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# ADDITIVE MANUFACTURING REVOLUTION IN THE CONTEXT OF TECHNOLOGY REVOLUTIONS

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**ABSTRACT**

This article positions Additive Manufacturing (AM) within the broader context of historical technological revolutions, recognizing its transformative impact while acknowledging that future generations may perceive it as an early-stage technology. AM has evolved through several industrial revolutions, particularly benefiting from advancements in Artificial Intelligence (AI) and the Internet of Things (IoT). The convergence of traditional manufacturing techniques with these contemporary innovations has created a favorable environment for the widespread adoption of AM technologies. The article emphasizes the need for AM to fully embrace this integration to achieve its potential. The discussion highlights that the core objective of Focused Beam Additive Manufacturing (FBAM) is to control the solidification process, ensuring the production of sound and reliable components on the first attempt. Despite being a multidisciplinary technology, all relevant disciplines converge on achieving a flawless melting and solidification process. This involves precise modulation of energy sources, effective powder management, motion control systems, and temperature/environment regulation, all aimed at producing microstructurally and geometrically flawless components. The article concludes that the success of FBAM depends on the careful orchestration of these multidisciplinary activities, centered around a well-controlled solidification process, to deliver high-quality components that meet business needs.

**KEYWORDS:** technology revolutions, additive manufacturing, artificial intelligence, Internet of things

## INTRODUCTION

It is common to hear people talk of technology revolutions when referring to computers, artificial intelligence (AI), additive manufacturing (AM), and many more. The word “revolution” refers to an abrupt change in the status quo of a social structure or technology. An example for the social structure change is the socialist revolution that started with the beginning of the 20th century and expanded to different parts of the world in that century. Another example is the revolution brought about by the Black Death, the plaque in the late 1340s. It wiped out half of the population from China to Europe situated around the Silk Rod [1]. Reactions from peoples and leaders of the time were similar to what was heard during the COVID19. Some tried to protect themselves, and others preached it was a punishment from God so there was nothing humans could do. Whatever the messaging was, the plaque had a huge social effect; an economically extractive system of serfdom diminished starting from western Europe, mainly in England.

Both of these social events can rightfully be described as a revolution with a major difference between the two. The socialist revolution was imposed by a leadership team everywhere it was implemented, whereas the disappearance of serfdom was driven by the serf peasants themselves but was aided by an unpredictable event that changed the social force balance. When half of the population was exterminated, the survivors were at a better position to bargain for their labor. In fact, the peasant revolution had far reaching impacts on future social struggles, including the socialist revolution whose style of implementation was experimentally proven unsuccessful. False, under calculated, or over promised ideals were not sustainable.

Technology revolutions actually do not happen abruptly. They are rather a result of a series of evolutions in multiple technological fronts taking place in an unseen backstage. For example, what dazzles people as AI today has essentially evolved on algorithmic statistics, data science, and computers over decades [2].

Social and technology revolutions can have mutual influences. COVID19, for example, has initiated everlasting social changes to technology use. Similarly, technology (e.g., AI) will impact the future social structures in a very substantial way. In this interactive world, new technologies will survive as they deliver their promises. Additive Manufacturing (AM), as a significant revolution in manufacturing, has very strong promises. Luckily, it acquired the will of world leaders and peoples. Therefore, AM is at a very favorable historical spot to deliver its true promises without exaggeration for its sustainable future.

This article intends to place AM in a historical perspective. Technical arguments are qualitative. From that broad perspective, it is the aim to illustrate that although it is revolutionary, AM is part of a manufacturing sphere with centuries of experience and should interact with it constantly to increase its chance of rapid success.

## TECHNOLOGY REVOLUTIONS

Throughout history, human endeavor has developed various ways to make tools and devices to help sus-

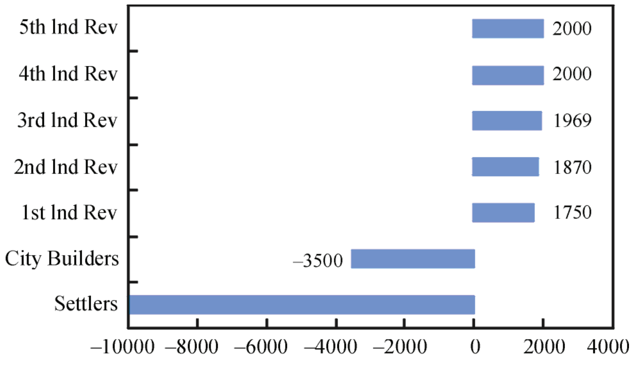


**Figure 1.** Technology revolutions [3]

tain human life. The pace of these developments was unnoticeable until the end of the last ice age in 10000 BCE, which then took a sharp stride as seen in Figure 1. After their first documented evidence of existence about 7 million years ago, early human migration from Africa to occupy the entire world dates back to 1.6 million years ago, and signs of tool making goes back to 2.5 million years ago [3]. Following a long period of hunting and gathering, humans settled and started agriculture in around 10000 BCE in the Fertile Crescent, which envelopes the Levant, southern Turkiye, and northern Iraq. This was the Neolithic revolution. Tools were made from naturally available materials such as bone, stone, wood, straw, mud, etc. The next revolution came 6500 years later in 3500 BCE. At this time, humans learned to use bronze and formed city states. It was also around this time the first examples of writing appeared in Mesopotamia by Sumerians. Another 5250 years were needed to reach the first industrial revolution in about the 1750s, started in England. Mechanization was the motivation of this revolution. At that point, it became clear that human intellect dominated the manual labor of old times. That surged brainpower brought the second industrial revolution, electrification, in the 1870s, only about 120 years after the first one. The third industrial revolution, automation, ensued even faster in 1969, less than 100 years following the second. Digitization, the fourth industrial revolution, in the 2000s is the latest advancement in the human endeavor to control their destiny through the use of new manufacturing technologies, Internet of Things (IoT), and Artificial Intelligence (AI). This evolution took place only 31 years after its predecessor. The fifth industrial revolution has already been underway since 2020 [4]. Obviously, time lapse between the revolutions has shrunk rapidly.

