



Effect of heat treatment on residual stress in Selective Laser Melted CoCrMo

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DEDICATION

I dedicate this work first to my Creator, who gave me the strength and determination to persevere, and who lifted me whenever I stumbled.

I dedicate it also to my parents, whose belief in me and unwavering support carried me through my university years. Thank you for allowing me the freedom to grow and pursue my passion. This is dedicated to my father who walked with me in spirit through every step of this journey, and to my mother for every prayer, every thought, and every call you answered when I needed you. To my grandparents and my sister, thank you for your love and support through the years and for always believing in me.

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ABSTRACT

Selective Laser Melting (SLM) of Cobalt Chrome Molybdenum (CoCrMo) alloys presents major advantages for producing high-performance biomedical and aerospace components. However, the process induces significant residual stresses due to large thermal gradient development during the layer-by-layer manufacturing method. Residual stresses are important to mitigate as they can compromise dimensional accuracy, accelerate crack formation, and decrease component reliability. This study aims to evaluate the effect of stress-relief heat treatments on the reduction of residual stresses in SLM-fabricated CoCrMo alloys.

Cantilever and cubic specimens were manufactured to evaluate the effect heat treatment has on residual stresses through the cantilever deflections (inherent strain method), XRD and microstructural analysis. Numerical simulations were implemented to predict the effects of 700°C, 770°C, and 1065°C heat treatments. Experimental results showed substantial reductions in cantilever deflection, with stress relief of 54% at 700°C and 82% at 770°C. Heat treatment at 1065°C led to stress reversal, indicating significant redistribution of residual stress as inferred from cantilever deflection. Simulations highlighted the trend of decreasing residual stress with an increase in temperature, although they underestimated the magnitude of experimental stress relief, particularly at higher temperature, suggesting unmodelled phase-transformation effects.

Microstructural analysis revealed microstructure development from elongated columnar grains in the as-built condition to partial recrystallised structures at 770°C and mixed elongated and equiaxed microstructures at 1065°C. XRD confirmed the presence of γ -phase and ϵ -phase across all conditions, with the γ -phase being the most dominant. The XRD also showed that heat treatment caused shifts and broadening in peaks, intensity changes, and the appearance of an additional peak when heat treatments were applied.

The combined simulations and experiments show that heat treatment is an effective approach for residual stress reduction in SLM CoCrMo alloys. The study also found that calibrated finite element simulations can serve as a valuable predictive tool for optimising heat treatment strategies and minimising trial-and-error experiments in SLM. It should be noted that residual stresses were inferred indirectly from cantilever deflection measurements using the inherent strain method, and that the investigation was limited to selected stress-relief temperatures for a single SLM CoCrMo material system. Within these constraints, a heat temperature of 770°C provides a desirable balance between stress relief and dimensional stability.

Keywords: *Additive Manufacturing, Selective Laser Melting, Cobalt-Chrome-Molybdenum, Residual Stress, Finite Element Simulations, Simufact Additive, Heat Treatment, X-Ray Diffraction, Microstructure Analysis, Inherent Strain Method*

LIST OF ABBREVIATIONS

2 θ	Diffraction Angle
ASTM	American Society for Testing and Materials
AM	Additive Manufacturing
BJT	Binder Jetting
CHT	Heat Treatment Temperature (°C)
CAD	Computer-Aided Design
CMM	Coordinate Measuring Machine
CoCrMo	Cobalt Chrome Molybdenum
DED	Directed Energy Deposition
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
EBSD	Electron Backscatter Diffraction
FCC	Face-Centred Cubic
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
HCP	Hexagonal Close-Packed
HIP	Hot Isostatic Pressing
ISM	Inherent Strain Method
MEX	Material Extrusion
MJT	Material Jetting
PBF	Powder Bed Fusion
SHL	Sheet Lamination
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Standard Triangulate Language
VPP	Vat Photopolymerization

Wire-EDM

Wire Electrical Discharge Machine

XRD

X-Ray Diffraction

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CHAPTER 1 INTRODUCTION

Additive manufacturing (AM) has gained significant attention in recent years due to its ability to produce lightweight components with complex geometrical features and customisable designs tailored to specific applications [1, 2]. AM's capability to manufacture lightweight, intricate structures is often achieved by design methods such as topology optimisation and part consolidation, which enhance design freedom [3, 4]. Unlike traditional subtractive manufacturing, AM builds components by depositing material layer by layer from Computer-Aided Design (CAD) data, a process that not only supports these advanced design strategies but also reduces material waste and increases production rates [3, 5, 6, 7].

Although AM was originally developed for rapid prototyping using polymer materials, it has since evolved to include metals, composites, and ceramic materials as well [6, 8]. According to the ISO/ASTM 52900 standard [9], AM techniques can be divided into seven main categories, one of which is Powder Bed Fusion (PBF). PBF processes use “thermal energy to selectively fuse regions of a powder bed”, and include Electron Beam Melting (EBM), Selective Laser Sintering (SLS), and Selective Laser Melting (SLM) [9, 10]. The SLM and SLS methods are also referred to as Laser Powder Bed Fusion (L-PBF) since both methods rely on a laser as their thermal energy source [11]. While both SLS and SLM are L-PBF methods conducted in an inert atmosphere, SLS partially sinters the powder and typically requires post-processing to achieve full density, whereas SLM fully melts the powder to produce near fully dense components directly during the build process [12, 13]. L-PBF is generally the most popular choice for manufacturing metal components as it offers higher dimensional accuracy and better surface quality compared to other AM processes [10, 14]. Consequently, SLM is widely adopted to produce high-performance parts for industries such as medical, aerospace, and automotive [15, 12, 16].

The capability of SLM to produce patient-specific geometries, intricate internal features, and near-net-shape components without extensive tooling [17], makes it particularly well-suited for biomedical applications, including maxillofacial implants, removable and partial dental bridges, and prostheses [13, 18, 19, 20]. Metals such as stainless steel, titanium, and cobalt-chromium-molybdenum (CoCrMo) are frequently used for manufacturing biomedical implants due to their excellent mechanical properties, corrosion resistance, and biocompatibility [21, 22]. Although titanium remains a popular choice, CoCrMo alloys are increasingly used because they provide comparable mechanical properties and corrosion resistance while often offering a more cost-effective alternative [23, 24].

Despite SLM's success in producing high-performance parts for demanding applications such as biomedical devices, it also introduces the significant challenge of residual stresses, particularly in metal components [25, 26, 27]. These stresses arise from the thermal gradients inherent in SLM's layer-by-layer fusion process [25, 28]. When residual stresses become excessive, they often lead to part distortion, compromised mechanical properties, and cracking, ultimately reducing reliability and leading to component failure [5, 27, 29, 30, 31]. Consequently, identifying and mitigating these stresses remains a concern for industrial applications of SLM-fabricated components [21].

A common strategy for mitigating residual stresses in SLM is post-process heat treatment, which promotes microstructural homogenisation and consequently stress relaxation [21, 32, 33, 34, 35, 36]. In CoCrMo alloys specifically, carefully controlled heat treatment regimens have been linked to improved mechanical properties and corrosion resistance, by relieving residual stresses [21, 24, 37]. Understanding the relationship between heat treatment parameters and residual stress relief is essential for ensuring consistent part quality and overall reliability. While some existing studies have examined the effect of heat treatment on microstructural or mechanical properties of SLM CoCrMo components, limited research is available on the influence of heat treatment parameters, such as soaking temperature, on residual stress reduction [34, 37].

1.1 Problem Statement

Selective Laser Melting of CoCrMo alloys generates significant residual stresses due to steep thermal gradients inherent to the SLM process. These residual stresses can cause distortion, dimensional inaccuracy, and reduce component reliability. Although stress-relief heat treatment is commonly applied to SLM CoCrMo components, the effect of heat treatment soaking temperature on residual stress reduction in SLM-fabricated CoCrMo remains insufficiently characterised. Existing studies largely focus on microstructural evolution or mechanical properties, with limited focus on evaluating residual stress relief. Consequently, there is a need to determine how heat treatment temperature influences residual stress reduction and distortion behaviour in SLM-fabricated CoCrMo.

1.2 Research Aim

This study aims to evaluate the effect of heat treatment on residual stress in Selective Laser Melted CoCrMo alloys using the Inherent Strain Method.

1.3 Research Objectives

The objectives of this study are to:

1. Validate the effectiveness of Finite Element Modelling approach for predicting residual stress and component distortion in SLM CoCrMo alloys by comparing simulated residual stress distributions and predicted distortion values to experimentally measured component deflection.
2. Determine an effective heat treatment temperature for reducing residual stress in SLM CoCrMo alloys by conducting an in-depth literature review to establish an appropriate heat treatment temperature range and then evaluating the effectiveness of the selected temperature by measuring component deflections before and after heat treatment.
3. Investigate the metallurgical phase evolution and microstructure of SLM CoCrMo alloys across different heat treatments by analysing phase composition using X-ray diffraction and grain morphology to determine how microstructural changes affect residual stress reduction.
4. Recommend a suitable heat treatment regime for residual stress relief in SLM CoCrMo alloys by comparing heat treatment parameters, distortion measurements, and microstructural changes across the investigated heat treatment conditions.

1.4 Research Scope

The research is limited to CoCrMo parts manufactured by SLM, with a focus on investigating the effect of temperature variations in the stress-relief annealing process. Finite element modelling (FEM) software, Simufact Additive, which uses the inherent strain method for its calculations, is employed to predict residual stress and distortion in CoCrMo SLM samples. These simulation results are compared against experimental measurements to validate the accuracy and reliability of the modelling approach. Microstructural investigation, including metallurgical phase identification and microstructure analysis, is also performed on each sample to investigate microstructural evolution and its effect of residual stress reduction.

1.5 Outline of the Dissertation

This dissertation is structured into five chapters, each addressing a specific aspect of the study. Chapter 1 introduces the research by providing an overview of SLM, focusing on its advantages and challenges, particularly the development of residual stresses that can compromise part quality. The chapter outlines the research problem, aim, objectives, scope, and delimitations, providing a foundation for the study.

Chapter 2 presents a review of the existing literature on SLM and residual stress development. It explores the influence of process parameters, build orientation, and scanning strategies on residual stress development. Various mitigation techniques are discussed, with particular emphasis on post-processing heat treatments and the use of FEA for predicting and controlling residual stresses.

