Residual stress in additive manufacturing

- Control using orientation and scan strategies

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Abstract

Components with complex features that are designed with their function as a core aspect often are not viable to be manufactured with traditional methods. This has been a bottleneck in the past, leading to heavier parts with various sub-assemblies and a significant waste of material. With the emergence of additive manufacturing (AM) technology manufacturing of complex components has now turned into reality. Within AM, the laser-based powder-based fusion (LPBF) method is one of the most widely adopted methods to manufacture near net shape complex metal components. However, to be implemented on a larger scale various hurdles must be mitigated first.

One of the main persistent issues in LPBF is of residual stresses (RS), which are formed due to repeated sequences of heating and cooling, creating a high thermal gradient between the layers. These RS can play a significant role in the component’s functionality during service, but also can affect the manufacturing process. Therefore, a detailed investigation into the formation and control of RS is of foremost importance. This thesis aims at shedding light on various aspects of the RS formation especially, the effect of build orientations and different scan strategies. For this purpose, Inconel 718 (IN718) was selected as a material for investigation due to its wide use in gas turbine components and good weldability making it a good material for additive manufacturing processes.

L-shaped components and test cubes were prepared for residual stress mapping and microstructure study. The RS were measured using neutron and X-ray diffraction methods where applicable. From the investigations, it was revealed that the L-shape components built in different orientations showed significant variation in RS magnitude, but a general trend of RS distribution with tensile stresses at the surface and compressive at the bulk for all the components. A simplified finite element model for RS prediction was established and validated based on the experimental results. Similarly,
the use of different scan strategies can lead to a different magnitude of RS for the L-shape components. The remelting strategy with remelting done after every 3rd printed layer seems to decrease the RS magnitude in comparison to the counterparts printed without remelting. This has also been verified with a simplified finite element simulation. The microstructure study showed that crystallographic texture can also vary with the different scan strategies and no significant preferred orientations of the grains were found with the remelting done at every 3rd printed layer. However, with the total fill strategy, strong crystallographic texture was observed in the scan direction. Further investigations into the remelting scan strategies with different variables of remelting such as power, speed, and number of layers between the remelting scan revealed an effect of the laser power in the increment of texture intensity along the building direction. A combination of chess pattern and remelting every 3rd layer decreased the RS magnitude in comparison with other samples, where parameters for remelting strategies were changed. In addition, the crystallographic texture varied with different process parameters used for the remelting. For further reduction of RS without employing post-processing, investigations into novel scan strategies need to be undertaken and at the same time texture formation also needs to be investigated.

**Keywords**: Additive manufacturing, residual stress, neutron diffraction, FEM, scan strategies, build orientations.
Populärvetenskaplig sammanfattning

Tillförlitligheten under drift för metallkomponenter kan kopplas till möjligheten att förutsäga deras beteende och möjligheten att förhindra haveri genom design av materialet, bearbetningstekniken och själva komponenten. Det har skett en snabb tillväxt i användningen av laserbaserad additiv tillverkningsteknik där man via ett lager-för-lager-förfarande kan producera lätt komponenter med förbättrad prestanda. Denna teknik har en stor designfrilighet så därför kan mer komplexa geometrier nu tillverkas vilka tidigare var svåra att realisera med traditionella tillverkningsmetoder.

Med mer komplexa former blir problemet med spänningar som finns kvar inuti komponenten under tillverkningen allt viktigare. Dessa kvarstående spänningar kallas restspänningar och de medför en hög risk för komponentfel under drift om de inte hanteras. Dragrestspänningar vid ytan är kända för att påskynda spricktillväxten till haveri och tryckrestspänningar är kända för att vara fördelaktiga för att förlänga utmattningslivslängden hos komponenterna. Eftersom dessa spänningar uppstår under tillverkningsprocessen så är de även nära kopplade till de processparametrar som används för att producera dem. Relationen mellan restspänningar och processparametrar har inte undersökts i någon större utsträckning och branschen följar sig på ”trial and error” för att välja de bäst lämpliga processparametrarna. Detta arbete syftar till att koppla restspänningsarna till några av de viktigare processparametrarna som lasers rörelsemönster, lasers hastighet och effekt, och den orientering i vilken de producerades för att kunna skapa komponenter med bättre kvalitet och ge möjlighet att förutsäga komponenternas beteende.

Metalliska material är kristallina till sin natur, dvs. de har ett periodiskt arrangemang av atomerna och det finns ett visst avstånd mellan atomernas plan. Förekomst av restspänningar oavsett om de är drag eller kompressiva ändrar avståndet mellan atomplanen. Förr att mäta de spännings som
orsakar denna förändring av atomplansavståndet så har en icke-destruktiv teknik via neutrondiffraktion användes under hela projektet.

I det aktuella arbetet har det fastställts att en betydande skillnad i restspänningsstorlek kan observeras helt enkelt genom att ändra orienteringen av komponenten vid tillverkningen. Det har också observerats att den del med ett stort område i kontakt med byggplattan ovanpå vilken den var tillverkad har den största deformationen när komponenterna avlägsnas från byggplattan. En annan aspekt av arbetet var att upprätta en förenklad beräkningsmodell för att förutsäga restspännningarna och att verifiera den med resultatet av experimenten. Den förenklade modellen gav samma fördelning av spänningsarna men med högre värden än de experimentella resultaten. Modellen kan därför användas för att hitta de kritiska områdena och förbättra designen före tillverkningen.

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Cheers, and enjoy what life throws at you!

Prabhat

[Signature]

Linköping, April 2022
Outline

This thesis work is an extension of the work presented in the Licentiate thesis presented in 2020 [1] and is divided into two parts:

**Part I** - Background on Additive manufacturing, Residual Stresses, Measurement of Residual stresses, influence of processing parameters on residual stresses, the influence of residual stress on mechanical properties, modeling approaches for prediction of residual stresses, a summary of the appended papers, discussion, and outlook.

**Part II** – Appended Papers and Manuscripts

List of papers


Papers not included in the thesis:


Author's contribution to the papers

**Paper-I**
Conceptualization, selection of sample geometry and strategy after discussion with co-authors, and execution of neutron experiment along with data analysis and writing and revising of the manuscript.

**Paper-II**
Conceptualization and implementation of the model with help of supervisors, running simulation, and optimization of the simulation were done, data extraction from the model and comparison with the experimental result. Writing of original draft and revision of the manuscript.

**Paper-III**
Selection of scan strategy after discussion with co-authors, experiment planning and execution, and data analysis for neutron diffraction experiment and microstructure analysis. Writing of original draft and revising of the manuscript after feedback.

**Paper-IV**
Selection of scan strategy after discussion with co-authors, experiment planning and execution, and data analysis for neutron diffraction experiment and comparison of results between the samples. Writing of original draft and revising of the manuscript after feedback.

**Paper-V**
Selection of printing strategies for texture investigation after discussion with supervisors and collaborators and execution of neutron diffraction experiment along with data, and microstructure analysis. Writing and revising the manuscript after feedback from co-authors.
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To my grandfather

बाजेमा समर्पित
PART-I
Chapter 1

Aim and overview

Manufacturing complex components with a design optimized for the function of the part is one of the primary advantages of additive manufacturing (AM) in comparison with traditional manufacturing methods. Laser-based powder bed fusion technology (LPBF) is one of the prime methods to manufacture components out of nickel-based superalloy for demanding applications such as in aero and gas turbine engines. Due to their function-centered design rather than being limited by the manufacturing process, innovative designs can be implemented in production with ease, often leading to components with a lighter weight and improved functionality [2]. Due to the aforementioned reasons, the demand for metal AM components is also on the rise year by year [3].