While manufacturing has transitioned from serving individual needs to serving societal needs (a tribe, local ruler, city, or country), it progressively has generated knowledge of making things, named technology. At some point, research based technology creation ensued. A systematically reasoned research then led to science, although it must have intuitively influenced the decisions of a stone-age tool maker, because he/she most probably had had a thought process about how to shave a piece of stone into a tool. In fact, the words science and technology are used, most of the time, in a compound form almost to mean the same thing, though they are different. Technology goes back to the time when humans developed the skills to make tools. This activity, however, did not need a deep understanding of fundamental principles of making or using the tools, which is defined as science. In other words, early humans did not need science to create technology. A more recent example may be the steam engine which was developed by Newcomen in 1712 and substantially improved by Watt in 1769. A scientific foundation for the working principles of the steam engine was offered by Sadi Carnot in 1824 when the first industrial revolution was already paving the way for the second [5]. Thus, the steam engine served human needs for more than a century without humans understanding its science, thermodynamics.

None of these revolutions were introduced or evolved without problems. A consequential anecdote from Queen Elisabeth 1st of England can be cited here [1]. William Lee develops the first stocking frame knitting machine in 1589. He seeks an interview with Queen Elisabeth 1st to show his invention and secure patent rights. The Queen refuses to grant a patent by asserting “Thou aimest high, Master Lee. Consider thou what the invention could do to my poor subjects. It would assuredly bring to them ruin by depriving them of employment, thus making them beggars.” This and similar events delayed the first industrial revolution almost by two centuries. It is insightful to keep in mind that all industrial revolutions brought tragedies, but, like the people of England, humans always have found ways to better their lives. In fact, leaders and peoples who embraced contingent creative destructions have succeeded eventually [1]. Fast forward to today, it is very fortunate that there has been a desire from world leaders and peoples to implement new technologies to improve the competition in technology creation and subsequently human lives.

## KNOWLEDGE CREATION

Scientific methodology for knowledge creation follows a series of steps such as observation, data collection and analysis, hypothesis development, hypothesis testing, refinement, and generalization. This is a mixture of two historical approaches, a deductive one and an inductive one. The inductive approach, initiator of the scientific methodology, sets out experiments to generate data to help understand a phenomenon, whereas the deductive approach devises a hypothesis to explain a phenomenon. Both of these approaches have pros and cons. It is good to have a hypothesis that can explain multiple phenomena via a systematic approach, and it is also good to generate data based on observations of the physical world rather than on hypotheses created just for the sake of creating hypotheses. The inductive approach can also be termed a trial-and-error approach. For example, the Edisonian approach is this type. It is commonly attributed to Thomas Edison that success is meticulously exhausting thousands of unsuccessful ways to single out one successful way of developing a product or a process. This approach appeals to many as it infers perseverance, and Edison, indeed, created several great products/technologies. However, if a phenomenon can be explained by a simple, systematic calculation, why try to exhaust thousands of alternatives by experimentation [6]. In fact, modern economy does necessitate efficient use of resources. Thus, technology and science should rely on waste-free research approaches; an approach that is based on fundamental understanding of the interested phenomena coupled with lean project management.

## ADDITIVE MANUFACTURING REVOLUTION

Additive manufacturing (AM) is one of the latest beads in the string of technology revolutions. Since its first patent granted in 1971 [7] at the dawn of the 3rd industrial revolution and its first wider appearance in rapid prototyping applications in the early 1980s, AM has evolved to become a functional part manufacturing technology. Although its evolution has taken place during the 3rd industrial revolution, it is frequently cited as one of the keystones of the Industry 4.0, Factory 4.0, or Manufacturing 4.0. It is a bottom-up, disruptive manufacturing approach which offers flexibility in time and space and makes on-time and on-site customized manufacturing possible. Thus, it has received tremendous attention from several industries ranging from toys to aerospace.

Interestingly though, AM has introduced itself as an immiscible entity within the global manufacturing industry which has a significant share (16 %) in the global economy [8]. In contrast, AM is only a blob of oil (0.057 %) in a large ocean of manufacturing [9]. The effort has been to emphesize how AM is superior to and different from traditional manufacturing (TM). While there is a truth to this and are significant differences, there are also fundamental similarities and opportunities where they can complement each other. Perhaps, enthusiasm and overexcitement, as a reflection of human nature to new beginnings, have led to the immiscibility.

However, all past revolutions were transient (evolutionary) socio-technological processes that lasted hundreds to thousands of years, except for the recent acceleration, paving the way to the next revolution. Each revolution was built over the knowledge generated during its predecessor. It is important to note that all human achievements should be revered, so AM is no different than the stone age technology revolution from a technology revolution perspective. Indeed, AM has stretched over several technology revolutions, 3rd, 4th, and 5th. Hence, it should embrace the vast knowledge that can be inherited from the earlier and present-day manufacturing as well as other contemporary technologies like AI and IoT. Indeed, AM can accelerate its success by interacting with TM. It is only that way AM can see what TM components it can transition, what gaps exist that cannot be covered by TM, and how it can fill those gaps.

## ADDITIVE MANUFACTURING METHOD

Following sections intend to provide a comparative insight between AM and TM of metals to provoke a hand shake between the two. After a general focus on process reliability and comparison, fusion-based AM (FBAM), which is a melting-solidification process, is used as an example to illustrate fundamental similarities. Then, the article ends with sections on recent FBAM trends and effective utilization of skills. Although FBAM is exemplified, there are implications in the article that are applicable across various AM technologies (modalities) and material types. In any case, FBAM modalities comprise >90 % of the metal AM industry [9], so concepts in this article would resonate with most of the AM industry.