Chapter 3 describes the materials and methods used in the study. It outlines the selection of CoCrMo as the test material and details the experimental procedures, including cantilever fabrication using SLM, heat treatment application, and deflection measurements. The chapter also explains the simulation process in Simufact Additive, covering calibration steps and the setup used to predict residual stresses and optimise heat treatments.

Chapter 4 presents and discusses the results obtained from both simulations and experimental testing. It highlights the correlation between simulation predictions and experimental findings, focusing on deflection measurements, XRD analysis, and microstructure observations. The effectiveness of different heat treatment conditions in reducing residual stresses is analysed, with particular attention given to the observed changes in microstructure.

Finally, Chapter 5 concludes the dissertation by summarising the key findings and discussing their practical implications for improving component reliability in SLM-manufactured parts. Recommendations for future work are provided, including refining simulation models and exploring hybrid approaches that combine real-time monitoring with predictive simulations to enhance stress management in complex geometries and diverse materials.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of existing literature relevant to the Selective Laser Melting process, with a specific focus on the development and mitigation of residual stresses. It provides an overview of Powder Bed Fusion, highlighting the advantages and industrial applications of SLM in producing complex metal components. The chapter then explores the fundamental aspects of the SLM process, including critical process parameters and commonly used materials.

A detailed discussion follows on the origins and classification of residual stresses in manufacturing, with specific attention given to the mechanisms driving residual stress development in SLM components. Subsequently, the chapter reviews established techniques for residual stress measurement and evaluates post-processing strategies such as heat treatment for stress relief. The final section explains the role of Finite Element Analysis (FEA) in predicting residual stress and component distortion, with a focus on the application of simulation software such as Simufact Additive.

2.2 Additive Manufacturing

Additive Manufacturing (AM) has progressed considerably since its origin in the 1980s, when it was used for rapid prototyping using polymers [38, 39]. Since then, AM has expanded to include a range of specialised manufacturing techniques capable of producing components from a range of materials, including ceramics, composites, and metals [6, 8, 40]. The American Society for Testing and Materials (ASTM) [9] has categorised the AM technologies into seven classes, namely Binder Jetting (BJT), Directed Energy Deposition (DED), Material Extrusion (MEX), Material Jetting (MTJ), Powder Bed Fusion (PBF), Sheet Lamination (SHL), and Vat Photopolymerization (VPP).

A significant attraction of AM is the freedom to tailor material properties and component geometry, enabling the manufacturing of highly specialised components for specific industry needs [3, 4]. The potential applications of AM are broad across various industries, including medical, dental, aerospace, and automotive [15, 12, 16]. Each of these industries imposes stringent requirements for material performance, such as mechanical strength, fatigue resistance, corrosion resistance, or biocompatibility, depending on the application. Among the AM technologies, PBF is increasingly being used as the preferred method for metal component manufacturing [3, 39], particularly in industries requiring complex geometries and high-density parts.

For industrial applications where materials would require good mechanical properties and corrosion resistance, materials such as stainless steel are the preferred choice as they are suitable for a wide variety of applications. Aluminium alloys are advantageous to use for automotive and aerospace components, as they are lightweight and have good thermal properties. Other materials that are used in aerospace applications due to their excellent strength-to-weight ratio are titanium alloys, or cobalt-chrome alloys for their high wear resistance [38, 41].

In both the medical and dental fields, titanium alloys are widely used due to their biocompatibility, high corrosion resistance, and mechanical strength [3, 42]. However, elevated aluminium and vanadium ion concentrations have been detected in patients with titanium implants, posing potential health risks, as aluminium can impair bone mineralisation and vanadium is associated with cytotoxicity and type IV allergic reactions [43]. Due to the cost of these alloys and the increasing concern about the potential health risks associated with titanium implants, alternative materials have been investigated [23]. CoCrMo alloys have been shown to be a promising substitute, offering excellent wear resistance, biocompatibility, and mechanical strength [21]. These properties make CoCrMo particularly well-suited for applications such as orthopaedic implants and high-performance aerospace components [44]. However, additively manufactured metals like CoCrMo alloys are particularly susceptible to residual stress development due to their high melting points and unique thermal properties. The inherent characteristics of some AM processes can lead to significant residual stress development, which can compromise part quality [44, 45].

2.3 Powder Bed Fusion

PBF is one of two AM techniques that use a high-energy source to selectively bind or melt material powder together [18, 46]. The PBF techniques include Electron Beam Melting (EBM), Selective Laser Sintering (SLS), and Selective Laser Melting (SLM) [12, 47]. Although all three processes fabricate components layer by layer from a powder bed, they differ significantly in energy source, processing environment, degree of powder fusion, and thermal history, all of which directly influence residual stress development [39, 48].

In EBM, a high-energy electron beam is operated within a vacuum chamber. The powder bed is initially lightly sintered to prevent electrostatic charging, after which the material is fully fused to form dense components [1]. The process typically involves preheating and maintaining the build plate at an elevated temperature, which reduces thermal gradients between successive layers and consequently lowers residual stresses [15]. The vacuum environment further minimises oxidation in oxygen-sensitive materials and contributes to the production of high-performance

components with relatively lower residual stresses compared to laser-based PBF methods [39, 42].

In contrast, laser-based PBF methods such as SLS and SLM are conducted in an inert gas atmosphere to prevent oxidation [41]. In SLS, one or multiple lasers selectively sinter the powder, forming solid structures through partial fusion of particles [39]. Due to the sintering process where powder is not completely melted, SLS generally results in lower density components and requires post-processing to achieve full density [49].

The most common of these techniques is SLM due to its ability to produce high-performance components with complex geometries [3, 40]. The technique uses a high-powered laser to selectively melt and fuse metal powder in a layer-by-layer fashion[46]. SLM, however, fully melts the metal powder using a high-powered laser, producing fully dense metallic components with high mechanical strength [39, 46]. The complete melting and rapid solidification inherent to SLM generate steep thermal gradients and repeated thermal cycling, which increase susceptibility to residual stress formation and potential distortion if not properly managed [39]. Industries benefiting from using SLM are the aerospace, medical and dental fields due to its capability to produce lightweight structures and highly intricate parts with complex geometrical features with minimal material waste [15, 13, 18, 20]. However, compared to EBM and SLS, the higher thermal gradients associated with full laser melting make residual stress control an important consideration for SLM fabricated components [48].

While EBM reduces residual stresses through preheating the build plate which reduces thermal gradient development, SLM does not preheat the build plate, resulting in rapid cooling rates and steep thermal gradients. Similarly, due to SLS sintering the powder at lower temperatures, it reduces thermal gradient development compared to SLM which melts the powder at high temperatures. This distinction reinforces the need to evaluate post-processing heat treatments specifically for SLM-fabricated components.

2.3.1 Selective Laser Melting Process

SLM is a multi-step process and starts off with the creation of a detailed design concept, which is developed into a Computer-Aided Design (CAD) model. After the design has been finalised, the CAD file is converted into a format compatible with the SLM machine, which is typically a Standard Triangulate Language (STL) file, and then “sliced” into layers that correspond to thin cross-sections of the model [50]. Support structures are generated and added during slicing to prevent warping in overhanging features and can also serve as additional heat sinks during the

manufacturing process to influence thermal gradients [9]. The sliced file is then transferred to the machine where it will be manufactured.

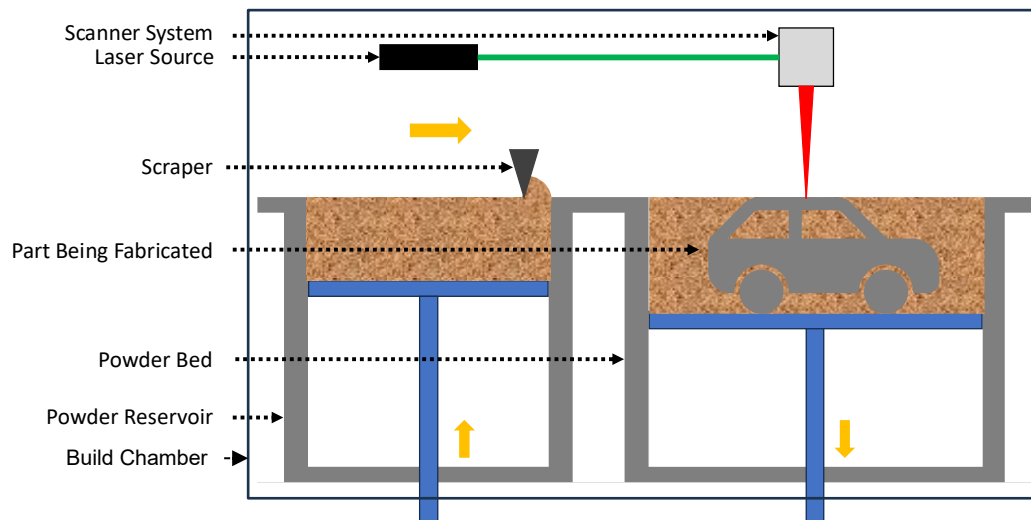


Figure 2-1: Selective Laser Melting Process [51]

Once the machine preparation is complete, the atmosphere inside the build chamber is purged with an inert gas (typically argon or nitrogen) to prevent component oxidation from occurring [52]. In addition to shielding, the gas flow enhances process stability and reduces porosity by removing spatter particles and weld fumes that could attenuate the laser or redeposit spatter on subsequent layers [53], and by promoting convective heat transfer from the melt pool, which influences material cooling rates and thermal gradients [54].

The powder reservoir's base is then raised by a single layer thickness to supply enough powder material to cover the build plate. A thin layer of powder, ranging from 20 to 50 μm thick [55], is deposited evenly across the build plate using a roller or scraper, as illustrated in Figure 2-1. After the metal powder is deposited on the build plate, the high-powered laser then selectively melts the powder, guided by the sliced data. This process is repeated in succession until the entire component is completed. Once manufacturing is finished, the machine and component are cleaned and removed from the build chamber, and the part can undergo post-processing treatments if required such as removing support structures, applying surface finishing, or heat treatment [39, 56].