There are a few hurdles to be overcome before LPBF technology can be widely used in different industries. This thesis aims at bringing light to the prevalent issue of residual stresses (RS) in components manufactured using LPBF technology. These RS are generated during the printing of the part, and due to the nature of the manufacturing process itself, they cannot be avoided. As LPBF itself is a very complex process dealing with powder, laser, powder interaction, airflow in the chamber, etc., a systematic study into the main parameters influencing the RS formation and magnitude was necessary. This work is focused on the mitigation and control of the RS formed during the process of manufacturing by utilizing the build orientations, scan strategies, etc. Further, it presents insight into the influence of the printing parameters including laser scan speed, power, and remelting sequences on the microstructure as well as crystallographic texture respectively.
The following research questions are addressed by the work presented in this thesis:

1. How do the printing orientations influence the residual stress magnitude and distribution?
2. Can time effective simplified model be used for the residual stress control in LPBF?
3. How do the novel scan strategies influence the residual stresses and the microstructure in as-built samples?
4. How do the process parameters for the remelting/rescanning strategies influence the residual stresses and texture development?

Limitation of the thesis

The work is solely focused on the investigation of as-built components/samples printed from Inconel 718 powder using the laser-based powder bed fusion method. No investigations are made on samples printed using Electron beam melting methods or heat treatments influence on the microstructure of the components.
Chapter 2
Additive manufacturing

2.1 Introduction

Manufacturing of parts with the process of adding material in a stepwise sequence to create a three-dimensional object can be called Additive Manufacturing (AM) in a broad sense. According to ASTM F42, AM is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods” [4]. AM technologies were widely used to create prototype components with polymer-based materials in the 80’s but since then it has seen a journey to create fully functional parts made from a range of different polymer-based materials to metallic materials. The AM process is classified into seven categories by International Organization for Standardization (ISO) [5] and is presented in Fig. 1.

![Fig. 1 Classification of AM processes according to ISO/ASTM 52900:2015.](image-url)
Material Extrusion is the process where a wire form of polymer-based material is fed via a movable heated nozzle head to melt and create a low viscous material. This material then gets deposited continuously on top of the base plate in a layer-by-layer fashion to obtain a solid part. The movement of the nozzle head is governed by the CAD file of the part which dictates the path for the nozzle head to move. In most systems, either the base plate or the nozzle head or both of them are movable in three orthogonal directions to create the shape.

Material Jetting is a process similar to material extrusion but instead of continuous deposition, the material is deposited as liquid droplets from the nozzle to form a part based on the CAD input.

Binder Jetting is a process in which a polymeric binder is used to bind the powder together to form the shape of the components. The process starts with selectively depositing the liquid binder via a feeder onto the powder bed, governed by the CAD input as in other processes. When a new layer of powder is applied using a roller the binder droplets will bind the powder to give a shape of the cross-section of the component. This is repeated until the entire part is printed and after each layer, the object is lowered on its build platform. Next, the curing process of the binder is done, and the remaining unbound powder is removed before the de-binding and sintering process is performed in a uniform thermal environment to get a dense component. This method can be used for manufacturing both metal and ceramic components.

Powder Bed Fusion is a process that utilizes a moving heat source being applied to powder particles contained within a powder bed on a layer-by-layer basis based upon the CAD geometry to form a component. In most cases, either a laser or electron beam is used as a heat source to consolidate the powder particles. This method is suitable for producing both metal and polymer components and is one of the most common methods to produce near-net-shape components. Further, the PBF process can be sub-categorized into electron beam melting and laser beam melting depending upon the heat source being used for melting the powder. To be aligned with the focus of
the thesis, the laser-based powder bed fusion (LPBF) method will be disused in detail in the following section.

*Direct energy deposition* process is similar to the powder bed fusion process in many aspects, but metals in the form of powder or wire can be used. They are fed directly into the energy source to be melted and deposited on top of the base plate to form a component layer-by-layer.

*Vat polymerization* uses a liquid photopolymer resin in a vat to produce a part using ultraviolet (UV) light. The UV light is shined from the top or bottom depending upon the system to selectively harden the resin in the areas governed by the CAD model of the part. As the resin is solidified the platform moves either up or down to print another layer on top of it. It is also known as the stereolithography technique.

*Sheet lamination* is a process where metal or paper sheets are cut out and bonded together in a stack to form a 3D component.

### 2.2 Laser-based powder bed fusion (LPBF)

Out of various methods for additively manufacturing metallic components the laser-based powder bed fusion (LPBF) method is one of the main methods to get high-quality net shape or near-net shape components with the least post-processing being involved. Metal manufacturing has seen a large increase in demand in recent years and is predicted to increase in the future as well primarily due to the vast variety of materials that can be used, and the new development of the different alloys particularly tailored for the laser bed fusion method.

The process of printing part starts with a CAD model of the part which is then sliced into several layers based on the size of the feedstock powder particle size being used for the printing. The layer size is typically in the range of 30-60 microns depending upon the materials and powder. The sliced part is used as an input for the printing machine. The machine has two separate chambers one for the powder feedstock and one for the printing of
the part. A simplified sketch of the process is shown in Fig. 2. Both of these chambers move up and down during the printing process. As the name says, the source for melting the powder particle is a laser, and both pulsed or continuous types of lasers can be found in the systems. Nowadays even multi-laser systems are being used to increase productivity further. Depending upon the material being used for the printing, processing parameters such as laser speed, power, etc. are selected to get the maximum density of the part.

For printing, a thick plate is used as a base material, which is also pre-heated up to a certain temperature in most of the systems. To start printing, the powder chamber moves up and the re-coater will start to move the powder from the powder chamber to the printing chamber. This movement of the powder chamber and the re-coater governs the layer thickness being used for the part printing. Once the fresh layer of powder is applied on top of the base plate, the laser starts to selectively melt specific regions in the powder bed to create the cross-section of the component given by the CAD model. Once the layer is printed, the part chamber moves down to accommodate a new layer and this process continues until the entire part is printed. Finally, the part chamber is moved up to remove the part from the machine along with the base plate after removing the remaining powder. It has to be noted that this entire process is done in an inert atmosphere to prevent the oxidation of metals while being melted.

A number of conventional alloys including 316L, Ti64AlV, and IN718 have been extensively studied for use in additive manufacturing [6–8]. Tailored compositions of conventional alloys and alloys of innovative compositions with better manufacturability for LPBF are also being developed and investigated. For example, superalloys with gamma' precipitates that can be sensitive to post-processing cracking due to residual stresses and phase transformation are being investigated. Also, novel approaches to tailor the composition to the LPBF process are being done [9,10].
2.3 Common terminologies used in AM

To understand the process and implication of the process parameters it is necessary to address some of the basic terminologies that are commonly used in the AM processes.

2.3.1 Scan strategies

This is commonly used to describe the movement of the laser with respect to the powder bed. There are various ways to selectively melt the powder and most of them are predefined by machine manufacturers. Some standard scan strategies used can be seen in Fig. 3. Among these scan strategies using a rotation of scan vector every layer by 67° or 17°, using chess pattern are commonly selected to get denser material and lower residual stresses [11,12]. Other strategies such as one-directional or bi-directional scan strategies are also used to increase the throughput as these strategies are generally less time-consuming than the previously mentioned ones. Similarly, the use of fractals and other novel scan strategies are also being investigated to enhance the properties of as-built components [13,14].
2.3.2 Laser parameters

As the primary source for melting is a laser, its parameters such as speed and power play a significant role in the outcome of the parts. Machine manufacturers may provide processing windows for some commonly used alloys but for the novel alloy compositions, the processing window is selected based on a set of experiments to finalize the optimum speed and power, laser spot size, etc.