AM is a multidisciplinary technology. It takes sufficient understanding of each discipline to comprehend what it really takes to manufacture a validated component additively at a reasonable cost and scale. FBAM is a sub family of the AM technologies (modalities), primarily categorized into two groups in ASTM 52900 [10], powder bed fusion (PBF) and directed energy deposition (DED). The former uses powder as feedstock, and its energy source is either laser (PBF-L/M) or electron beam (PBF-EB/M). The latter can use powder or wire feedstock, and its energy source is laser (DED-L/M), electron beam (DED-EB/M), or electric arc (DED-Arc/M).

FBAM of metals involves transforming a feedstock into 3-dimensional (3D) components via first melting (fusion) and then solidifying it. The solidification behavior of the molten metal is very important for the final part performance. After all, it is the solidification behavior of the melt which leads to a distinct microstructure that essentially determines a variety of properties and performances (e.g., mechanical, thermal, environmental, etc.) of an AM fabricated component. In addition, it is critical to understand the AM machine systems and their sub-systems such as the energy source, build chamber, feedstock management system, motion system, the atmosphere, and thermal management system. These functional systems enable AM to be an automated fabrication method. Furthermore, validation is a necessity for safe utilization and certification of a component. Hence, it should also be understood why a statistically significant validation is necessary for this complex process that is expected to yield a reliable product performance repeatedly. All these concepts are interrelated and can be successfully orchestrated for a business success by effective and efficient skills/resource utilization.

## AM AS A RELIABLE PROCESS

AM is an automated, push-button process as advertised globally. Nevertheless, it takes a good amount of effort to make it really a reliable push-button process. It has been a misconception, at least in some spheres, that sophisticated manufacturing systems, such as those used for AM, should create parts so perfect that they should not require a thorough validation that quantifies reliability via qualification. In fact, validation is a piece within the total quality assurance in manufacturing. If the quality assurance is planned considering key performance indicators (KPIs) imposed by the application, there shouldn't be any awe or surprise when an AM fabricated component functions well in the aerospace, medical, high pressure/temperature, or other challenging applications. Nevertheless, the initial excitement on AM concealed the effort needed for Process Qualification (a.k.a. Operational Qualification, OQ) that confirms required material properties and final-product qualification (a.k.a. Performance Qualification, PQ) that guaranties the expected performance. Of course, the AM system itself and the operators should be qualified, too. These qualifications ensure a repeatable process and product performance for an AM system or reproducibility across several AM systems. They enable certification, too. It is a sour fact that validation is expensive and time consuming. Luckily though, multiphysics and multiscale simulations aided by AI can offer a tremendous help in the design of AM suitable feedstock (alloys) [11], component geometry [12–14], and process [13–15]. They will, in turn, enable desired product performance at a reduced time and cost by enabling print/fabricate right the first time and validate the first time.

Additive Manufacturing Original Equipment Manufacturer, AM OEMs have an obligation to assure safe and reliable operation of their sub-systems and integrated systems through statistically significant repeatability and reproducibility analyses. It is good to see the OEMs continue to release improved new systems. It would be even more appealing if they also published their process capability indices or Sigma levels for each one of their systems. The OEMs should be encouraged through regulations and customer behavior. Nonetheless, it is the due responsibility of the final component manufacturers and users to make sure a component is appropriately validated for a safe utilization. As such, it is essential to realize that validation is a cumbersome but a necessary step in manufacturing, and there is not a magical wand to make stuff happen. Standards such as ASTM 52920 and 52930 [10] can provide guidance in qualifications of the systems, processes, and part performances. Actually, the AM community can borrow a lot from the experiences of the Technological Manufacturing (TM) community with regards to validation and standardization. After all, analysis methods (data generation and processing) used for a component's testing and validation are agnostic to how the component is manufactured. Fortunately, AM service providers recently started implementing AM according to principles of manufacturing [16].

## AM PROMISES AS A MANUFACTURING TECHNOLOGY

Let's step back and revisit a question, backed up with an almost 40 years of AM evolution. How advantageous is AM compared to, for example, Computer Numerical Control, CNC machining which has about 80 years of history as a TM method? When talking about AM, almost everybody starts by expressing that AM is a digital manufacturing; it is enabler of the Industry 4.0. Yes, everybody is correct. However, CNC manufacturing is also fully digital. A CAD is used in Computer Aided Manufacturing, CAM operations to fabricate the final part directly. Feedstock management during the machining is not as complex as it is in AM. Heat treatments or surface treatments are generally the only and well-understood post processes, unlike elaborate AM post processes. It is hard for AM actually to compete with fully digital CNC machining centers without its other advantages such as part consolidation, possibility of complex geometries especially with internal features or lattice structures that improve product functionality and/or performance, low buy-to-fly ratio, no-tooling requirements, rapid prototyping for design iterations, and low inventory requirements. Furthermore, since a single AM machine is able to build multiple geometries, shop floor complexities can be reduced. These are obviously significant advantages. One other advantage AM has promised is distributed manufacturing. Design files can be sent to AM farms in multiple locations on earth (and space) to print the same geometry with the same qualities everywhere. Even so, considering increased footprints and investment costs of AM systems, one can make a similar claim for CNC machining centers, though this is still a realizable promise with small footprint AM systems. Yet another promise of AM is the democratization of manufacturing. Nevertheless, the democratization can also be tarnished by similar arguments made for distributed manufacturing. Of course, when possible, the distributed manufacturing can help with supply chain. In view of the foregoing, it seems an overall reevaluation of the AM promises is due. Beyond all, a real value assessment of AM is only possible through a total life cycle analysis which fortunately has gained traction in recent years [17].

Surely, AM has a disruptive potential that may make some TM methods obsolete in the long run, but it has a complementary, enabler characteristic for TM as well. For example, AM can fabricate tools and equipment for TM such as metal injection molds, forging dies, casting molds and cores, etc. Either disruptive or with great complementary potentials, AM is another manufacturing method. As such, it can learn a lot from the TM experience, especially with regards to statistically significant process and product validation procedures. Conversely, instead of behaving as an immiscible entity within the manufacturing community, AM should establish a bridge into traditional manufacturing and use its knowledgebase.