There are several process parameters that have a strong influence on the quality and properties of selective laser melted parts. These include laser power, scanning speed, hatch spacing, and layer thickness [57]. Laser power refers to the energy delivered by the high-powered laser to the powder bed, while scanning speed refers to the velocity at which the laser moves around the

powder bed. When high scanning speeds are combined with low laser power, it results in insufficient energy delivery, causing incomplete melting, balling, and poor bonding between layers [13]. Hatch spacing refers to the distance between subsequent laser scanning tracks. When scanning tracks overlap, it ensures effective fusion between consecutive tracks. However, excessive overlap can result in localised heat accumulation and increased thermal gradients. Insufficient overlap can lead to poor track fusion, causing defect formation such as porosity [13, 46, 54]. The layer thickness is the height of the volume of powder that is deposited onto the build plate. As thicker layers require more energy to melt, resulting in larger melt pools, they increase the likelihood of porosity and shrinkage-related stresses. In contrast, thinner layers reduce the energy requirement and thermal gradients but increase build time, potentially limiting production efficiency [13]. The combination of steep thermal gradients, constrained solidification, and repeated thermal cycling inherent to SLM leads to residual stress development.

2.4 Residual Stress

Residual stress is defined as the self-balanced state of stress that exists within a material or part after manufacturing and processing have occurred, without the presence of any external load [30, 58, 59]. Such residual stresses are internally balanced, as tensile stress in one region is compensated by compressive stress in another. Residual stresses primarily result from non-uniform plastic deformations across the material plane. For example, during drilling, residual stresses may arise from plastic deformation associated with chip formation, thermal stresses induced by localised heating, and possible phase transformations occurring at elevated temperatures [59].

Residual stresses are therefore an inherent consequence of many manufacturing processes and are introduced across a wide range of metal part manufacturing methods, including machining, sintering, die casting and investment casting, and AM. In processes such as welding and PBF, residual stresses are predominantly generated by rapid heating and cooling cycles, solidification shrinkage, temperature gradients, and phase transformations [59].

Residual stresses are generally classified into three types based on their characteristic length scales, namely Type I (σ^I), Type II (σ^{II}), and Type III (σ^{III}) [5, 30, 35, 59]. These residual stress types are shown in Figure 2-2, which classifies residual stresses according to their characteristic length scales, ranging from macroscopic (Type I) stresses spanning the entire component, to microscopic (Type II and Type III) stresses acting at the grain and sub-grain levels.

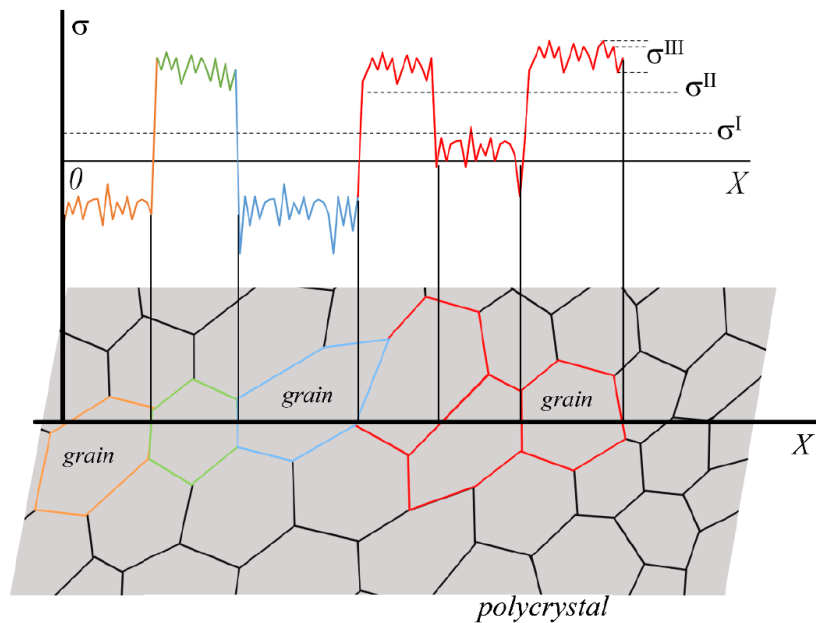


Figure 2-2: Residual Stress Type Classifications According to Length Scales [59]

Type I residual stress, also referred to as “macro” residual stress, develop over dimensions that are larger than the material’s grain size, typically greater than 1 mm [5, 30, 35, 58, 59]. Once the equilibrium of macro residual stress is disturbed, it can result in macroscopic deformation of the component [30]. Type I stresses are commonly induced through non-uniform plastic deformation during material processing activities such as forging, welding, milling, bending, shot peening, and surface treatments like plating and hardening, or during thermal processes such as heat treating. Additionally, Type I residual stresses may arise during operational use like from mechanical loads, temperature gradients, or chemical changes [59].

Type II and III residual stresses are frequently grouped together as “micro” stresses, which often arise from the existence of different phases or microstructures within a material. Their magnitude and direction (tensile or compressive) can vary over distances comparable to the specific material’s grain size [58]. Type II residual stress, also referred to as “intergranular” residual stress, is commonly associated with material phase transformations and exists across multiple grain lengths within a range of approximately 0.01 mm to 1.0 mm [5, 30, 58, 59]. Type II residual stresses generally occur due to the anisotropic properties of the material at the grain scale [35, 59].

Type III residual stresses are restricted within individual grain crystals, resulting from coherency at grain boundaries and dislocation stress fields at the atomic level, typically over a length scale smaller than 0.01 mm [5, 30, 35, 58, 59]. Although this classification provides a useful framework, many studies on SLM components focus primarily on Type I residual stresses due to

measurement accessibility. Micro-scale stresses (Type II and III) are more difficult to quantify and often inferred and require more complex measurement methods.

2.4.1 Residual Stress Formation in Selective Laser Melting

The layer-by-layer manufacturing nature of the SLM process, combined with rapid thermal cycling, leads to the development of residual stresses [5, 30, 31]. These stresses arise from uneven cooling rates between newly solidified layers and the underlying material, creating temperature imbalances known as thermal boundary effects. This results in non-uniform heating and cooling, inducing tensile stresses in the newly solidified layers and compressive residual stresses in the cooled layers, as illustrated in Figure 2-3 [18, 60, 61]. The high melting point of many AM alloys, including CoCrMo, can hinder complete melting during SLM, increasing the risk of tensile stress development in the upper component layers and compressive stress in lower layers [59, 62, 63]. Over time, this cyclic process accumulates residual stresses, potentially causing warping, cracking, and dimensional inaccuracies in the final component [29, 64, 65]. Several studies have been conducted on residual stress in SLM of alloys.

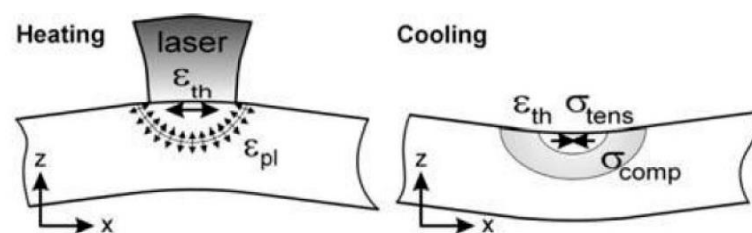


Figure 2-3: Thermal Gradient Mechanism [5]

Liu et al. [44] conducted a study on 316L stainless steel, where they explained that constrained thermal expansion and contraction create tensile stresses at the surface and compressive stresses within a component. They highlighted that the high-energy laser that melts successive layers of powder generates large temperature gradients as heat from melt pools conducts to the surrounding unmelted powder. The temperature distribution during the SLM process can be subdivided into three regions as described in Figure 2-4.

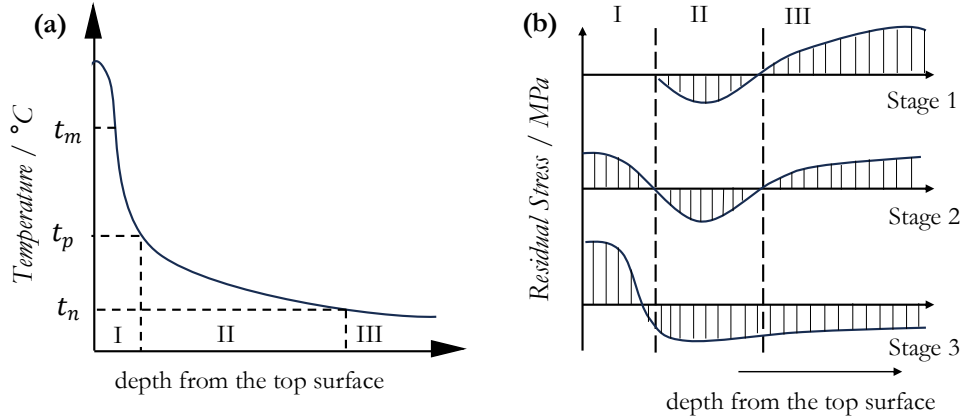


Figure 2-4: Temperature vs Residual Stress Distribution [44]

In Region I, temperatures exceed the plastic transformation temperature (T_p), transforming the material into a fully plastic state with no residual stresses induced. The irradiation of the powder at a specific location during melting results in Region II temperatures ranging between ambient temperature (T_n) and T_p of the material. Furthermore, expansion in Region III restricts material movement, generating tensile stress there while compressive stress develops in Region II. [15, 44].

As the laser moves away from a melted location, the temperature in Region I drops below the T_p , transitioning from a fully plastic to an incomplete plastic state. This transformation causes volume shrinkage in Region I, which is subsequently restricted by Region II. Consequently, tensile stresses develop in Region I while compressive stresses increase in Region II (see Figure 2-4(b) at stage 2). As the melt pool cools further, tensile stresses in Region I and compressive stresses in Region II continue to rise; compressive stresses also begin to develop in Region III [15, 44].

In their study Liu et al. [44] highlighted the role of subsequent thermal cycling, which redistributes stresses, increasing tensile stresses in the upper layers. These thermal stresses can lead to cracks with macrocracks of up to 500 μ m forming due to rapid solidification. Supporting the findings of Liu et al.'s study, Parry et al. [66] investigated the residual stresses in the SLM of Ti-6Al-4V. They emphasized the role of thermal gradients, where residual stress generation is driven by constrained thermal expansion in solidified layers, highlighting that longitudinal stresses parallel to scan vectors dominate, aligning with Liu et al.'s findings on macro and microcracks caused by steep temperature gradients.

Although the mechanisms of residual stress development in SLM are well documented for alloys such as 316L and Ti6Al4V, comparatively fewer studies analyse residual stress evolution, effect of heat treatment, and microstructural transformation in SLM CoCrMo alloys. In particular, the

relationship between heat treatment temperature, recrystallisation behaviour, and redistribution of residual stresses remains insufficiently studied in the literature. While understanding how residual stresses form during the SLM process provides a necessary foundation, examining how specific process parameters influence these stresses enables more targeted and practically implementable mitigation strategies.