One of the primary sources of defects in the build is the wrong selection of the laser power and speed. Different cases of defect formation due to a combination of laser speed and power are discussed in later chapters.

Along with the laser parameters, build flaws can originate from defects in the powder and contamination of powder as well. Also, the layer thickness that is being applied also plays a role in defect formation.

2.3.3 Hatch distance and contours

The hatch distance is the distance between the center of two neighboring laser passes (See Fig. 4). In most cases for metals, the outer perimeter of the cross-section layer is melted with different parameters than the bulk, which are commonly known as contours or borders depending on the equipment being used (see Fig. 4). This is typically done to achieve a smoother exterior surface and better tolerance. The hatching distance and laser spot size also make a difference. The hatching distance should be selected such that there is no lack of fusion between two neighboring scanning vectors.

The quality of the produced part in terms of microstructure and mechanical properties is highly influenced by the scan techniques and process parameters being utilized. A detailed discussion about the importance of these parameters is given in later chapters.
2.4 Applications of the metal additive manufacturing
As the metal AM technologies have been improved, they are now utilized on a bigger scale to create a net shape or near-net shape components with good tolerance and properties. They have found or have been explored for applications in many different fields. Among other sub-branches of metal
AM, LPBF is one of the most popular mainly due to the variety of metal powders available for it. The potential of the LPBF technology has been utilized in different fields. For example, a hydraulic manifold seen in Fig. 5 is re-designed from original components with many sub-assemblies into one single component whilst saving the weight by approximately 90% and improving the performance as well [16]. The application of the AM for the space also can be seen in Fig. 6a which is a topologically optimized satellite bracket saving weight but delivering the required performance. Similarly, complex features such as the internal cooling channel for combustion chambers of a rocket engine can be now easily printed into one single component, which with other manufacturing processes has been difficult to produce (see Fig. 6b). Also, in the realm of the consumer electronics AM has shown potential to manufacture unique designs and performance as seen for earphones in Fig. 7.
Further, in the case of the implants for joints and dental implants which are often complex in shape are being manufactured using AM and tailored for each individual. (see Fig. 8). Further investigation on printing scaffolds and stents that can be used during surgery is also going on [17,18].

All the examples given above are only a few areas where AM of metals has been used. However, many other areas have not been covered here.

With the design freedom given by the AM, and design adapted for the AM, both weight savings and improved functionality can be achieved while using less raw materials as seen by the previous examples. However, there are hurdles before this technology can be widely incorporated into the current manufacturing ecosystem. One such hurdle is the management of residual stresses (RS) generated and is the focus of this thesis and the next chapters deal with it.
Chapter 3

Residual stresses

Residual stresses (RS) are self-balanced stresses that are present inside a part when no external forces are applied to it. The generation of residual stresses is an intrinsic part of many manufacturing processes and depending upon the distribution and magnitude they can alleviate or degrade the mechanical properties of the components. Depending upon the length scale they are equilibrated over, RS are divided into three major groups as seen in Fig. 9.

In reality, RS at a point is a combination of all of the types of residual stresses [19]. The different types of RS are described next.

*Type-I* (macro-RS): These are residual stresses that equilibrate over a large length scale such as the dimension of the sample and are also known as macro-RS. They are average stresses which contain the stresses within smaller domains or phases. Upon change of boundary conditions, these RS can lead to deformation in the component as they try to get a new equilibrium state.

*Type-II*: They are the stresses that are in equilibrium over a smaller length scale such as in between a couple of grains or in between phases. In the case of polycrystalline material, they are present in almost all the cases due to grain orientations and anisotropy present in crystals.

*Type-III*: These RS are self-balanced in ever-smaller domains such as around dislocations point defects caused due to intragranular defects such as point defects, vacancies dislocations, etc. [20]. Both *Type-II* and *Type-III* are collectively known as the micro-RS.

All of these RS are of significance as they can alter the performance of the components. Also, depending upon the use case of the component one or another type of RS is of interest for investigation.
3.1 Origin of residual stresses

Residual stresses (RS) as mentioned earlier are intrinsic to the manufacturing processing. They are the result of spatially inhomogeneous plastic deformation occurring during the process. It is also known that local RS can be developed due to mechanical mismatch between grains of different orientations and thermal/mechanical mismatch between the constituent phases of a multi-phase material. Depending upon the manufacturing process the cause of the formation of RS varies and they can be grouped into three major branches.

Mechanical origin

This is one of the commonly encountered origins of RS formation. Any manufacturing that causes non-uniform plastic deformation will result in RS formation and examples of such processes are rolling, forging, bending, extrusion, drawing, etc. in metal forming [21–23]. This RS generation
mechanism is also utilized to introduce beneficial residual stresses such as the surface mechanical treatments including shot peening and deep rolling [23–29]. Also, RS related to inhomogeneous plasticity can develop during the operation of the component.

**Thermal origins**

The stresses can arise from the temperature gradients within the component developed during the manufacturing process or during the service. Both Type-I and II stresses can arise due to the temperature gradients. For example, in the case of welding, the misfit of thermal expansion between the weld seam and surrounding material gives rise to the formation of Type-I stresses. In the case of the multi-material system such as ceramic matrix composite Type-II stresses are exhibited from the local mismatch of the thermal expansion between the materials [20,30].

**Phase transformation origins**

These are caused due to localized changes in the phases induced during phase transformation when heat treatment or chemical treatments are done. For example, in the case of through hardening of steel, a transformation from austenite to martensite results in volume changes, and residual stresses are formed [31,32].

Residual stresses are not always harmful. Whether they are beneficial or detrimental in a specific case depends upon the magnitude and distribution of the residual stresses and external loading. Careful engineering of the RS can be useful to further alleviate the mechanical properties of the part. This is done mostly by using mechanical methods where a compressive RS are introduced at the surface of the sample which is known to increase the fatigue life of the component in comparison with having tensile RS (T-RS) at the surface [33–37]. This is related to the fact that the surface T-RS can help in the crack opening and growth. Also, the introduction of compressive stress can help in the extension of fatigue life by hindering the crack growth and opening mechanism.
RS control in manufacturing is important for the successful production of parts with desired properties. The generation of significant RS can lead to part failure during the manufacturing process, compromise part tolerance, result in sub-optimal mechanical performance, or reduce the service life of the part.

3.2 Residual stresses in LPBF

In the case of LPBF, the formation of RS is primarily related to the thermal gradient mechanism (TGM) and shrinkage mechanism [38,39]. This thermal gradient ($\Delta T$) is a result of very localized heating for a short time interval and rapid cooling thereafter. The main heat transfer mechanism in the LPBF is due to the conduction to the base plate through already built material and other secondary mechanisms such as radiation heat losses to the chamber, convection, and conduction to the powder bed from the exposed surfaces of the component also plays a role in the RS formation.

Let us consider the simplest case where an entire layer made out of material that does not undergo a phase transformation during cooling is printed on top of already printed layers that are solidified and have lower temperatures in comparison to the newly printed layer. This results in temperature gradients between the layers. The temperature variation is $\Delta T(Z)$ in the vertical direction and $\Delta T(X, Y)$ in the X-Y plane due to different boundary conditions in different directions. For further simplification, it is assumed that the printing of layer $N+2$ does not cause the melting of the already printed layer $N+1$, (see Fig. 10). Initial cooling of the $N+2$ layer will not result in residual stress development in the layer as it is in liquid form. When the layer has solidified but still has a higher temperature than $N+1$, the continued cooling to lower temperatures will lead to a build-up of residual stresses in both layers. The $N+2$ layer will shrink more than the $N+1$ layer due to the temperature gradient $\Delta T(Z)$. Constraint from the $N+1$ layer will generate in-plane tensile stresses in the $N+2$ layer, which are balanced by compressive stresses in the $N+1$ layer. The higher shrinkage of the $N+2$ layer also causes an upward type bending moment acting on the layer. This
bending moment is constrained from the N layer and the base plate, leading to tensile stresses in the Z direction in the outer regions of the N+1 and N+2 layers which decreases towards the center with balancing compressive stresses [40].