## FUNDAMENTAL SIMILARITIES BETWEEN THE TM AND AM SOLIDIFICATION PROCESSES

As stated earlier, solidification behavior determines the microstructure of a component which in turn dictates the performance. Hence, knowledge of solidification is essential for a successful FBAM fabrication. This knowledge also can orchestrate the AM systems/sub-systems to prevent formation of micro defects like pores and cracks and macro defects like geometric/dimensional nonconformity. Furthermore, understanding of the solidification process helps achieve desired AM fabricated component performance.

It is relavant to mention here, in passing, that powder metallurgy routes for component manufacturing also exist and form the basis for sinter-based additive manufacturing (SBAM) technologies. There is a vast amount of knowledge in the powder metallurgy industry that SBAM can benefit.

Performance of a component depends on its material properties which, in turn, are dependent of its microstructure that is dictated by its processing history. When the ingredients (chemical composition) of a component is fixed, the process history defines its performance. Until they are ready for service, most industrial components go through primary/secondary melting operations that form the raw feedstock as billets or rods to be used in primary/secondary manufacturing operations like casting, atomization, forming, joining, or machining. An AM fabricated component assumes its net-/near net-shape during the AM process. It cannot, for example, go through a forming (forging or rolling) operation that can modify the grain structure and may alleviate internal porosity. Therefore, AM is a single step, final operation to create a geometry, similar to casting.

All AM modalities that involve melting of a feedstock followed by its solidification can be analyzed by principles of the solidification science. Some of the processes that involve solidification are casting, directional solidification, single crystal growth, vacuum arc re-melting (VAR), electro slag re-melting (ESR), welding, and FBAM. These methods are illustrated by cartoons in Figure 2.

In FBAM, creation of a desired microstructure in a component for a given alloy and a geometry conforming to CAD is attainable by managing thermally driven phenomena like heat transfer, fluid dynamics, undercooling, stress, etc. One should realize that equation systems that describe these phenomena are same for the FBAM and other solidification processes with varying boundary conditions. For example, FBAM is very similar to traditional melting based welding which is similar to traditional continuous directional solidification. They are all dynamic solidification processes with a moving heat source, but the fundamentals are similar to stationary casting, too.

During solidification, a molten substance starts transforming into a solid when its temperature drops below the melting point. This transformation forms a solid-liquid (s-l) boundary (interface) separating the two phases. Fate of this interface is driven by the heat flux and the composition profile ahead of it, which in turn, controls the morphology and size of the forming solid.

Heat flux during solidification can be from the melt to the solid or vice versa. In the former case, the interface moves in the opposite direction to a constrained heat flux in a positive temperature gradient. However, when solid grains form in the melt due to random temperature fluctuations or inoculation, the interface advances in the direction of an unconstrained heat flux in a negative temperature gradient. The temperature gradient is defined from the melt to the solid. In other words, in directional solidification, the heat is extract-

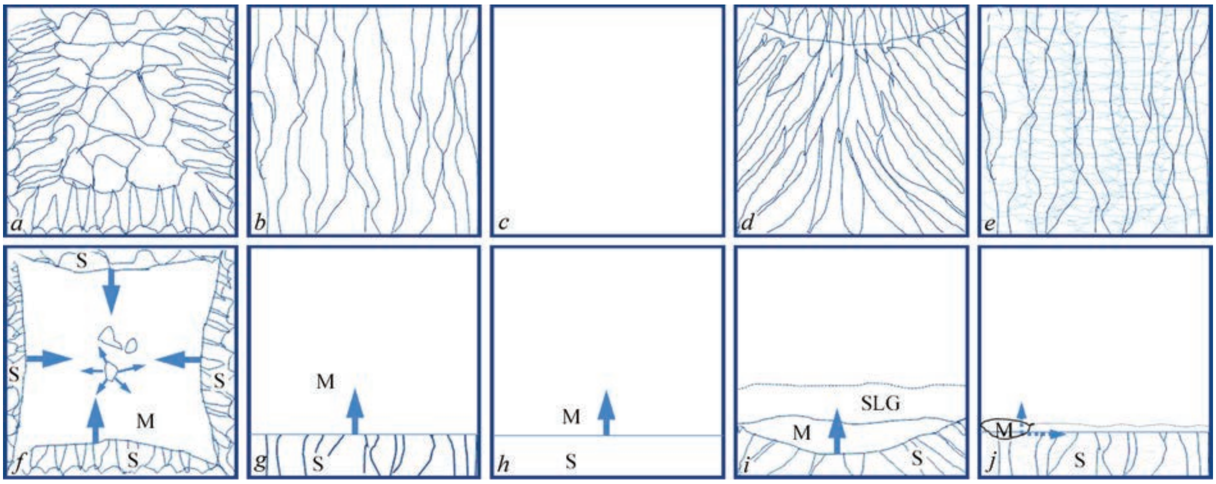


**Figure 2.** The top row sketches illustrate grain microstructures that can be created by solidification methods sketched in the bottom row. Grain structure after (*a*) casting, (*b*) directional solidification, (*c*) vertical Bridgman type single crystal growth, (*d*) electroslag re-melting (ESR) and vacuum arc re-melting (VAR), (*e*) FBAM. Arrows in (*f–j*) show direction of the solid-liquid interface during solidification. A slag (SLG) layer exists in ESR, shown by a dashed line in (*i*). A melt pool is outlined in (*j*) with dotted line representing powder bed. S indicates the solid and M the melt

ed thorough the solid (melt is hottest), but in the equiaxed solidification, the heat is extracted through the melt (solid is hottest, the middle grains in Figure 2, *f* and Figure 3, *b*). Although an interface stability analysis is beyond the scope of this article, it is important to review the basic conditions leading to the stability/instability as they determine the morphology of the grain microstructure. When the interface advances in a planar fashion, it is said that the interface is stable. On the other hand, when random perturbations form at the interface and grow in time, the interface becomes unstable. The perturbations follow a direction defined by the heat flux and the crystallographic orientation of the solid perturbation. The directional solidification may take place with a stable interface to yield a single grain (single crystalline) microstructure, while the equiaxed solidification has an unstable interface with random nucleation sites that leads always to a poly grain (polycrystalline) microstructure.