2.5 Effect of Selective Laser Melting Parameters on Residual Stress

SLM parameters such as process parameters, scanning strategies, build orientation, and support structures have been observed to have a significant influence on the final part properties, including development and distribution of residual stresses [39]. However, the sensitivity of residual stress to these parameters is alloy dependent.

2.5.1 Process Parameters

Process parameters such as laser power, scanning speed, hatch spacing, and layer thickness are factors influencing the development of residual stresses in SLM [39]. Each of these parameters directly impacts the thermal gradients and the solidification process, which in turn affects the residual stress distribution within the component.

Studies have shown that low scanning speeds result in larger melt pools, which undergo greater shrinkage during solidification, leading to higher residual stresses. Conversely, higher scanning speeds produce smaller melt pools with reduced shrinkage, thus minimising residual stresses [31, 35, 44, 67, 68]. When high scanning speeds are combined with low laser power, it results in insufficient energy delivery, causing incomplete melting, which exacerbate residual stress development [13]. Robinson et al. [69] used 180 W for hatching and 100 W for boundaries, with a scanning speed of 1000 mm/s and a hatch distance of 100 μm . These parameters resulted in high part densities but required careful optimisation to control residual stresses.

Liu et al. [44] investigated the effect of process parameters on residual stress development in SLM components. Their study used laser parameters of a maximum power of 200 W, a continuous wavelength of 1090 nm, spot size of 70 μm , and a focal length of 163 mm. Before manufacturing, the build plates were stress-relieved to prevent any external influences on the stress fields. The samples were manufactured on a single build plate, arranged as shown in Figure 2-5, with designated measuring points spaced 3mm from the edges and 6mm between adjacent points.

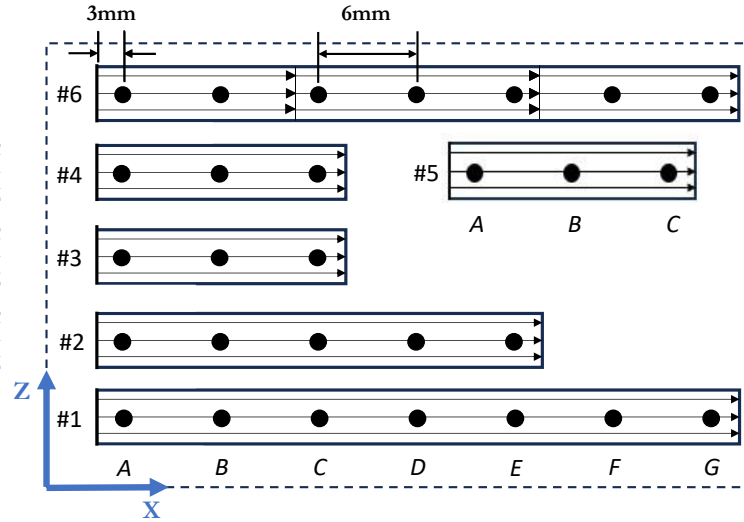


Figure 2-5: Models for Experiments of Residual Stress Distribution [44]

Three identical samples were manufactured to evaluate the influence of scanning speeds on residual stress. Each sample had a layer thickness of 0.035mm, a hatch spacing of 0.08mm, and identical scanning strategies, with dimensions of 18mm in length and a height of 50 layers. The scanning speeds used were 200mm/s, 400mm/s and 800mm/s. The study revealed that lower scanning speeds, such as 200mm/s, produced the highest residual stresses, while higher scanning speeds of 800mm/s induced the lowest residual stresses. This was attributed to the melt pool size, where slower scanning speeds create larger melt pools, which undergo greater shrinkage during solidification, resulting in higher residual stresses [44].

Several studies have further reported anisotropic residual stress distributions, with higher stress magnitudes observed parallel to the scanning direction than perpendicular to it. This behaviour is attributed to larger temperature gradients and constrained shrinkage along the scanning direction, which promote higher residual stress accumulation in that direction [31, 35, 44, 67].

The influence of scanning track length was examined by varying this parameter across three samples while keeping other parameters constant: scanning speed (400mm/s), hatch spacing (0.08mm), layer thickness (0.035mm), and scanning strategy. The track lengths used were 18mm, 32mm, and 44mm. Their study demonstrated that residual stress development is proportional to the scanning track length, as longer tracks create insufficient shrinkage compensation for the melt pool, leading to higher residual stresses. Additionally, the stress levels were consistently higher in the scanning direction than perpendicular to it, with the highest stresses occurring at the initiation point of each track. At the start of a scanning track, the melt pool is surrounded by loosely packed powder, which limits heat dissipation, creating large temperature gradients and high residual stresses [13]. As the scanning track progresses, heat readily conducts through the

previously melted scanning track resulting in lower temperature gradients and, consequently, reduced residual stress further along the scanning track [44, 67, 68].

Hatch spacing also significantly influences the development of residual stresses. Excessive overlap can result in increased thermal gradients and, therefore, residual stress formation [13, 18, 46, 54]. Parry et al. [66] observed that increasing hatch distances beyond 90µm led to incomplete fusion between tracks, which exacerbated thermal gradients and stress buildup.

Across studies, a consistent trend is that parameter sets that increase energy input per unit length, or prolong local thermal exposure, tend to increase residual stresses through larger melt pools and greater constrained shrinkage. The practical limitation is that parameters cannot be tuned for lower stress development alone. Low energy density risks lack-of-fusion defects, while high-energy density can increase stress and distortion. This indicates that optimal parameters are application-specific rather than universal and explains why many studies report residual stress reduction strategies that combine parameter optimisation with scan strategy selection and post-build heat treatment. While process parameters directly control melt pool behaviour and thermal gradients, the scanning strategy determines how these thermal cycles accumulate, transfer and disperse across layers, further influencing residual stress development.

2.5.2 Scanning Strategies

The scanning strategy used during SLM manufacturing also has a substantial impact on determining the temperature and stress distribution within each layer, subsequently impacting the overall residual stress accumulation in the manufactured part [70]. Simply explained, the scanning strategy is the pattern the laser follows when moving across the powder bed, influencing heat flow, cooling rates, and stress fields. Key factors such as scanning track length, scan direction, start point, and melt pool penetration depth, which is the extent to which the laser penetrates and remelts previous material layers, have been shown to significantly influence residual stresses [70]. While investigating the effect that variations in hatch rotation strategies have on various properties of commercially pure Titanium, which included residual stress, Robinson et al. [69] reported that tensile residual stresses align with scan vectors due to constrained contraction during cooling, resulting in increased stress magnitudes.

Several common scanning patterns have been studied, including alternating, island (also known as chessboard or chequerboard), unidirectional, bidirectional, and in-out or out-in spiral strategies [70, 71, 72, 73]. Each pattern affects residual stress differently, as it varies in terms of heat distribution and thermal cycling characteristics.

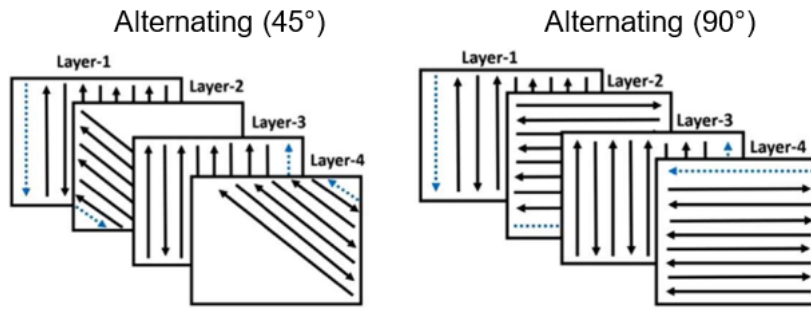


Figure 2-6: Schematics of Alternating Scanning Strategies [71]

Alternating scanning patterns, shown in Figure 2-6, where the scan direction changes between layers, can help distribute residual stresses more evenly within the component. Studies have shown that rotating the scan pattern by 45° between layers reduces overall residual stresses and deformations, largely because directional stresses do not accumulate layer after layer in the same alignment, decreasing anisotropy and thermal accumulation [71]. Research also indicates that residual stress within SLM parts is typically higher in the scan direction, with components deforming more along this path due to accumulated longitudinal stresses. While longer scan vectors increase longitudinal stress, shorter scan vectors are generally associated with lower residual stress [71, 72]. Alternating scan patterns, such as the 90° alternating strategy studied by Ali et al. [71], reduced stress anisotropy by promoting uniform heat distribution across layers. Robinson et al. [69] found that hatch rotations, such as 67° rotations, reduced stress anisotropy effectively in general geometries. However, the 90° alternating strategy was often more efficient in achieving lower stress magnitudes and uniform distributions. Alternating scan patterns, as noted by Yap et al., [13] can also distribute residual stresses more evenly and reduce deformation. Scan vector length is a critical factor influencing residual stress. Liu et al. [44] demonstrated that shorter scan vectors reduce stress magnitudes by improving heat dissipation, particularly at the track initiation points. However, Ali et al. [71] found that shorter vectors can also exacerbate heat accumulation, increasing the likelihood of microcracking in localised regions.

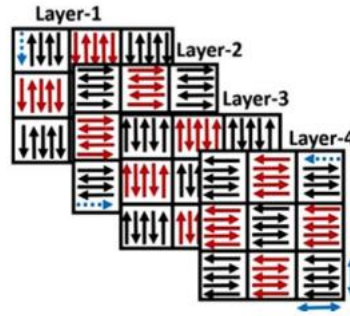


Figure 2-7: Schematics of Island Scanning Strategies [71]

The island scanning strategy shown in Figure 2-7, where each layer is divided into small separate sections that are scanned independently, has especially been examined for its potential to reduce residual stresses. By limiting the length of the scan path within each island, thermal gradients are minimised, resulting in reduced stress accumulation [71]. Fang et al. [31] highlighted the importance of smaller island sizes for reducing residual stresses, concluding that 3mm x 3mm islands for stainless steel and 5mm x 5mm for Inconel 718 balanced their thermal gradients effectively. Li et al. [35] also emphasized the effectiveness of island scanning. This strategy minimises thermal gradients and reduces stress accumulation. Li et al. also demonstrated that a rotation angle of 67° between layers evenly distributed heat and reduced stress anisotropy.