Due to additional boundary conditions for heat dissipation in the X-Y plane, the outer regions tend to cool faster than permitted by the bulk at the center. This differential cooling rate induces the temperature gradient in the X-Y plane (\( \Delta T(X, Y) \)) and may generate additional in-plane stresses as well as out-plane stresses that vary with X and Y axes.

In reality, the temperature gradient keeps changing when an additional layer is added on top of the N+2 layer as the laser can penetrate multiple layers in one scan and the compressive stress at the bulk continues to accumulate with balancing tensile stresses developed near the surface [40–46]. For the final residual stress retained in the part after it is printed and cooled down to room temperature, the thermal strains that get transformed into plastic strains due to ease of yielding at high temperature are responsible.

The evolution of the residual stress can be traced with the FE model presented in Paper-II. Consider, for example, the development of residual stresses in the building direction during printing at two elements at 4 mm above the base plate, with one of them at the surface and the other at the center of the cross-section. Fig. 11 reveals tensile residual stresses develop at the outer element and compressive stresses at the inner element.

The generation of residual stresses is a much more complex scenario due to the complex interaction between the laser and the powder layer. So, the scan strategies, build orientations, and geometry of the part can significantly affect this RS formation during printing and the retained RS levels after removal from the base plate.

In the case of printing materials where phase transformation in solid-state can occur during the printing, additional stresses are generated due to the incompatibility between different phases due to different thermal properties.
Also, a volume change will further add-on to the RS generated due to TGM and shrinkage mechanism.

Upper layer cools faster and shrinks more than the lower layer due to high temperature.

Further cooling leads to tensile stresses in the N+2 layer and compressive in the N+1 layer.

With additional cooling from the surface and more layers being added on top leads to tensile stresses near the surface and balancing compressive stresses in the bulk.

Fig. 10 Origin of residual stresses in additive manufacturing
Fig. 11 Evolution of the stress for selected elements 4 mm away from base plate both at the surface and at the bulk of the cross-section for an L-shaped part. Adapted from [47]
Chapter 4

Neutron diffraction: Unique tool for residual stress measurements

In order to assess the levels of the stresses inside a component, several methods are widely used in the field. Among various tools for non-destructive residual stress analysis, diffraction-based techniques are widely used in industrial and research environments. Diffraction-based techniques are based on Bragg’s law of diffraction and use a radiation source such as an X-ray or neutron. X-ray diffraction is a fast measurement technique, but laboratory X-ray diffractometers are suitable for quantifying the surface or close to the surface stress due to the lack of penetration depth.

The principle of diffraction-based techniques is based on Bragg’s law of diffraction for crystalline materials. For the diffraction configuration shown in Fig. 12, constructive interferences between radiations scattered by the lattice plane will occur when Bragg’s law given by Eq.1 below is satisfied and thus a diffraction peak is obtained.

\[ n\lambda = 2d_{hkl}\sin\theta_{hkl} \]  

where \( n \) is an integer, \( \lambda \) is the wavelength of the radiation used, \( d_{hkl} \) is the inter-planar distance of \( hkl \) planes, and \( \theta \) is the incident angle for the radiation.

![Fig. 12 Bragg’s law of diffraction](image-url)
A laboratory X-ray diffractometer uses an X-ray source of fixed wavelength (monochromatic beam). Neutron diffractometers may use a monochromatic beam or a beam of a certain wavelength range and depending upon the source of neutron generation, the process of measurement slightly varies.

- In the case of reactor sources that produce a steady flow of neutrons, a monochromatic beam with the fixed wavelength of the neutrons is used and intensity is measured with the diffracted angle.
- In the case of spallation sources where neutrons with all the wavelengths are generated, a scattering angle is selected, and the diffraction intensity is measured with respect to the wavelength by the energy dispersive technique.

Both techniques utilize Bragg’s law, and the setup is slightly different, schematically shown in Fig. 13 and Fig. 14.

For residual stress measurements, the interplanar distance is used as a strain gauge and changes in the interplanar distances are measured and compared to a stress-free reference sample to get the stresses. After the stress-free interplanar distance $d_0$ measurement, the strain can be calculated as

$$\varepsilon = \frac{(d - d_0)}{d_0}$$

(2)

As the strains measured are elastic, the stresses are calculated using Hooke’s law as shown in Eq 3. However, it is to be noted that these changes can occur due to some inhomogeneous plastic flow as well.

$$\sigma_{ij} = \frac{E_{hkl}}{1 + \nu_{hkl}} \left( \varepsilon_{ij} + \frac{\nu_{hkl}}{1 - 2\nu_{hkl}} \varepsilon_{qq}\delta_{ij} \right)$$

(3)

where,

- $\sigma_{ij}$ – stress calculated for a direction
- $E_{hkl}$- Elastic coefficient for hkl plane
- $\nu_{hkl}$- Poisson’s ratio for hkl plane
To get full information about the stress state for the site of interest, measurements in at least six directions are needed to derive the full strain tensor and thereafter the full stress tensor. However, in practice to reduce the time for the measurements, strains along with the principal directions or three orthogonal directions if the principal directions are not known measured. Another consideration that needs to be taken into account is the shape of the neutron gauge volume that is being probed. The beam slit and detector slit are used to define the probed (gauge) volume of measurement in a component, see Fig. 13. To have a similar spatial resolution in all measurement directions along which stress variation may exist, a $2\theta$ of approximately $90^\circ$ is preferred to have a cube-shaped gauge.

*Fig. 13 Simplified setup for residual stress measurement at reactor-based source*
As seen in Fig. 14 for the case of energy-dispersive experiments, the diffractometer is configured such that two strains components can be measured simultaneously, and the acquired spectrum contains diffraction peaks from several lattice planes as well. As for the wavelength selective method in Fig. 13, only one strain component is measured at a time. More than one lattice plane can be probed by scanning the detector over the corresponding $2\theta$ range or using a detector of a large $2\theta$ range, which, however, leads to large deviations from $90^\circ 2\theta$. So, performing the experiments at a continuous source is more time-consuming than in a spallation source.

Details about the analysis of strains and thus stresses using spallation sources can be found elsewhere [19,49].

For the work in this thesis, a continuous neutron source was used, and the measurements were done at the KOWARI instrument at ANSTO.

In the case of a continuous neutron source, the lattice plane $hkl$ for which the interplanar distance is going to be measured needs to be identified based on the type of material being investigated. For the case of the FCC dominant material, $311$ or $111$ planes are recommended. Whereas, for BCC material $110$ and $211$ planes are recommended as these planes are found to be least affected by the intergranular strains (micro-strains) [49]. Also, the strains measured for these planes are close to the overall macroscopic engineering strain measured during tensile loading.
From the measurement, diffraction peaks are obtained, and then the position of the peak center is extracted using a mathematical fitting function. For most reactor-based sources, the gaussian type function is often used as it fits the diffraction peak shape well. After the peak fitting, interplanar distances are calculated from the peak positions and then converted into strains and consequentially to stresses.

The strains are calculated by having a reference sample measured for the same $hkl$ planes and with the same composition as for the sample of interest. The measured reference sample ($d_0$) should be stress-free i.e., no stresses, macroscopic or microscopic (intergranular or interphase) are present in the sample, which in practice is difficult to obtain.