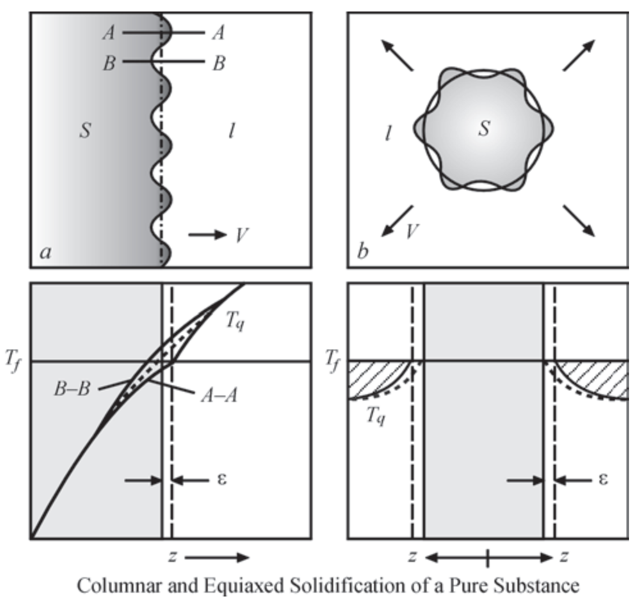


**Figure 3.** In directional solidification of pure substances, any perturbation (ε) in a positive temperature gradient melts back (left images). A solid nucleus in the melt assumes a dendritic morphology at its interface and grows into an undercooled melt (hatched) in its vicinity (right images). $T_f$ is the melting temperature, and $T_q$ is the real temperature [18]

Composition profile ahead of the interface also plays a decisive role in the stability/instability of the interface. In fact, a positive temperature gradient is adequate to suppress the instability during the solidification of pure substances, like pure metals or semiconductors, because thermal undercooling is the only driving force for the instability, Figure 3. This is useful to keep in mind when AM fabricating pure metals. However, during the solidification of alloys, another phenomenon, called constitutional (compositional) undercooling, develops due to a solute accumulation or depletion ($C_L$) ahead of the interface. Figure 4 represents the case of the solute accumulation. Equilibrium melting temperature ($T_L$) in this undercooled region of the melt is greater than the actual local temperature ($T_F$). Hence, the s-l interface advances into this undercooled region between the $T_L$ and $T_F$ to form cellular or dendritic grains depending on the s-l interface velocity ($V$) and temperature gradient ($G$) ahead of the interface.

In casting (Figure 2, *a*, *f*), the melt loses its heat into its surroundings in all directions. This enables formation of solidification fronts initiating from periphery of the melt's container, the mold. The result is a non-uniform grain morphology ranging from fine equiaxed at the periphery to coarse equiaxed ones in the middle. Elongated grains exist between the two regions. It is noteworthy that grain morphology (shape) as well as the scale (fine vs coarse) change during the solidification. Two main parameters are responsible for these, s-l interface velocity ($V$) and temperature gradient ($G$) ahead of the interface as seen in Figure 4. The GxV controls the scale of the microstructure where a high value leads to a fine microstructure (cast periphery, Figure 2 (F)) and a low value leads to a coarse one (cast middle). The ratio G/V controls the morphology. The middle of the cast has a low value of the G/V that gives rise to an equiaxed dendritic solidification. In contrast, intermediate values of GxV and G/V between the periphery and middle of the cast yield a columnar dendritic grain morphology.

Directional solidification (Figure 2, *b*, *g*) restricts the heat transfer to the axial direction. Therefore, the solid grains form and grow bottom-up in this direction, and grains take an elongated morphology because their lateral growth is restricted. Although all of the grains are largely aligned in the axial direction, their crystallographic orientations are different. That is the reason for the existence of grain boundaries. A more precise solidification control is necessary to suppress the grain boundary formation during the solidification. First, the lateral temperature and composition variations should be eliminated. Second, a high positive G/V is necessary in the axial (vertical) direction to suppress s-l interface instability, Figure 5. These conditions should yield a single grain (Figure 2, *c*, *h*) when the solidification is complete.

Grain microstructure of the Vacuum Induction Melting/Vacuum Arc Remelting, VIM/VAR continuous solidification (Figure 2, *d*, *i*) follows similar arguments where a vertical steady temperature gradient leads to elongated grains, and the lateral temperature variations generate a polycrystalline grain structure.

It is worth noting that the s-l interface in all of these solidification methods advances by addition of new atoms from the liquid to the solid. That is to say the interface advances continuously by additions of new atomic layers. This is additive manufacturing at atomic scale. The single crystal growth processes (Figure 2, *h*) is especially useful to visualize the additive nature of the solidification. It is also important to understand that the solidification takes place in the entire interface at the same time in these traditional solidifications. In contrast, in FBAM, an energy source melts a metallic feedstock (powder or wire) and then allows for its solidification following a lateral path in a plane. This is to say the solidification is compartmentalized. When the melting and the solidification of the geometry in the lateral plane is complete, several atomic layers are added to the previously created solid layer, and the additions repeat in a compartmentalized (lateral) and discontinuous (axial) manner until all of the planned number of lateral planes (layers/slices) are melted/solidified. A checkerboard scan strategy or the area melting, to be briefly introduced later, may be useful to visualize the compartmentalized solidification. Therefore, FBAM is new only in that the solidification is compartmentalized into a much finer