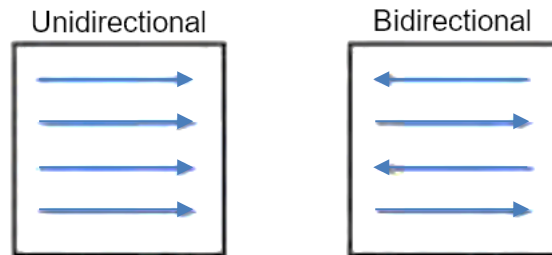


Figure 2-8: Schematics of Unidirectional & Bidirectional Scanning Strategies [73]

Unidirectional scanning, where the laser moves in a single direction across each layer, tends to create a highly anisotropic stress state due to the uniform thermal gradients aligned with the scan direction. This approach often leads to higher stress concentrations along the scan vector compared to the transverse direction [72]. Unidirectional scanning often results in higher longitudinal stresses due to consistent thermal gradients aligned with the scan direction. Parry et al. [66] found that unidirectional scanning produced the highest longitudinal stresses due to the consistent alignment of scan vectors, resulting in anisotropic stress distributions.

These studies suggest that scan strategy influences residual stress primarily by changing the time and spatial distribution of the heat input, which alters both thermal gradients and the directionality

of constrained shrinkages. A limitation in the literature is that comparisons are not always directly transferable because island size, hatch rotation angle, and scan vector length are frequently changed alongside other parameters. In addition to scanning strategies, build orientation influences how heat dissipates through the structure during solidification and therefore affects residual stress distribution.

2.5.3 Build Orientation

The build orientation of the component further contributes to the residual stress distribution, as it determines the angle between the component's primary axis and the vertical build direction on the platform [18, 74]. Components built at certain orientations are more prone to stress concentration in specific regions due to the directional nature of heat dissipation during layer deposition, generally from the cooler build platform towards the warmer upper layers. For example, parts manufactured in vertical orientations experience larger thermal gradients along their height, leading to greater residual stress accumulation in the vertical direction. In contrast, horizontal or angled orientations can help mitigate this effect, as heat dissipation is spread more evenly across layers [18].

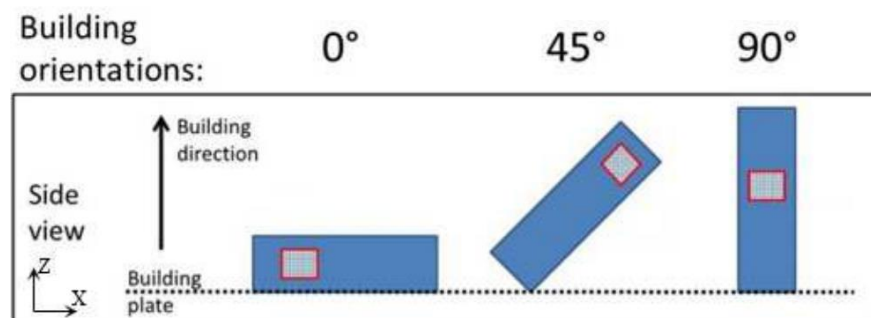


Figure 2-9: Build Orientation [74]

The illustration in Figure 2-9 highlights the effect build orientation has on residual stress development, showing that components built at certain orientations, particularly near 90° or 45°, create more overlapping molten pool boundaries due to the greater number of layers required for these orientations. These molten pool boundaries act as weak points where fractures and cracks can initiate and propagate, particularly under tensile stresses [18].

The build orientation not only plays a crucial role in residual stress development due to the number of layers required to complete a component but also determines the need for support structures. These support structures impact the stress distribution introduced by the manufacturing process, particularly in areas with bridges and overhangs that require additional stability. The volume and placement of support structures are highly dependent on the component's build orientation, as

shown in Figure 2-10. This is explained in a study done by Cheng, et al. [75], which analysed the residual stress distribution across different build orientations.

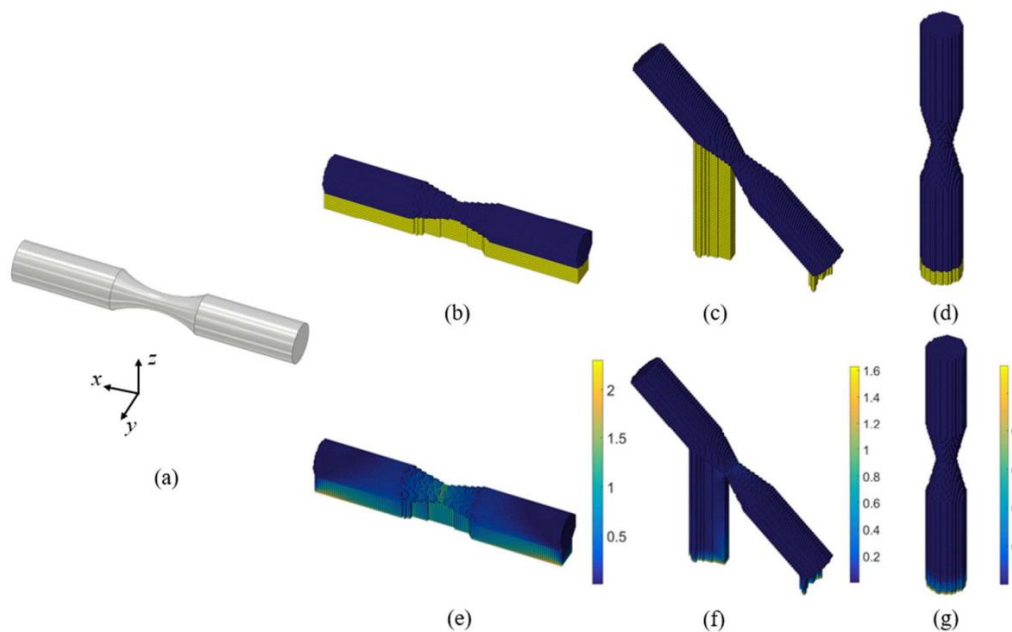


Figure 2-10: Influence of Build Orientation on Support Generation [75]

The results of their study showed that the maximum normalized residual stress values varied substantially: the horizontal orientation (Figure 2-10 (e)) had the highest residual stress value at 2.30, followed by the 45° orientation (Figure 2-10 (f)) at 1.62, and then the vertical orientation (Figure 2-10 (g)) at 1.14. The vertical build orientation, Figure 2-10 (g), required fewer supports and exhibited the lowest maximum residual stress, while the horizontal orientation, Figure 2-10 (e), required the most supports and experienced the highest stress concentration. This outcome demonstrates that build orientation significantly influences both the volume of support structures and the residual stress distribution in SLM-manufactured components.

Fang et al. [31] also corroborates this finding, noting that vertical orientations lead to fewer supports and residual stresses with lower magnitudes, while horizontal orientations, requiring more supports, exhibit higher stress concentrations. Robinson et al. [72] noted that vertical orientations typically experience more uniform stress distributions due to improved heat dissipation across layers. However, slender geometries built using unidirectional scans exhibited higher residual stress magnitudes due to the alignment of stresses with scan vectors. Given the complex interaction between process parameters, scan strategy, and build orientation, accurate quantification of residual stresses is essential for both validation and optimisation.

2.6 Residual Stress Measurement Techniques

Residual stress measurement techniques typically measure strain, from which residual stresses are subsequently calculated using material properties such as Young's modulus and Poisson's ratio [58]. Various residual stress measurement techniques exist, broadly classified into non-destructive methods, which largely preserve the part, and destructive or semi-destructive methods which involve material removal or sectioning [30, 76, 77]. The non-destructive methods generally include diffraction-based techniques such as X-Ray Diffraction (XRD) and Neutron Diffraction [35, 77]. The most widely known destructive and semi-destructive residual stress measurement techniques are the hole-drilling and contour methods [76, 78].

2.6.1 Destructive Methods

Destructive measuring techniques take advantage of the balanced state of residual stresses within a component by destroying the part through cutting, sectioning, or material removal to redistribute the residual stress [30]. These techniques are commonly referred to as stress relaxation methods as internal stresses are released and redistributed when sectioning or drilling is performed [51, 79]. Measuring the subsequent strains after destruction is used to calculate the remaining residual stresses within the component by using Hooke's Law [30]. The most common destructive measurement techniques used to determine residual stress are the hole-drilling method and the contour method [30, 59].

In the hole-drilling method, illustrated in Figure 2-11, a small hole of approximately 1.8 mm in diameter and approximately 2 mm deep is drilled in the focus region [5]. Strain gauges are arranged at 120° around the hole location to measure the relaxation strains that occur once the material is removed [79]. From the measured strains, the residual stress at that location is calculated. This technique is relatively simple and quick to perform, and in some cases the drilled region can be repaired with minimal effect on the component's integrity [5].

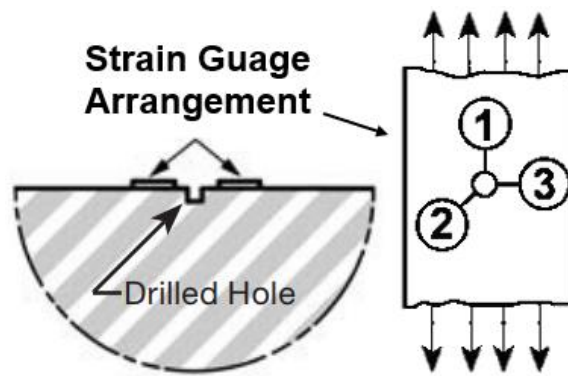


Figure 2-11: Hole-Drilling Method Setup & Strain Gauge Arrangement, Adapted from [80]

The hole-drilling method assumes linear elastic material behaviour during stress relaxation and relies on accurate calibration coefficients to calculate stresses from measured strains. It is primarily valid for near-surface, approximately biaxial stress states and is typically limited to depths of 1–2 mm [80]. Measurement accuracy may be compromised if local plasticity occurs during drilling, particularly in regions with high residual stress magnitude. Reliable measurements also require flat, accessible surfaces and careful drilling procedures to avoid introducing additional stresses or geometric artefacts.

The contour method involves cutting a sample along a chosen plane, commonly using a non-abrasive technique such as the wire electron discharge machine (wire-EDM) [5]. Residual stresses acting normal to that plane are released and cause the cut faces to deform slightly. This out-of-plane deformation can then be measured using methods such as coordinate measuring machine (CMM), micrometer screw gauge, or digital image correlation. The residual stresses present can be determined [5, 81].