In many cases, powders that are prepared by mechanical methods from the sample or twin sample are used as stress-free reference samples. This approach is based upon the assumption that small particles of the powder cannot sustain macroscopic RS. In some cases, areas that can be assumed unaffected by processing conditions generating RS can be used as stress-free references. Especially, welds areas far away from the highly stressed areas can be used as reference samples. Another way is to use comb-type samples that are prepared out of the twin sample for the residual stress measurement to keep the chemical composition the same in both cases. By cutting into small volumes, the macroscopic residual stresses are largely relaxed in the transverse direction to the comb teeth, however, micro residual stresses are largely retained.

In the case of AM samples, the use of feedstock powders will not be a good reference sample, as due to the manufacturing process, the chemical composition of the phases in the builds can be different from that in the raw powders. To avoid such an effect, a modified comb-type sample extracted from the twin sample was used as a $d_0$ sample in Paper-I [50]. In Paper-III [51], another approach was employed, which used a thin slice extracted from a twin sample for residual stress measurement and assuming the plane stress condition to derive the $d_0$ values. They both can be seen in Fig. 15.
For the final $d_0$ selection, further refinement of $d_0$ might be necessary to satisfy the boundary conditions and the force or moment balance for the measured cross-sections. Details regarding this refinement can be found in Paper-I and Paper-III respectively.

*Fig. 15 Types of $d_0$ sample used for strain calculations*
Chapter 5

Process parameters: implications on defects, microstructure, and residual stresses

As LPBF technique gives a vast matrix of choices of process parameters to manufacture the components. These choices and strategies are responsible for either better or worse properties of the component. As these are the fundamental process controlling parameters, small changes in these parameters can have a large impact on different properties such as density, texture, RS, etc.

The parameters can be divided into laser-related parameters (power, spot size, continuous/pulsed type), strategy-related parameters (pattern, hatch distance, speed, etc.), and powder-related parameters.

Out of various implications, some of the primary implications of the process parameters are discussed in the next section.

5.1 Defect formation

The origin of the defects can be traced back to the laser speed, powder, layer thickness, and contamination in the print chamber. There are different types of the defects such as lack of fusion (LOF), keyhole defects, porosities, etc. The lack of fusion (LOF) is due to imperfect laser melting resulting from insufficient melt pool overlaps. These are mostly observed when very high speed in combination with low laser power is used and is also related to the melt pool depth and layer thickness [52,53]. When the layer thickness is increased, LOF defects occurrence is observed more which also narrows down the optimal processing window. In contrast, keyhole defects are formed when a very high laser power in combination with a lower speed is used, causing excessive thermal energy being focused on a tiny volume [54–57].

Balling up phenomenon happens when a very high speed in combination with high laser power is used resulting in unstable scan tracks thus leading to the
formation of agglomerates [58–60]. To quantify the defects, mostly optical/scanning electron microscopy (SEM) is used but the use of non-destructive techniques such as X-ray computed tomography, and neutron imaging is also on the rise. The example of such defects quantified can be seen in Fig. 16, where the defects arising from lack of fusion are observed using neutron imaging and regular SEM.

All these defects and their relationship with process parameters are shown in Fig. 17. It must be noted that these defects are one of the primary reasons for lower mechanical properties due to the lower density of the printed parts.

Fig. 16 Defects due to lack of fusion and improper parameters selection for sectional strategy A) neutron imaging showing the defects mostly confined at the boundaries of the sections B) optical microscope image showing lack of fusion at the boundaries of the sections. Adapted from [51]
5.2 Texture formation

The formation of texture is another outcome of the process parameters used in the LPBF. In most cases, it is desired to have isotropic properties but often it has been observed that LPBF parts have some degree of anisotropy. As grain growth is dependent upon the dominant direction of the heat flow and this changes with the scan strategies implemented and the material system being printed. Some of the materials have a more favorable crystallographic grain growth direction and this crystallographic orientation tries to align with the heat flow direction. To have a uniform texture and to avoid one dominant heat flow direction in most cases, the laser sequence is altered with each consecutive layer and commonly the laser scan vectors are rotated at 67° every layer. In the case of scan strategies where no rotation of scan vectors has been used and the direction of heat flow matches in every layer, it will have an orientation of the grains favored in one direction [51,61] (see Fig. 18) and this can lead to anisotropic mechanical properties [61–63]. However, sometimes it is necessary to have anisotropic properties as well to get tailored mechanical properties in one direction and these choices of scan strategies help to create tailored properties [61].
5.3 Residual stresses

As discussed earlier, the RS in LPBF are mostly due to the temperature gradient $\Delta T$ between the subsequent layers. So, the increment or decrement in this $\Delta T$ can increase or decrease the RS formed. In most cases of the parts printed with LPBF technology, tensile stresses are observed at the surface and the balancing compressive stresses at the bulk of the cross-section [45,50,51,64].

Residual stresses are also connected to the scan strategies being used. In the first thought, it can be trivial to see if we decrease the temperature gradient between the layer then the RS can be reduced. This can be achieved either by an increase in the laser speed such that the time elapsed between the layer is shorter or by using higher power to get more energy into the powder which in turn will take a longer time to cool down. However, increasing the power and speed can lead to a negative result due to defect formation as
discussed earlier. Therefore, a careful balance between the process parameters is necessary and must be carefully chosen.

Earlier reports have shown that preheating the powder bed and the base plate resulted in lower RS. This is related to a reduced temperature gradient and the cooling rate is also slow due to the overall higher temperature of the system [11,54,65–72]. Indeed RS is not significant in parts built using the electron beam melting technology as a high temperature is maintained during the printing [73,74].

Other tested ways to reduce the RS are implementation of scan strategies with shorter scan vectors such as island or chessboard strategy that shows reduction RS [38,75]. However here also a careful selection of the size of the chess box has to be done as using very small islands can lead to excessive energy density thus leading to defects [76]. Most of these scan strategies are focused on achieving high density which is important for the mechanical integrity of the parts and one of the common scan strategies is to use a rotation of the scan vectors to get a more uniform texture and have a high density. These kinds of scan strategies often lead to high RS formation during printing and cracks and warping of the part from the base plate is frequent.

One of the strategies to reduce RS is by using rescanning or remelting of the layers. It has been shown that remelting can reduce the porosities and at the same time decrease the RS [77,78]. This however can lead to increased time in the printing of the parts. It has been reported that using remelting every 3rd layer for IN718 with lower power than that used for primary printing can reduce the RS [51]. The influence of various parameters such as power, speed, number of layers, and scan strategies for remelting has been investigated as well. It has been observed that with remelting every layer there is no big benefit in RS reduction.

The following table (Table 1) summarizes the general dependency of residual stress on a few main processing parameters as reported in various literature sources.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect on RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan speed</td>
<td>Higher scan speed used — lower RS [66,67,79–82]</td>
</tr>
<tr>
<td>Source power</td>
<td>Higher power used — higher RS [83–87]</td>
</tr>
<tr>
<td>Rescan/ pre-scan</td>
<td>With proper implementation overall lower RS [51,65,77,78,88–90]</td>
</tr>
<tr>
<td>Pre-heating of the base plate</td>
<td>Higher temperature of baseplate—lower RS [11,54,65–72]</td>
</tr>
<tr>
<td>Scan orientation</td>
<td>Effects on RS distribution and magnitude depend upon the geometry and scan strategy [11,15,65,89,91–95]</td>
</tr>
<tr>
<td>Vector length</td>
<td>Shorter scan vector — lower RS [65,75,92–95]</td>
</tr>
</tbody>
</table>
Chapter 6

Residual stress implications on the mechanical properties

Process parameters will have a significant influence on the RS generated during the printing and these RS are of great importance to the mechanical integrity of the components. RS are known to superimpose on the applied load and can lead to earlier failure. Part orientation and geometry can also lead to variation in RS and these are interlinked to the anisotropic properties observed [62]. The most dominant influence of RS can be observed for dynamic loading. The tensile RS at the surface is one of the big contributors to the crack opening and growth in the fatigue scenario [33–36]. Whereas, with compressive RS at the surface, it is known to have a positive influence on fatigue properties by delaying the crack opening and hindering the crack growth as well [34–37].

