,374,375].

8. Conclusions

This review paper has provided a comprehensive overview of the history of X-ray imaging, detailing the development of X-ray facilities worldwide since the invention of X-rays by Röntgen in the 1890s. It also explored the progress of applying X-ray images, especially "in-situ" X-ray images, to material and manufacturing sciences, particularly in welding, additive manufacturing, casting, and furnace processes. Additionally, the paper offers a vision for the future of "in-situ" X-ray imaging, discussing the history and current status of efficiently utilizing X-ray facilities, especially synchrotron X-ray facilities. The expansion of X-ray imaging technology for advanced materials and novel technologies is crucial. Researchers should focus on applying "in-situ" X-ray imaging to develop new materials and manufacturing processes, incorporating deep-learning and simulation models. To achieve this, it is essential to create new X-ray facilities or improve existing ones to capture high-resolution images.

Abbreviation Table

Abbreviation	Meaning
AM	Additive Manufacturing
AI	Artificial Intelligence
ML	Machine learning
MAM	Metal Additive Manufacturing
DED	Directed Energy Deposition
LPB/LPBF	Laser Powder Bed Fusion
WAAM	Wire Arc Additive Manufacturing
EBPBF	Electron Beam Powder Bed Fusion
TIG	Tungsten Inert Gas
GTAW	Gas Tungsten Arc Welding
MIG/MAG	Metal Inert Gas/Metal Active Gas
SAW	Submerged Arc Welding
PKAW	Plasma Keyhole Arc Welding
VPPA	Variable Polarity Plasma Arc
SEM	Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
EBSD	Electron Backscatter Diffraction
NDT	Non-Destructive Testing
ICI	Inline Coherent Imaging
FGM	Functionally Graded Materials
AI/ML	Artificial Intelligence/Machine Learning
APS	Advanced Photon Source
ESRF	European Synchrotron Radiation Facility
SSRL	Stanford Synchrotron Radiation Lightsource
SSRF	Shanghai Synchrotron Radiation Facility
SLS	Swiss Light Source
DESY	Deutsches Elektronen-Synchrotron
CET	Columnar-Equiaxed Transition
HEA	High-Entropy Alloy
IMC	Intermetallic Component
LBR	Laser Back-Reflected
POV	Point of View
SLAC	Stanford Linear Accelerator Center
NIST	National Institute of Standards and Technology
CALPHAD	CALculation of PHase Diagrams
IR	Infrared
US	United State
UK	United Kingdom

CRedit Authorship Contribution Statement

Van Anh Nguyen: Writing – original draft, methodology, investigation, formal analysis, supervision, sourcing, project administration, and conceptualization.

Duy Han Le: Writing – review and editing.

Dilen Damian: Data collection and analysis.

The Bach Tran: Data collection and analysis.

Quang Hung Le: Data collection and analysis.

Nhu Tung Nguyen: Data collection and analysis.

Declaration of Competing Interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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