The contour method assumes that material behaviour during stress release is predominantly elastic and that the cutting process does not introduce significant additional plastic deformation. The accuracy of the stress representations depends on the precision of the cut made and the quality of surface deformation measurements. Although the method provides high-resolution, stress quantification over large cross-sectional areas, it is fully destructive and yields stress information only on the sectioned plane [82]. Obtaining stress distributions on multiple planes therefore requires multiple sacrificial specimens.

A commonly used geometry in stress relaxation methods is a cantilever geometry. With this geometry, a beam is fabricated with one end attached to the build plate and is subsequently sectioned to release residual stresses. Once cut from the baseplate, the free end deflects in response to stress redistribution. Measuring the deflection at the tip provides an indication of the

overall residual stress in the cantilever beam [59, 81]. However, it should be noted that cantilever deflection methods do not directly measure residual stress magnitude. Instead, they quantify deformation resulting from stress redistribution after sectioning, and interpretation relies on assumptions such as bending-dominated behaviour and linear elastic response.

2.6.2 Non-Destructive Methods

Due to the destructive methods rendering part unusable, non-destructive measurement methods are often preferred for expensive or critical components, as they do not significantly alter the part, thus preserving its functionality [5]. These techniques typically determine residual stress indirectly by measuring lattice strain through diffraction-based approaches using Bragg's law [59], as demonstrated in Figure 2-12. Unstrained lattice parameters are then compared to the measured lattice spacings, which are used to determine the lattice strain present within components [59].

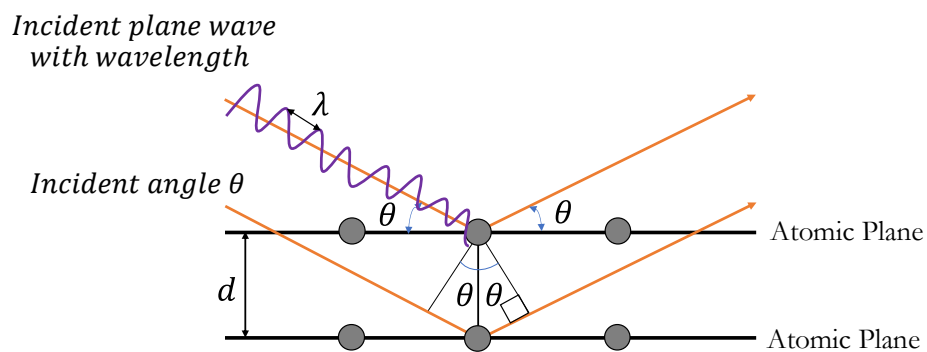


Figure 2-12: Bragg's Law Diffraction [59]

Non-destructive measurement techniques include ultrasonic waves, magnetic methods, XRD, and neutron diffraction, although the XRD and neutron diffraction methods are the most widely used of these methods [30, 35].

XRD utilises the direct relationship between the interplanar spacing and residual stress [5]. It measures lattice strains by detecting shifts in Bragg peaks, typically through the $\sin^2\psi$ method. An X-ray beam is directed at a sample surface at a known angle, and a detector records the diffracted intensity over a range of angles. Comparing the diffraction pattern of a stressed sample with that of an unstressed reference sample, such as a virgin powder sample, enables the calculation of strain using Bragg's law [5, 77].

XRD-based stress determination assumes that lattice strains are purely elastic and that appropriate diffraction elastic constants are available for the material and crystallographic planes analysed. Coarse grains, surface curvature, or insufficient surface preparation may reduce

measurement accuracy. Sample geometry is also constrained by instrument size. Furthermore, due to the limited penetration depth of X-rays in metals, XRD primarily characterises near-surface residual stresses and may not represent subsurface stresses [5, 77].

Each diffraction peak in an XRD pattern corresponds to the diffraction from specific crystallographic planes and provides insight into atomic arrangement, interatomic spacing, and phase composition. Residual stresses influence the material's crystal lattice by causing local distortions, which manifest as shifts in peak positions, changes in Miller indices, or peak broadening. Such variations can indicate stress gradients or microstructural heterogeneity within the material [83].

Furthermore, the crystallographic planes with specific Miller indices have different atomic arrangements and orientations. A change in the Miller indices implies a reorientation or a shift in the lattice planes, which can be attributed to the effect of the applied heat treatment on the material. While Miller indices themselves do not directly represent residual stresses, they reflect changes in crystallographic orientation and lattice parameters, which can be related to residual stress effects. This alteration can be suggestive of residual stress relaxation or redistribution in the material. The magnitude and distribution of residual stresses can affect the lattice parameters and alter the crystallographic orientation, leading to changes in the observed Miller indices [84, 85].

Consequently, XRD is not only useful for phase identification but also for assessing how thermal gradients, plastic deformation, or phase transformations affect the crystal structure during manufacturing or heat treatment. XRD is commonly applied to AM components with relatively small geometries, though it is typically limited to measuring near-surface stresses only a few micrometres deep [5, 77].

Neutron diffraction also measures lattice spacing changes resulting from residual stress, but uses neutrons, which have a much greater penetration depth [77, 86]. If the measured lattice spacing is larger than the reference spacing, tensile stresses are present, and if it is smaller, the stresses are compressive [86]. Neutron diffraction can use a constant-wavelength source by applying Bragg's law or using a pulsed beam known as the time-of-flight technique. Although this method can yield valuable 3D stress information, it relies on specialised facilities and can be time-consuming [5]. Once quantified, residual stresses may be mitigated through either process-level optimisation or post-processing treatments. Among these, stress-relief heat treatment remains the most widely adopted industrial strategy.

2.7 Residual Stress Reduction

Stress-relief heat treatment is commonly used to reduce the residual stresses introduced during manufacturing. This is achieved by heating the material to a specific temperature, determined by its composition, holding it for a defined duration, and then cooling it under controlled conditions to promote stress relaxation while minimising the risk of reintroducing thermal stresses [87]. Heat treatment is also one of the most widely applied methods for reducing residual stresses in metal AM components, particularly in SLM-fabricated parts of a variety of materials including titanium, nickel and CoCrMo alloys [27, 88, 89, 90]. Its effectiveness lies in promoting atomic diffusion and microstructural homogenisation, thereby relieving internal stresses while also improving mechanical properties [21, 27]. The key parameters that influence the outcome of heat treatments include the soaking temperature, dwell time, and cooling rate [21]. Higher temperatures and longer durations enhance stress relief through increased atomic mobility, while the cooling rate determines the final microstructure [21, 27].

To contextualise these parameters within the broader AM field, several studies have demonstrated the effectiveness of annealing heat treatments in reducing residual stresses in SLM-manufactured components. Liu et al. [44], working with 316L stainless steel, showed that annealing at 450°C for 2 hours significantly reduces surface tensile stresses. However, deeper internal stresses required higher temperatures for adequate relief. Li et al. [35], using AlSi10Mg alloy, reported similar results and further noted that preheating the build platform above 570°C could remove tensile stresses and even introduce beneficial compressive stresses. Both Liu et al. [44] and Li et al. [35] demonstrated that annealing heat treatments can reduce residual stresses in SLM-manufactured components by as much as 70%.

In addition to post-manufacturing annealing, Fang et al. [31], reviewed studies on a variety of materials, including tool steels, mild steels, 316L stainless steel, Inconel 718, titanium alloys, aluminium alloys, and Zr-based amorphous alloys. Their analysis showed that substrate preheating to 550°C during the build phase reduced residual stresses by 46%, highlighting the potential benefits of combining preheating with post-processing treatments for enhanced stress relief.

Beyond post-processing heat treatment, in-process parameter optimisation has also been explored. In terms of scanning track optimisation, Ali et al. [71] demonstrated that re-scanning with a 150% energy density in Ti6Al4V alloys reduced residual stresses by 33.6%, with the greatest improvements observed in the top layers. Similarly, Parry et al. [66], also working with Ti6Al4V, recommended substrate preheating at 470°C to reduce thermal gradients and residual stress accumulation during the SLM process.

Shiomi et al. [91] investigated residual stress development and reduction in SLM-fabricated metallic beam specimens. The as-built components exhibited tensile residual stresses in the top surface layer, in the range of 300–400 MPa, largely independent of scan speed, indicating that stress magnitude was primarily governed by inherent thermal gradients rather than scan speed alone. Residual stresses were evaluated using a progressive layer-removal method combined with strain measurements, and stresses were calculated assuming elastic behaviour and a Young's modulus determined experimentally for the SLM material. Heat treatment was performed without an inert atmosphere at soaking temperatures of 500°C, 600°C and 700°C respectively, for one hour. The study reported that the 600°C and 700°C heat treatments showed a reduction in residual stresses within the top layer of the components of 70%, demonstrating that moderate-temperature annealing is effective in relieving macroscopic (Type I) stresses. However, the study did not evaluate microstructural phase evolution or deeper residual stress distributions, and the measurement technique primarily captured near-surface stress redistribution. In addition to post-build annealing, Shiomi et al. also examined in-process mitigation strategies. Re-scanning each layer at 150% of the laser's forming energy reduced tensile stress by approximately 55%, while preheating the base plate to 160°C reduced stress by 40%. These findings suggest that both thermal post-treatment and in-situ thermal control influence residual stress, although heat treatment at elevated temperature produced the most significant stress reduction.

While moderate annealing temperatures are sufficient for stress reduction in alloys such as 316L and AlSi10Mg, CoCrMo exhibits different phase stability and recrystallisation behaviour, necessitating higher treatment temperatures. For CoCrMo alloys, stress-relief annealing is typically achieved at soaking temperatures between 1050°C and 1150°C. Guoqing et al. [92], using CoCrMo, found that soaking at 1200°C with a controlled heating rate of 8°C/min effectively reduced residual stresses. They also noted that cooling rate plays a significant role in determining the final properties of the material: furnace cooling generally results in higher elongation, while rapid quenching improves yield strength but may leave some residual stresses.

Ko et al. [37] conducted a detailed investigation into the effect of heat treatment temperature on the microstructure, residual stress, and mechanical properties of SLM-fabricated CoCrMo alloys. They evaluated heat treatments at 750°C, 950°C, and 1150°C for one hour in an argon atmosphere, followed by furnace cooling. Residual stress was measured using the $\sin^2\psi$ XRD method after removal of approximately 100µm of surface material to eliminate polishing-induced stresses. The as-built SLM specimens exhibited high tensile residual stresses, with stresses perpendicular to the build direction approximately 2.4 times higher than those parallel to it, highlighting directional anisotropy inherent to the SLM process.