As in the case of components manufactured with traditional methods, for AM parts also the fatigue properties are highly sensitive to the environment and the surface characteristics. For the case of EBM materials, the surface roughness is very high and it has been reported that in as-built conditions they have very limited fatigue life properties [96], and by different surface treatments to reduce the roughness, the fatigue life was improved [97].

To relate the influence of residual stress state on LPBF samples, two sets of bar samples manufactured from IN718 powder in vertical orientation were investigated. The dimension was 80 ×10 ×10 mm and a chamfer of 1 mm was added on the side surfaces to reduce the stress concentration as seen in Fig. 19. One set of bars (GR-A) was printed with standard printing parameters and the other set (GR-B) was printed with surface reworking or remelting of the surface contours after every layer group. The idea behind the surface reworking was to understand if there is any difference in RS and fatigue life for these two sets of samples in as-built conditions and shot-peened conditions.
Neutron diffraction measurements were done at the cross-section at the mid-length of the bars for representative samples from both sets, and no big variations were observed. Also, depth profiling at the near-surface for as-built conditions was done and here also no big variation in RS was observed between the sample sets. After shot peening, the stresses at the surface were measured and stresses in the range of -800 MPa were measured for both groups. Results from neutron diffraction and XRD for the Gr-A sample are shown in Fig. 20 and Fig. 21.

The fatigue tests were carried out using a self-aligning four-point bending test rig and the test was done at constant stress amplitude with R= 0.1 with different stress levels from 800 MPa to 400 MPa. The samples were tested in two different conditions as-built and shot-peened, the results for both the sets are presented in Fig. 22.

From the results, it can be observed that the samples in as-built conditions have failed at lower life cycles when compared to the shot-peened samples. The shot-peened sample failed at cycles of one order magnitude more than those tested in as-built conditions for the same load level. This indicated the positive effects of having compressive stresses at the surface. Further analysis of the effect of the microstructure on the fatigue life properties is necessary to be able to connect it to the manufacturing conditions.

Fig. 19 Geometry of bar for bending fatigue test and simplified sketch of the test setup.
Fig. 20 Residual stress distribution for one representative sample of GR-A

Fig. 21 Depth profiling of representative sample of GR-A
Fig. 22 Four-point bending test for as-built samples and shot-peened samples
Chapter 7

Modeling of residual stresses in AM

As mentioned earlier, residual stresses are one of the primary issues in the components manufactured with the LPBF process. Quantification of the magnitude and distribution of RS gets critically important for complex geometries and new kinds of material as well. Using both non-destructive and destructive techniques to measure the RS cannot be always technically feasible in many cases. Due to these reasons, the necessity of computational tools to predict the RS arises as the level of RS formed can vary based on the geometry, process parameters, material, etc. It is very important to know the levels that can be expected in the component before printing can be performed. A high level of RS can cause warping of the part from the base plate and crack formation. Warping of the component will hinder the proper functioning of the re-coater blade as the layers are in the range of 30-60µ only. So slightest warping can damage the re-coater system leading to an increase in downtime for the print.

Looking at the prospect of different scenarios to print and finalize the process parameters, it is desired to have a model that can easily predict the level and distribution of the RS before the printing. This also helps to improve the design of the components as features in complex geometries often lead to concentrated stresses due to uneven temperature distribution and non-uniform cooling due to different boundary conditions. For example, the component with support structures tends to have higher RS than those without the support structure [50]. In an industrial setting for most of the material, the finalization of the process window as mentioned earlier is done by trial and error method. Even the parameters identified in this way can lead to very high RS purely due to the geometry of the part and this is where various kinds of computational approaches are being investigated.

For modeling the LPBF process, computational approaches are used at both micro-level and macro levels. Micro-level simulations using a multi-physics
approach deals especially with the dynamic and interaction of the laser with powder, and, are oriented more towards the melt pool evaluation to identify the shape, size, and reasons behind the defects such as keyhole formation, lack of fusion, etc. This is also one of the vital aspects to qualify process parameters to get a better-quality product. Within these micro-level simulations, RS prediction also is done with great detail concerning the laser power and beam shape, and beamwidth. These kinds of extensive detailed simulation with the movement of laser source also taken into account leads to the issue of choice between accuracy and time/resource needed for the computation to be done. So often these kinds of simulations are restricted to a small scale and few layers or even a few lasers pass in a single layer. Thus, they are not a feasible option to simulate a complex component build-up process. However, macro-level simulations which are mostly based on the finite element method have been used without using a detailed laser interaction and melt pool phenomenon into account. To simplify the interaction heat flux has been used instead of modeling the laser interaction with laser movements and this allows for a reduction in computational time as exact laser path simulation for each layer is not feasible for the real-life components used in an industrial setting [94,98,99]. It has been reported that using a detailed level of heat flux and having laser movement simulated has resulted in up to 70% accurate prediction of residual stress when compared to the experimental values [100]. Multi-track simulations where multiple scan paths are simulated are also being utilized but they are also mostly employed to simulate a few layers due to the high computation power required [66,93,101,102]. To reduce the amount of computation resources one way is to use a combined layer approach where multiple real layers are simulated instead of laser tracks being simulated one by one.

The combined layer approach reduces the computational time but a compromise between the accuracy and the time needed to perform the simulation has to be made. These kinds of models can be useful to see the stress distribution pattern in a complex geometry and help to identify the most critical areas in the part with respect to the RS. In the combined or lumped sum model approach, the printing of numerous layers is simulated.
in one step and different boundary conditions are adjusted for the numbers of layers that are being printed i.e., time for cooling, time for the printing, etc. As these layers are simulated by activation of elements at a certain amount of time and then subjected to the boundary conditions, they usually are less time-consuming than using a laser track movement and layer by layer simulation approach. As temperature gradient between subsequent layers is identified as the main reason for the RS formation so these approaches can also be divided into a transient thermal and mechanical simulation where the stresses are calculated based upon the temperature history separately. Another way is to have a coupled simulation where both thermal and mechanical computation is done side by side.

These lumped models are the easiest and quick way in the realm of finite elements to visualize the influence of the parts orientations, geometry, and process parameters in the outcome of the RS magnitude and distribution. These results can be further used to identify the most critical areas for RS in complex geometry and can help in the modification of the geometry to minimize the RS in those critical areas.

On the same basis, a model using the temperature as the initial loading condition has been established and verified using neutron diffraction data [47](Paper-II). Here the temperature close to the melting point of the material is used and it is assumed that the stresses are developed during the cooling phase. So, at the start, no stresses are present at the melting temperature but as soon as the temperature starts to drop, and material starts to solidify, RS starts to develop.