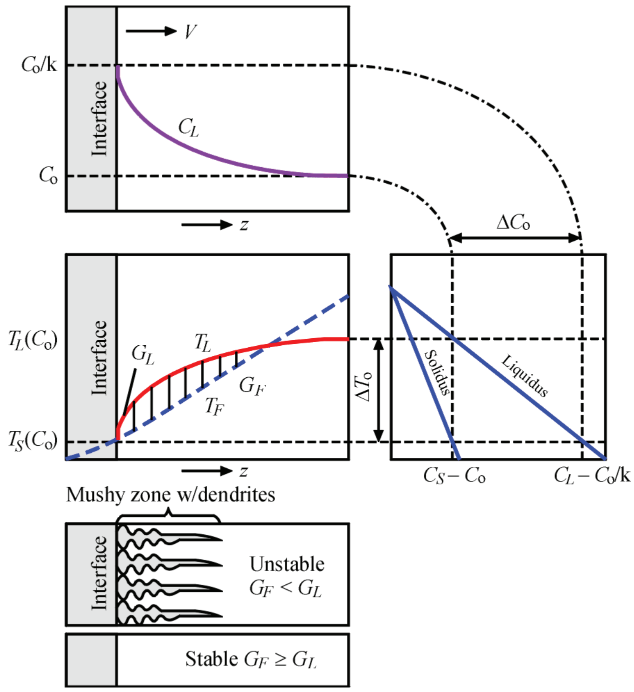


**Figure 4.** Accumulated solute profile $C_L$ ahead of the interface (top) leads to temperature profile $T_L$ (middle-left). The hatched region is undercooled into which s-l interface advances (bottom). A sketch of the partial phase diagram is on the middle-right. $G_L$ is the equilibrium temperature gradient, and $G_F$ is the actual one

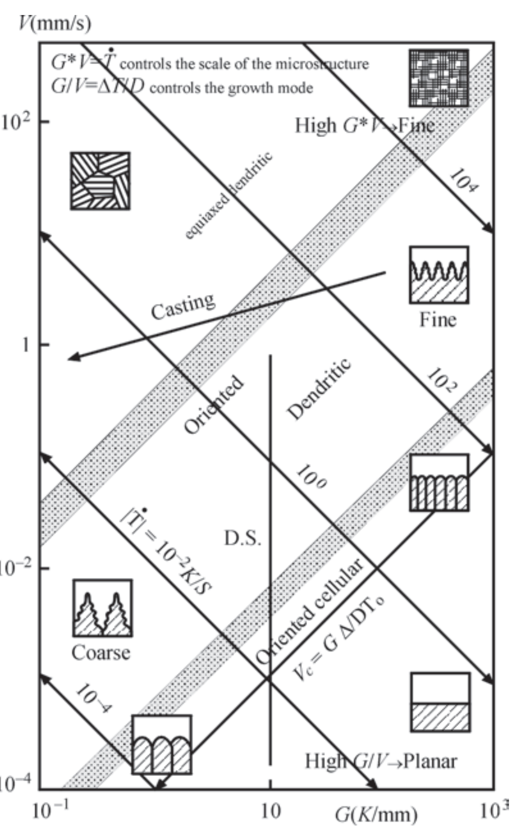


**Figure 5.** Solidification morphologies [18]

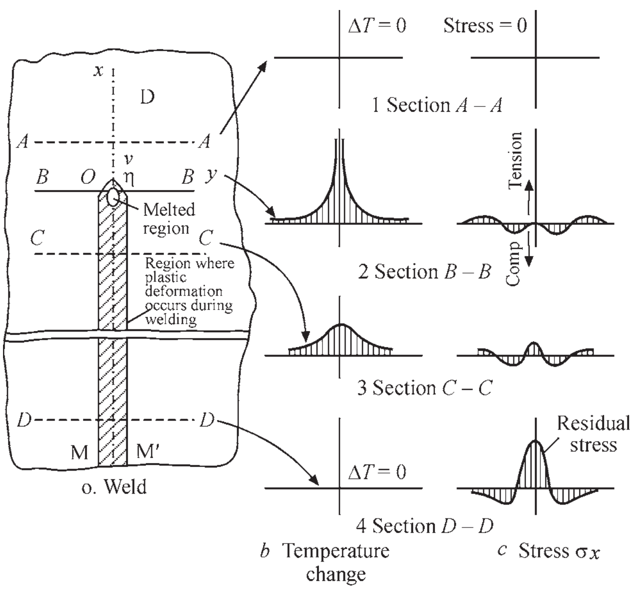


**Figure 6.** Evolution of temperature and stress during a single-track melting [19]

resolution in the lateral directions. Otherwise, layered (additive) solidification is a very old method that can be seen in a variety of methods as explained so far and illustrated in Figure 2.

Whether it is PBF or DED, in essence, FBAM is a process akin to welding by melting. Nevertheless, there are differences between the welding and FBAM processes. In the welding, microstructure in and around the weld is discontinuous. The temperature and stress fields are also localized to the welded region as seen in Figure 6 [19]. In contrast, a repeated melting and solidification in FBAM alleviates the stress localization and the grain structure is not discontinuous, as seen in Figure 2, *e*. The energy source (laser, electron beam, or electric arc) creates a melt pool on the previously produced layer on interacting with the feedstock (Figure 2, *j*). When the energy source moves, the melt pool then starts solidifying from the tail. The solidification is certainly similar to the welding and in a way similar to casting as described above. Thus, the melt pool solidifies from the periphery towards the middle. The previously created layer serves as the mold. Boundary conditions of the melt pool (solid, packed powder, or gas) determines the grain microstructure according to $G/V$ and $GxV$ of the interface [20]. Usually, the elongated grains, similar to ones in Figure 2, *a* and commonly seen in the welds, extend from both sides and collide at the weld centerline because of the welded plates acting as heat sink and a much narrower mold width than the conventional cast mold. A side water cooling in continuous casting creates a grain structure more similar to welding (Figure 2, *d*). Of course, the grain structure that forms in a layer is re-melted during creation of a subsequent layer. Thus, the grains in the new layer continues from the previous ones. This leads to a typical directional, long grain structure in the FBAM fabricated parts (Figure 2, *e*). Additionally, the boundaries of the individual melt pools are discernible in FBAM. That is because of the rapid solidification yielding fine grains at the base of the mold (previous layer) and trapping of accumulated solute ahead of the interface (Figure 4). Such marks are also commonly observed in single crystal growth when the interface velocity rapidly changes [21]. The degree to which melt pool boundaries show up depends on the solidification rate and alloying elements that are rejected from the solid solution. However, observed dendritic or cellular grains in these regions indicate absence of an absolute solute trapping which manifests itself with a planar interface and partitionless solidification (uniform composition) at extreme high solidification rates. As seen in Figure 7, the dendritic/cellular tip radius and spacing decreases with solidification velocity where capillary forces lead to the absolute interface stability. On a similar note, dendritic grain structures seen in atomized powders indicate that solidification rate is not high enough to experience the absolute stability. These basic solidification principles have guided many research works in academia and industry to create engineered grains in FBAM fabricated components. The attempts range from local grain engineering to single crystal solidification [20].