Their study found that heat treatment at 750°C does reduce Type I residual stresses, with reductions of approximately 93% reported. However, EBSD analysis suggested that heat treatment at 1150°C was unable to alleviate deeper Types II and III stresses. Furthermore, 750°C heat treatment increased the fraction of the HCP phase relative to FCC phase. At 950°C, most macroscopic residual stresses were eliminated, melt pool boundaries became indistinct, and microstructural homogenisation was improved. At 1150°C, although residual stresses remained low, slight compressive surface stresses were observed, attributed to rapid cooling after heat treatment. Complete recrystallisation was not achieved even at this temperature, as some columnar grain features remained.

Ko et al. concluded that heat treatment at 950°C or higher provides a desirable balance between residual stress relief, microstructural homogenisation, and mechanical properties. Importantly, their findings distinguish between macroscopic residual stress reduction and persistence of micro-scale strains, demonstrating that high-temperature annealing does not eliminate all forms of residual stress in SLM CoCrMo alloys.

While Ko et al. emphasised temperature-dependent microstructural evolution, Rousseau et al. [93] investigated the effect of various stress-relief annealing times on CoCrMo components using a combined simulation and neutron diffraction approach. Their simulation was performed using a calibrated thermo-mechanical workflow that combined inherent strain calibration with thermal calibration via an exposed energy fraction parameter, followed by thermo-mechanical calibration through a volumetric expansion factor. For experimental analysis, thin-walled specimens were stress-relieved at 1065°C using multiple holding times of 15 minutes, 1 hour, 2 hours, and 3 hours, with a further comparison specimen heat treated at 750°C for 1 hour, and an as-built control specimen.

Neutron diffraction results confirmed that heat-treated specimens exhibit substantially lower residual stress than the as-built condition. The range of holding times at 1065°C produced near-identical residual stress levels, indicating that stress relief at this elevated temperature occurs rapidly, suggesting that higher temperatures are more critical than extended holding times. A clearer distinction was observed between annealing temperatures, with 1065°C producing lower residual stresses than 750°C. These findings show that annealing temperature is the dominant parameter for macroscopic stress relief in SLM CoCrMo alloys, whereas holding time holds a secondary role once recovery and recrystallisation mechanisms occur. The simulation and neutron diffraction datasets showed close agreement within experimental uncertainty for the normal stress component, supporting the biaxial assumption for this geometry. Larger discrepancies occurred in transverse stresses, with the authors attributing differences to

anisotropy inherent to layer-wise manufacturing and process variability not represented in the idealised simulation, including powder variability, powder distribution, furnace heat flux variation, ambient effects on cooling rate, furnace ramp variability, and microstructural defects.

The selection of 1065°C from Rousseau et al. is supported by thermodynamic considerations of phase stability in CoCrMo alloys. Phase diagrams for biomedical CoCrMo alloys indicate that the temperature range of approximately 1050°C – 1150°C lies within the single-phase (γ -phase) solid-solution region, where secondary phases such as carbides and σ -phase are largely dissolved. In addition, the recrystallisation temperature of additively manufactured CoCrMo alloys is typically reported within the range of 900°C and 1150°C [24, 94, 95]. Heat treatment at 1065°C therefore provides sufficient thermodynamic driving force for recovery, dislocation removal, and recrystallisation, while remaining below temperatures associated with undesirable phase instability.

Complementing these results, Takaichi et al. [95] investigated the effect of heat treatment temperature on the anisotropic microstructural and mechanical behaviour of SLM CoCrMo alloys. Samples were produced at build orientations of 0°, 45°, and 90° relative to the build direction and heat treated at 750°C, 900°C, 1050°C, and 1150°C, respectively for 6 hours. Their results showed that heat treatments up to 1050°C resulted primarily in microstructural recovery back to the as-built condition, with the retention of columnar grain structures inherited from the SLM process. Although partial stress relaxation and ductility improvements were observed, significant mechanical anisotropy persisted. In contrast, heat treatment at 1150°C resulted in complete recrystallisation, significantly reducing epitaxial columnar grains, and formation of uniform grain distributions. This microstructural homogenisation also led to a reduction in anisotropic behaviour. Their findings highlight that full recrystallisation, rather than recovery alone, is required to eliminate the directional effects introduced during SLM processing.

To compare the experimental parameters and findings reported in these studies, the material of the samples, heat treatment conditions, and observed residual stress trends are summarised in Table 2-1.

Table 2-1: Summary of heat treatment conditions and residual stress trends in SLM components

Study	Material	Residual Stress Reduction Strategy	Strategy Condition	Holding Time	Cooling Method	Residual Stress Trend
Liu et al. [44]	316L Stainless Steel	Post-process Annealing Heat Treatment	450°C Annealing	2 Hours	Furnace Cooling	Significant reduction in surface tensile stress, however, relieving deeper stress required higher temperatures
Ali et al. [71]	Ti6Al4V Alloy	In-Process Re-scanning	150% Laser Energy Density	-	-	Approximately 33.6% reduction in residual stress, with largest reduction in surface layers
Parry et al. [66]	Ti6Al4V Alloy	Build Plate Preheating	Preheating at 470°C	-	-	Reduced thermal gradients and residual stress
Shiomi et al. [91]	Metals	Post-process Annealing Heat Treatment	500°C, 600°C and 700°C Annealing with no controlled atmosphere;	1 Hour	Furnace Cooling	Approximately 70% reduction in Type I surface stress at 600°C – 700°C;

		In-Process Re-scanning Build Plate Preheating	150% Laser Energy Density; Preheating at 160°C			Re-scanning reduced residual stresses by approximately 55%; Build plate preheating reduced residual stresses by approximately 40%
Guoqing et al. [92]	CoCrMo Alloy	Post-process Annealing Heat Treatment	8°C/min Heating Rate and 1200°C Annealing in a nitrogen inert atmosphere	1 Hour and 2 Hours	Furnace Cooling and quenching	Significant residual stress reduction
Ko et al. [37]	CoCrMo Alloy	Post-process Annealing Heat Treatment	750°C, 950°C and 1150°C Annealing in an argon inert atmosphere	1 Hour	Furnace Cooling	750°C annealing reduced Type I residual stress by approximately 93% reduction; 950°C annealing nearly removed all macroscopic stresses; 1150°C annealing significant tensile residual stress reduction with some compressive stresses observed

Rousseau et al. [93]	CoCrMo Alloy	Post-process Annealing Heat Treatment	750°C and 1065°C Annealing	15 Minutes, 1 Hour, 2 Hours and 3 Hours	Furnace Cooling	1065°C annealing significantly lower residual stress, more than 750°C annealing; Holding time has minimal influence on residual stress reduction
Takaichi et al. [95]	CoCrMo Alloy	Post-process Annealing Heat Treatment	750°C, 900°C, 1050°C and 1150°C Annealing in an argon inert atmosphere	6 Hours	Furnace Cooling	Annealing up to 1050°C resulted primarily in microstructural recovery with the retention of columnar grain structures; Annealing at 1150°C resulted in complete recrystallisation, significantly reducing residual stress.

Although the experimental approaches and evaluation methods differ between studies, several consistent trends emerge in SLM-fabricated CoCrMo alloys. Annealing temperatures in the 750°C range are reported to be generally sufficient to relieve macroscopic Type I residual stresses, while higher temperatures between approximately 900°C and 1150°C promote more extensive microstructural recovery and recrystallisation. These findings indicate that higher temperatures within the single γ -phase region are often selected when full stress relief and microstructural homogenisation are required beyond simple recovery. Furthermore, the literature indicates that annealing temperature has a more significant influence on residual stress reduction than holding time once sufficient atomic mobility is achieved. While experimental studies provide insight into stress evolution and mitigation, predictive modelling offers a complementary approach for anticipating residual stress distributions prior to manufacturing or post-processing.

2.8 Numerical Modelling of Residual Stress in SLM

Finite Element Analysis (FEA) simulations are widely used to predict material behaviour under both manufacturing conditions and its intended use environments, including potential stress applications and distortions [39, 59]. For SLM, these simulations offer valuable insights into the evolution of residual stress and component distortion, enabling users to adjust design or process parameters before manufacturing begins.

Advanced simulation tools, as highlighted by Li et al., [35], provide a powerful means to optimise heat treatment parameters, predict residual stress distribution, and target specific areas for post-processing. Such capabilities reduce the need for costly trial-and-error experiments and enhance overall process efficiency.

FEA simulations are a strategic tool that is used for predicting the residual stresses that develop during SLM manufacturing. These simulations provide valuable insights into how process parameters, such as laser power, scanning speed, and build orientation, influence the thermal history and resulting stress distribution within components. They can indicate whether residual stresses exceed acceptable levels, which allows for adjustments to be made to the design or process parameters beforehand, such as modifying support structures or optimising the build orientation, to control stress distribution.

Several simulation software packages are used for AM applications, including Altair, ANSYS Additive, Dassault Systèmes, Siemens NX, and Simufact Additive. Simufact Additive is well-suited for simulating metal powder bed fusion processes and offers comprehensive workflows for build simulations, support structure optimisation, and post-processing simulations [96, 97].

To overcome the substantial computational cost associated with specialised simulations of the SLM process, several researchers have adopted the Inherent Strain Method (ISM) as an efficient alternative for predicting residual stresses and distortions. Originating from welding processes, ISM has been adapted to accommodate additive manufacturing processes such as laser PBF as well due to the similarity between layer-by-layer melting and multi-pass welding [98]. The method involves two main steps, first, deriving the inherent strain field from an experimental calibration or comprehensive meso-scale thermo-mechanical simulations, and second, applying the pre-determined strains in a simplified mechanical layer-equivalent model through linear elastic analysis [99].

This approach enables rapid prediction of deformation and residual stress distributions without directly modelling the complex thermal cycles of the manufacturing process [98]. Studies have reported that ISM can reduce simulation times from weeks or days to only a few hours while maintaining comparable accuracy to full thermo-mechanical models [98, 99]. Ahmad et al. [100] and Siewert et al. [101] demonstrated consistency between ISM predictions of residual stresses and experimental results obtained using the contour method [99]. Setien et al. [102] further validated an empirical calibration approach based on cantilever deflection tests, confirming the method's reliability for residual stress evaluation in metal AM.