With this kind of simplified simulation, the results show that they are in line with the case of the stress distribution, but the magnitude of the stresses is higher than the experimentally obtained ones. This is related to the simplification done in the terms of the boundary conditions being imposed and the use of the temperature as the load. This also is related to the lack of temperature-dependent mechanical properties data in the literature for additively manufactured components such as thermal expansion coefficient, Young’s modulus, yield strength, etc. Nevertheless, the model has been
further extended to check the influence of remelting sequences as well and they are also in a reasonable range from the experimental data [51](Paper-III). This gives the confidence that the model can be used during the design process of the component as well as to check the influence of the process parameters by careful implementation of the boundary conditions.
Chapter 8

Summary of appended papers

Paper-I- Mapping of residual stresses in as-built Inconel 718 fabricated by laser powder bed fusion: A neutron diffraction study of build orientation influence on residual stresses

An investigation was conducted to study the influence of print orientation on distributions of residual stresses (RS) for L-shaped samples made out of Inconel 718 (IN718). These samples were printed in three different orientations vertically (VB), horizontally (HB), and at an angle of 45 degrees (45B) with respect to the base plate. The samples were removed from the base plate before the RS measurement with the help of the EDM process. RS at four selected cross-sections was measured with the neutron diffraction method to quantify the magnitude and distribution in the part. Also, the displacement of the parts when removed from the base plate was measured using a laser scanner. It was revealed that all the parts have tensile RS at the surface and are compressive at the bulk of the cross-sections. However, there was a difference in the magnitude of the stresses observed for the different parts. The part printed in the horizontal orientation (HB) has the lowest magnitude of the RS in all the directions measured in all the cross-sections and in contrast, the part printed in the vertical orientation (VB) presented the highest amount of stresses in all the directions of the measurements. A larger residual stress relaxation that occurred in HB than in VB during the removal of the parts from the base plate contributed to the observed difference. This was confirmed by the larger displacement measured when slicing the HB part from the base plate. It could be derived that residual stresses of different origins dominated the parts with different build orientations. For the HB part, residual stresses generated due to interactions between the base plate and the part denoted as RS1, prevail, and their relaxation after slicing left low residual stresses in the part. However, for the VB and 45B parts, residual stresses generated due to interactions between
the printed layers (RS2) were more substantial, which were largely retained after the part was removed from the base plate.

From the result presented in the work, it can be said that that component with a larger contact area with the base plate is likely to generate high RS1 and should be avoided particularly for thin-walled components which are not stiff enough and will lead to warping or de-lamination from the base plate. It also showed that a high level of RS2 can generate and still be retained in the part after removal from the base plate as well. Thus, the choice of print orientation has to be taken into account as the first step in the control of RS.

Paper-II  A simplified layer-by-layer model for prediction of residual stress distribution in additively manufactured parts

This work deals with the prediction of residual stress using a simplified simulation strategy and the validation of the strategy with the results obtained from the experimental work in Paper-I. Here a combined layer approach using 10 real layers combined into one was used with a temperature as a load for the residual stress prediction. The combined layers were activated successively at a certain interval depicted by the time it takes to print the part and it was allowed to cool down for a certain time length based on the total time for the re-coater to apply a new powder layer and the part chamber to move down.

The model has been implemented for L-shaped samples built in two different orientations from earlier work (Paper-I) to predict the residual stresses, both before and after being removed from the base plate. Good agreement with the experimental results was found for the RS distributions but a higher magnitude of the residual stresses was predicted for the samples removed from the base plate. Results from the model also showed that a very high magnitude of in-plane stresses were generated from the printing process, which however was significantly relaxed when the sample was removed from the base plate. In the case of the VB sample, high RS was predicted in the
build direction and very small relaxation is observed when the sample was removed from the base plate. With the simulation, the evolution of residual stresses during the printing could be illustrated. Tensile stresses near the surface started to develop in the newly printed layer as soon as it began to cool down and balancing compressive stresses were formed at the bulk. When the printing process continued and the number of layers added on top increased, the portion of the tensile region near the surface increased and eventually stabilized. Relaxation of the total residual stresses was observed when the entire part had been printed and the part as well as the base plate was allowed to cool down to room temperature.

The assumptions employed in the simulation are believed to contribute to the overpredicted residual stress magnitudes. Nevertheless, it requires less computational resources and can be used to predict the regions where the stresses can be critical in a complex component and used as an effective tool for print orientation selection as well as to refine the component design to reduce the RS.

Paper-III *A study of the influence of novel scan strategies on residual stress and microstructure of L-shaped LPBF IN718 samples.*

As a next step for the control of RS, different scan strategies were selected for printing a new set of L-shaped samples. Changing the scan strategy may affect not only the residual stresses generated but also the microstructure and texture which were therefore also investigated in the paper. The geometry of the sample was kept the same as in Paper-I and the parts were printed in a vertical orientation as this gave the highest residual stresses in both Paper-I and II. Four non-common scan strategies were implemented for printing the parts. The first one called the total fill strategy utilized border offsetting to print the part without any hatching sequence and with the scan starting from the outer surface and moving inwards. The second one employed a remelting technique, where after every 3rd layer of primary printing a new laser pass was made but without any powder being applied
on top. The third and fourth strategies divided the part into several sections which were printed in different orders from inside to outside and vice versa respectively.

The neutron diffraction method was used to measure the RS at the same cross-sections as in Paper-I and with the same setup for the result to be comparable. Also, the simplified model from Paper-II was adapted for the prediction of stresses for remelting strategy.

It was found out the remelting strategy is successful, achieving up to a 25% reduction of the near-surface residual stress without any significant influence on the microstructure when compared with the standard scan strategy (with 67° rotation of scan vectors every layer) without any remelting applied. The sectional strategies revealed a lower RS magnitude than the standard strategy but when checked with the neutron imaging technique for defects, a high concentration of defects greater than 50 microns was revealed at the interface between the sections, which likely caused the lower residual stresses. The total fill scan strategy revealed a significant texture formation of (001)//scan direction. This significant build-up in crystallographic texture is due to the alignment of the scan vector exactly on top of each other for every layer being printed and thus a more dominant heat flow direction parallel to the scan direction. Both the total fill strategy and remelting every 3rd layer did not show any big size defects when investigated with neutron imaging. A small number of porosities were detected for the sample with remelting done every 3rd layer and elongated defects were observed for the total fill strategy when observed using SEM.

A modified FE model from Paper-II was used for predicting residual stresses in the part printed using the remelting scan strategy. The simulation results showed that the lower residual stresses were related to stress relaxation when the remelting sequence is used. Combining all the results, it can be concluded that remelting strategies can be utilized to reduce the RS in as-built parts and the total fill strategy can be used to obtain tailored anisotropic parts. Also, it is necessary to optimize the printing parameters for the sectional strategy to avoid the formation and concentration of big defects.
Effect of re-melting strategies on the residual stresses in additively manufactured L-shaped IN718 parts

As from the previous work, it was known that the use of a remelting scan after every 3rd printed layer reduces the RS in the as-built sample. In this work, further studies were conducted to investigate whether an additional reduction in the residual stress magnitude can be achieved by changing the process parameters for the remelting sequence and compared with remelting done every 3rd layer with standard processing parameters from Paper-III. The investigation was carried out on L-shaped samples of the same geometry as those studied in the previous papers but printed using different laser scan speeds or power for the remelting sequence done at every 3rd layer or different remelting scan sequences. Residual stresses were measured with neutron diffraction at the same cross-sections as earlier work.

From the neutron diffraction results, it was found that remelting every layer (RM-1) with the same parameters used for the primary printing does not have a significant influence on the RS magnitude and distribution in comparison to the remelting done every 3rd layer (Paper-III). Further, the remelting of every 3rd layer with a higher speed and power, whilst keeping the energy density constant (RM-P) resulted in higher surface tensile stresses than remelting every 3rd layer. This can be related to the higher scan speed resulting in quicker heat conduction from the melt pool to the already solidified layers and bulk.