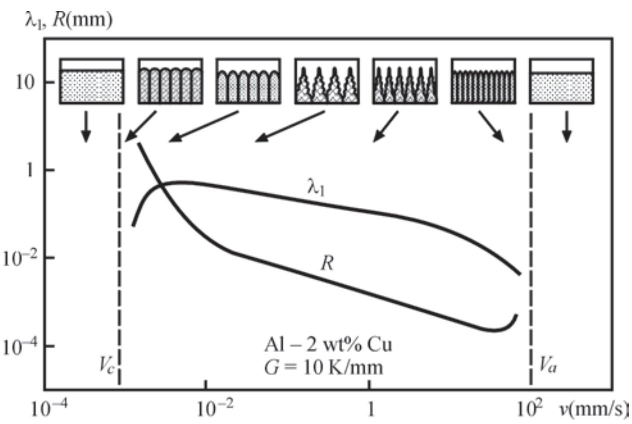


**Figure 7.** Morphology, tip radius ($R$), and spacing ($\lambda_1$) of cells and dendrites. $V_c$ is the boundary of the constitutional stability, and $V_a$ is the boundary of the absolute stability [18]

## RECENT TRENDS IN FBAM

A few recent advances, briefly touched upon below, are increasing melted area per unit time, low angle printing, laser beam modulation, process monitoring, and new alloy design. Without a doubt, each topic is actually so important that deserves to be treated in a separate article.

One recent trend, mainly in PBF-L/M, has focused on approaches to melt a larger area in a given time. This can provide a competitive edge to PBF-L/M against the other high yield AM modalities. Building AM systems with multiple (>1) lasers is one approach, and using expanded laser beams that can melt an area (area melting) several orders of magnitude larger than a conventional single point laser is another. The multi laser and area melting PBF-L/M can compete in production yield. Certainly, increasing number of lasers should increase the production yield, but at an increased initial investment cost. Stitching in multi laser PBF-L/M still needs to be characterized thoroughly. Similarly, spatter interactions from concurrently active lasers needs elucidation. Also, a careful control of thermal distribution in the build chamber with multiple active lasers is necessary as it can affect the melt pool dynamics as well as the thermal distortion of the solid. A variety of area melting approaches based on pulsed diode lasers can be found in the literature. Some create a line or rectangular shaped laser beam by combining several individually switchable Gaussian laser beams [22]. Scanning of this beam over the build plane consolidates the powder into a solid. The ability to switch an individual laser on and off provides the spatial resolution. In another approach, several diode laser beams are homogenized into an area and then shaped by an Optically Addressable Light Valve (OALV) [23]. In any area melting approach, the laser pulse frequency required to melt a given area as well as the penetration depth is critically important because they determine the volume melted per unit time. Also, due to a large lateral dimensions to very small thickness ratio of a melted/solidified volume, an appreciably high stress may prevail in this volume during the area melting process. Notably, in area melting, it can be possible to promote a single crystal solidification because of its melt pool shape. Firstly, the packed powder thermally insulates the melt pool laterally to minimize the heat loss in those directions. Secondly, the base of the melt pool is in direct contact with a higher thermal conductivity solid which is expected to create a large vertical temperature gradient (G), parallel to the build direction. Thirdly, the melt pool is expected to be more quiescent than that in the keyhole mode of the Gaussian laser beam. Finally, a melt pool with a large, flat base oriented perpendicular to the high vertical temperature gradient is in a favorable orientation to solidify as a single grain. Thus, a very carefully balanced area melting process control may promote a single crystal growth as well as alleviate the stress in the solid. The forgoing also implies that a spatial modulation (shape) of a single laser beam may help with single crystal solidification through modification of the melt pool shape.

Low angle printing is still an ongoing, recent effort to eliminate supports in PBF-L/M. Currently, there are AM systems that can fabricate as low as 20° planes from the horizontal without supports, which is a huge advance from 40° that was common just a few years ago. A cautionary note is necessary about this trend. The low angle printing is realized by manipulating the process parameters in downskin regions which serve as a crust to transition to the bulk build parameters. It goes then without saying that a downskin region has a different microstructure and so material properties due to different $G/V$ and $GxV$ than the bulk. Defect density in the downskin may be different, too. It is important to realize that this region is an external surface that interacts with its surroundings and influences surface related material properties and performance like corrosion and fatigue. At this point, it is trivial to see that a validation procedure must take this downskin into consideration. The downskin either should be appropriately validated or removed during a post-processing operation.

Laser beam wavelength and shape modulation, which have found a place both in the PBF and DED, is an advancement that can help control the solidification (melt pool) dynamics. The modulations can also help manipulate thermal conditions to alleviate fabricated component distortion. A vast number of academic and industrial work, as well as commercial [15] multiphysics and multiscale simulation tools, is available on melt pool dynamics and thermal management during the FBAM fabrication which can help to obtain desired part performance through engineered microstructures.