However, when the energy density was increased by changing the power (RM-ED), due to the slow scan speed than of the previous sample (RM-P), the heat accumulated gets dissipated to the bulk more gradually than in the RM-P sample. So, the change in increment of RS is slightly lower than in the RM-P case. However, the distribution remains the same as for the sample printed with remelting done every 3rd layer (Paper-III). Although no significant reduction in RS was observed in all the samples tested with respect to the sample where remelting was done every 3rd layer from Paper-III However, when compared to the sample printed without any remelting (VB from Paper-I) all the samples have a lower magnitude of stress.
It can be concluded that the choice of the number of layers after which the remelting should be carried out depends upon the laser power and penetration depth. The penetration depth of the laser beam and using the same energy density but a change in power and speed can result in different RS magnitude. So further refinement in remelting parameters is necessary for it to be adopted as a strategy to reduce the RS in as-built parts.

Manuscript-V- Remelting strategies: influence on texture, microstructure, residual stresses. - manuscript

Cubical samples from IN718 with different printing parameters for remelting sequence such as the number of layers after which remelting is done, scan strategies for remelting, change of speed, and power were printed. to study the influence of these parameters change on the crystallographic texture, microstructure, and residual stress. The crystallographic texture was measured using the traditional electron backscatter diffraction and neutron diffraction method. For the residual stress analysis lab XRD was used to analyze the surface residual stress using the $\sin^2 \Psi$ technique and neutron diffraction was used to measure the bulk stresses.

It was found that no big variation in microstructure was observed with variation in process parameters for the remelting sequence but the crystallographic texture in the building direction was changed and a strong texture $(011) // BD$ was observed when $180^\circ$ rotation of scan vector between the remelting sequence done after every 3rd layer with standard processing parameters (sample C7).

The influence of change in the power for the remelting sequence was found to be more prominent than the change in the speed on the $(011) // BD$ texture. Samples with higher power revealed higher texture intensity than lower power used for the remelting. Samples printed with chess pattern in combination with remelting done every 3rd layer and every layer have no big variation in the $(011) // BD$ texture in comparison to the sample without any remelting done.
All the samples tested presented tensile residual stress in the range of 700-1000 MPa in the building direction when measured with XRD, with the least being in the case of a sample where remelting every layer was done with a standard scan strategy (sample C6). However, the residual stress measured from neutron diffraction revealed that the sample with the chess pattern used for printing combined with remelting every 3rd layer had the lowest subsurface tensile stress in the building direction with compressive stresses in the center of the cross-section.

The variation in the texture (011)//BD is related to the heat dissipation mechanism. As IN718 is FCC material, the preferred grain growth direction is in the (001) direction, and in LPBF heat dominant heat flow is from the front of the laser to the back and it has been already established that (001) grain growth is observed parallel to the scan direction. Second heat dissipation is via conduction to the base plate, and it is parallel to the building direction. In all the samples tested the laser path do not coincide with reach other between the layer due to the rotation of the vector between the layers so only (011)//BD texture was observed. This observed texture intensity was increased i.e., more grains are oriented in (011) in the building direction when the laser power for the remelting was increased. This can be attributed to the narrow shape of the melt pool that forms with high power leading to more (011) grains to grow. With the change in speed, no significant change in the texture intensity was observed and similar results were observed with a change in scan strategy for the remelting sequence. Further investigation is needed to explain the high (011)//BD measured for sample C7.

The variation between the result from XRD and neutron diffraction for the residual stresses can be due to different lattice planes used for the measurement. For XRD, 220 planes were measured and for neutron 311 planes were measured. Since the penetration depth of XRD is minimum, the results can be affected by the surface roughness and further investigations are required to relate them.
Chapter 9

Conclusion and outlook

The work presented revolves around the research question formulated at the very beginning of the project and it is beneficial to discuss these formulated research questions and other related aspects in detail. The following section provides more insight into the research question and how they are addressed by the work presented in the thesis

1. How do the printing orientations influence the residual stress magnitude and distribution?

When the process parameters are kept identical, it is beneficial to print the samples in horizontal orientation i.e., the long axes of the parts lying parallel to the base plate. However, it has to be considered that in the case of thin-walled samples this might lead to a warping phenomenon as indicated by Paper-I and II. The part with a greater area of contact with the base plate (HB from Paper I and II) leads to higher stress during printing but after removal from the base plate, the stress relaxation occurs causing some distortion during removal. Whereas parts printed at 45° and 90° with respect to the base plate had higher stress retained after being removed from the base plate. So, the choice of print orientation must be done wisely, and simplified models can be used to check which orientation gives the least RS, and which gives the largest RS (Paper-I and Paper-II)

2. Can time effective simplified model be used for the residual stress control in LPBF?

The simplified model using combined layers is capable of predicting the residual stresses distribution very well with a higher magnitude than obtained from experiments (Paper-II). It predicted a difference in RS with print orientations both before and after the removal from the base plate. Due to its simplified nature, it is less time-consuming, and it can be adapted to
the design process not only to visualize the area of high-stress concentrations with different print orientations but to optimize the component design without actually printing the part. The model also was able to predict the reduction in RS with remelting (Paper-III) and this can also be used to refine the process parameters as well to control the RS.

3. How do the novel scan strategies influence the residual stresses and the microstructure variation in as-built samples?

With the change in scan strategy, the heat dissipation mechanism is changed, and thus the temperature distributions. As the main cause of RS formation in LPBF is due to the temperature gradients between the layers, a scan strategy that can reduce the temperature gradient such as remelting at every 3rd layer will help to reduce the RS. Further, scan strategies such as the total fill with no rotation of scan vectors can lead to a strong crystallographic texture and can be a reason for anisotropic mechanical properties (Paper-III).

4. How do the process parameters for the remelting/rescanning strategies influence the residual stresses and texture development?

The remelting scan strategy used after every 3rd layer has been shown to reduce the surface tensile RS up to 25% compared to the parts printed without any remelting sequence. On the other hand, the same remelting strategy but using higher speed and power than those used for the primary printing did not have a significant gain in the RS reduction. Also, the remelting after every layer did not show any significant changes in RS reduction.

Further, the combination of various process parameters for remelting sequence has shown no big change in microstructure but some combinations can lead to an increase in texture intensity, and some others can reduce the crystallographic texture as well. (Paper-IV and V)
Outlook

This entire work dealt with the use of diffraction-based techniques to investigate the influence of the print orientation, and scan strategies on the formation and reduction of RS formed during the manufacturing process. Together with this influence of processing parameters on microstructure crystallographic texture was studied and a simplified model was set up and validated for the RS prediction. The measured results and model can be used as starting point for the reduction of the residual stresses, and it opens up several interesting research questions that can be pursued:

- Further refinement in the FE model to get a more accurate magnitude of the predicted model with further reduction in time for simulation using adaptive mesh refinement techniques can be investigated.
- Investigation into other novel scan strategies such as fractal scans, helical scans, etc., and also refinement of the remelting scan strategy parameters.
- Test different heat treatments cycles that can be used to relieve the stresses and measure at the same cross-sections as conducted now and identification of the most efficient one in terms of energy and time consumption.
- Investigation into surface residual stresses for the samples investigated in the current work either by depth profiling or via synchrotron measurements to get even better and more accurate stress maps which can be used to verify results from computational models.
- Some work on microstructure and crystallographic texture was done in Paper-III and Paper-V but further investigation on the evolution of the microstructure after heat treatment can be an interesting study to realize if the different scan strategy leads to variation in microstructure after the same heat treatment procedure or not.
Bibliography


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PART-II
Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

https://doi.org/10.3384/9789179292935
Residual stress in additive manufacturing
-Control using orientation and scan strategies

Prabhat Pant