The FBAM process monitoring is still evolving. It is accomplished by either passive or active monitoring. In the passive monitoring, AM system parameters are monitored to predict process anomalies. In the active approach, different types of on-/off-axis sensors are utilized. The monitoring is useful in that it can tell where, when, and sometimes how/why a defect forms. Its technical feasibility and value per cost, however, prevent its full penetration into the AM fabrication. Data management is also a big issue. Defect information from each of the thousands of layers can be obtained at the scale of a melt pool or of a layer by visible/infrared based sensors (seeing eyes) with various spatial and/or spectral resolutions. Alternative approaches based on hearing, like acoustic and ultrasound, have been suggested. More elaborate monitoring approaches have been implemented by fusing several seeing and hearing sensors. Considering the complexities of the monitoring, it is legitimate to ask if the process can safely proceed without being monitored at all? In fact, a geometry and material specific process parameter set and path definition, empowered by physics in-formed AI, can prevent processing defects. Then, the focus may be on identifying the probability of a defect occurrence to prevent the occurrence.

Metal AM has been practiced so far by using conventional metallic materials (pure or alloy). Those materials are the ones usually available for welding. The reason is obviously the thermo-mechanical similarity between the welding and FBAM processes as stated earlier. The welding community has developed in many years the proper metals that are durable against phenomena like melt undercooling, strain age cracking, liquation cracking, centerline cracking, etc. New metals are necessary to push the frontiers of FBAM forward. Multiphysics and multiscale simulation tools based on thermodynamics and AI should be utilized for a faster material (alloy) design to keep up with fast pacing evolution of the AM technology [11].

## SKILLS REQUIRED IN FBAM

Among the essential resources of a company, human resources is the one with outmost importance. It is a company's personnel who simply make the business function. When a company secures required finances, facilities, and equipment, the success forward depends strongly on the human capital which includes leadership and individual contributors.

As mentioned at the start, AM is a multidisciplinary technology. Each discipline demands a specialized skill set. It is practical to group the skills as ones that relate to the AM processes and others that relate to building or operating the AM systems. Usually though, individuals carry out tasks in either group regardless where their strongest skills lie.

The process related skills in FBAM include specializations, for example, in heat transfer, fluid dynamics, solid mechanics, and solidification. The system related skills require specializations in the energy source, motion systems, temperature control, environment control, and feedstock management. Only a good match of a specialization and a required skill can lead to success. For example, an expert in mechatronics may be very skillful in operating an AM system, but process development in that system begs for other skills. Similarly, a fluid dynamics expert can very satisfactorily simulate and describe behavior of a melt pool in FBAM, but interpretation of why the solid does not follow a heat flux direction perhaps needs knowledge of preferred solidification directions dictated by heat flux as well as crystallographic structure of the solidifying metal.

In new technology development, concepts can be demonstrated and verified through multiple experimentations. However, when involved parameters are many, which is the case in FBAM, simulations can help. For an efficient resource utilization, both in the experimentations and simulations, it is important to know what parameters to investigate and how to investigate them. A purely inductive, trial-and-error approach will only generate waste in resource utilization, though success is possible. In contrast, a systematic approach based on fundamental understanding of the involved phenomena can help with an efficient AM technology development. Thus, suitable expertise and skills should be tasked to facilitate the correlations between the fundamental phenomena and the investigated concepts to correctly set a simulation or conduct only necessary experiments. That brings efficiency to an investigation and prevents waste in resource utilization.

A fast paced new technology development journey necessitates the highest level of expertise and skills that might be obtained either by formal education or by experience. This is presently relevant to AM as it still continues its technology developmental journey. The experts should recognize and dissect a problem effectively. They should be familiar with conducting systematic and efficient research which is essential to bringing a new technology to market fast and first in a cost effective manner. They also should know what information is needed to solve a problem, where to look for it, and how to access it. They should quickly absorb the information, analyze it, generate results, interpret them, and finally create procedures for implementation. This skilled workforce, of course, needs support of a servant leadership to function properly.

## CONCLUSIONS

Intention of this article is to place AM in a historical technology revolution perspective. AM is a revolutionary manufacturing technology, but it will certainly be seen as a "stone-age" technology for those living in millennia ahead of our present time. All revolutions (social or technological) come with an excitement which is in the human nature, but it should not curb seeing the broader landscape. The AM technologies have evolved passing through several industrial revolutionary epochs, the 3rd through the 5th. It is certainly very lucky that it can take advantage of many different types of technological and social advancements. The leaders and peoples of the world embrace the AM technologies. Traditional manufacturing methodologies that have been developed throughout the centuries together with contemporary AI and IoT are extending their hands to AM. It is time AM embraced this warm welcome.

The foregoing qualitative technical discussion has indicated that the core of FBAM is to have a controlled solidification process that yields sound products which can be validated at first trial and then utilized safely. Although FBAM is a multidisciplinary technology, all of the relavant disciplines essentially support accomplishment of a flawless melting and solidification of a small melt pool that when it traverses an entire build plane and then repeats this for all of the sliced planes of a geometry, a successful solid component is created. For instance, any advance in modulation of the energy source targets a desired control of the solidification process to, let's say, increase the melting efficiency, reduce the spatter, or manage the thermal field in and around the melt pool to promote desired grain structure and accomplish geometric conformity. Similarly, a powder management system that spreads (or blows) the powder perfectly and prevents powder contamination aims to have a flawless solidification process. Moreover, a motion control system either of the build platform or the energy source helps to melt and solidify the feedstock flawlessly. Temperature and environment control of the process area also establish necessary conditions to enable a flawless solidification process. Finally, accommodations to keep the thermal stress under control are implemented to have a steady melt pool and its uninterrupted in-plane translation. Hence, all FBAM multidisciplinary activities can be orchestrated, by accurately assigned skill sets, around the need for a well-controlled solidification process to fabricate a microstructurally and geometrically flawless component for business success.

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