Residual stress predictions in Simufact can be performed using either the coupled thermo-mechanical or pure mechanical simulation approach [96]. Mechanical simulations use the ISM to approximate the induced residual stresses by applying pre-determined strain values, while thermo-mechanical simulations use both mechanical and thermal analyses for a more detailed representation. The mechanical simulation approach provides an efficient approach to simulating residual stress, particularly for large-scale models. The ISM is one of the most widely used FEA approaches for predicting residual stresses due to its computational efficiency and relatively high accuracy [30]. This method simplifies the simulation by applying pre-determined inherent strain values to each layer of the build, representing the permanent deformation caused by thermal cycling [47]. The inherent strain for each layer can be estimated through detailed micro-scale simulations with a moving heat source or determined empirically using cantilever specimens [97, 96]. Originally developed for welding simulations, this method has been successfully adapted for SLM applications [96]. Rousseau et al. [93] validated the ISM for CoCrMo components by comparing simulation results with neutron diffraction measurements. The study found that the method accurately predicted the residual stress distribution, confirming its suitability for parts where full thermo-mechanical simulations may be impractical.

Thermo-mechanical simulations offer a more detailed representation of the interaction between the thermal and mechanical phenomena throughout the build process. By coupling these two factors, thermo-mechanical models can accurately simulate the evolution of residual stress across different regions of the part. Parry et al. [66] demonstrated the influence of scan strategy on residual stress formation by using a coupled thermo-mechanical model. Their study revealed that longitudinal stresses, which align with the scan vector, dominate the overall stress distribution. Although highly accurate, thermo-mechanical simulations are computationally expensive and time-consuming, limiting their practical application for small or intricate components where accuracy is essential [96].

For either of these simulations, Simufact Additive relies on a voxel-based meshing approach, which uses hexahedral elements to represent the component geometry as shown in Figure 2-13. This mesh type is particularly well-suited for additive manufacturing simulations, as it mirrors the layer-by-layer deposition inherent to processes like SLM [103]. This meshing technique enables precise modelling of stress and distortion, even in highly complex geometries, as it allows for efficient adaptive refinement. Regions requiring higher resolution can use smaller voxels, and coarser voxels elsewhere to reduce computational cost without sacrificing accuracy.

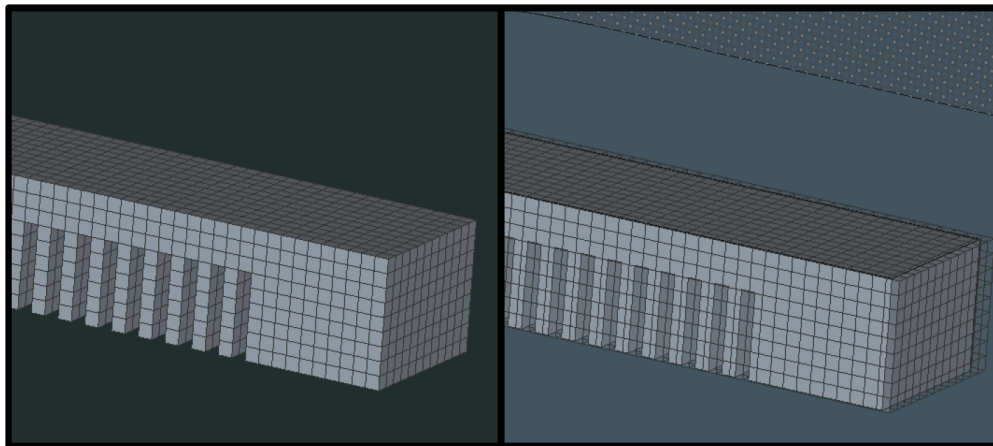


Figure 2-13: Illustration of a Voxel-Mesh [104]

Applying a voxel-mesh involves creating a 3D grid over the component and applying a surface mesh for complete coverage. The software connects all simulation outputs to this mesh, allowing detailed analysis at each nodal point. To ensure simulation reliability, the mesh must achieve high volume fractions, meaning that the voxels should be nearly full rather than partially intersected. Simufact provides a “volume fraction” display, as highlighted in Figure 2-13, that assists users in verifying that cuboidal elements represent most of the component’s solid volume. This meshing approach supports precise modelling and provides valuable insights into stress, strain, and potential distortion within the manufactured part.

Calibration is also an essential element for improving the accuracy of simulation model predictions. Simufact Additive allows users to refine predictions by comparing simulated results with experimental data, such as deflection measurements or neutron diffraction analysis [93]. This iterative process improves predictive reliability, particularly in high-stress regions. Parry et al. [66] emphasized the importance of validating simulation models against experimental results, such as deflection measurements and XRD data. This iterative calibration process improves the predictive accuracy of residual stress modelling.

2.8.1 Numerical Analysis using the Inherent Strain Method

ISM is a reduced-order approach used in finite element simulations to predict residual stresses and distortions in SLM parts by prescribing a layer-wise “inherent strain” field, thereby avoiding explicit thermal-history modelling [105, 106]. During the SLM process, localised heating from the laser causes rapid melting and solidification of the powder material. These repeated thermal cycles result in high temperature gradients and significant plastic deformation. Once the component cools to ambient temperature, these plastic strains become locked into the structure as residual stress. ISM captures these effects by applying an empirically derived or simulated strain field, which is referred to as the inherent strain, throughout the build layers and eliminates the need to explicitly model complex thermal histories [105].

Figure 2-14 represents the basic elemental deformation of a specimen during the SLM process, where the inherent strain represents the permanent deformation that would remain after the component is fully stress-relieved, with respect to its original undeformed state [105]. This strain field becomes the driving input for calculating displacement and stress in the simulation model.

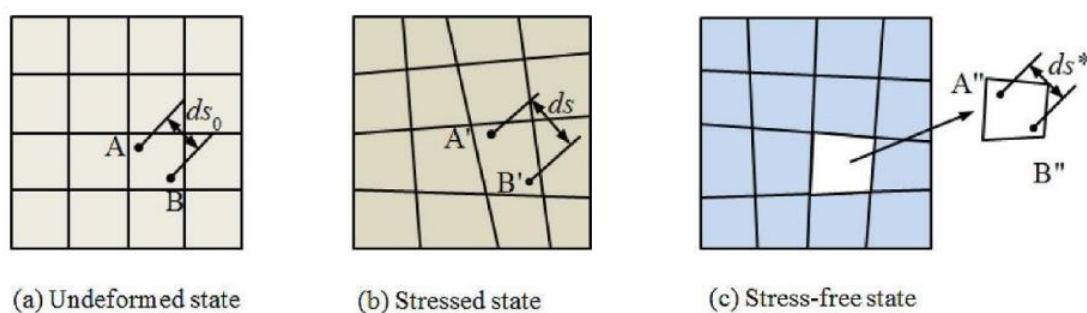


Figure 2-14: Simplified representation of inherent strain [105]

Following the original welding mechanics formulation, the inherent strain is defined as the residual strain in the stress-relieved state with respect to the undeformed configuration, as expressed in Equation 2-1 [105, 106]:

$$\varepsilon^* = \frac{ds^* - ds_0}{ds_0}$$

Equation 2-1

Using ambient temperature as the reference, the thermal strain is removed in this definition, and under the assumption of small strains ($ds \approx ds_0$), the inherent strain may alternatively be expressed as the difference between the total mechanical strain and the recoverable elastic strain, as shown in Equation 2-2 [105, 106]:

$$\varepsilon^* = \frac{ds^* - ds_0}{ds_0} - \frac{ds - ds^*}{ds}$$

Equation 2-2

In this formulation, the total mechanical strain ε and the elastic strain ε_e are defined according to Equation 2-3 and Equation 2-4, respectively:

$$\varepsilon = \frac{ds^* - ds_0}{ds_0}$$

Equation 2-3

And

$$\varepsilon_e = \frac{ds - ds^*}{ds}$$

Equation 2-4

Substituting Equation 2-3 and Equation 2-4 into Equation 2-2 yields the simplified relationship for inherent strain given in Equation 2-5:

$$\therefore \varepsilon^* = \varepsilon - \varepsilon_e$$

Equation 2-5

Here:

ε = total mechanical strain

ε_e = elastic strain

ε^* = inherent strain

Classical welding applications often assume that elastic strains are negligible compared with plastic strains, leading to the approximation $\varepsilon^* \approx \varepsilon_p$ [105, 106]. However, this assumption does not hold for additive manufacturing. In SLM, the continuous addition of new layers creates

evolving mechanical constraints, and elastic contributions remain significant in the final residual stress state [106]. To address this, a modified ISM has been proposed for AM, in which the inherent strain is defined by comparing two states of a material point: an intermediate state, immediately after solidification when compressive plastic strain is dominant, and the steady state after cooling to room temperature. The resulting formulation retains both plastic and elastic contributions to the inherent strain, reflecting the constraint-dependent behaviour in AM processes [106].

The total residual strain (ϵ_{tot}) in a manufactured component typically comprises several components, including elastic strain (ϵ_e), plastic strain (ϵ_p), thermal strain ($\epsilon_{thermal}$), and strain resulting from phase transformations (ϵ_{phase}). Where the total residual strain can be calculated using Equation 2-6 [105]:

$$\epsilon_{tot} = \epsilon_e + \epsilon_p + \epsilon_{thermal} + \epsilon_{phase}$$

Equation 2-6

By assuming that elastic strains are small compared to the permanent plastic strains, this method simplifies the simulation process and significantly reduces computational cost. The calculated inherent strain field is used to determine the resulting displacements and stresses by solving the mechanical equilibrium equations within the finite element model. Accordingly, the inherent strain may be expressed as the difference between the total residual strain and the elastic strain, as given in Equation 2-7 [105]:

$$\therefore \epsilon^* = \epsilon_{tot} - \epsilon_e$$

Equation 2-7

In practice, inherent strain values are often determined through experimental calibration using cantilever deflection data. The component is manufactured under controlled conditions, sectioned from the build plate, and the deflection is measured. Simulations are then adjusted to reproduce the observed deformations, allowing the inherent strain input to be refined. Once calibrated, the ISM can be used to simulate more complex geometries and evaluate stress-relief strategies such as heat treatments.

2.9 Summary

The literature clearly demonstrates that residual stresses represent a major challenge in SLM of metal components. These stresses arise due to the layer-by-layer nature of the process, where repeated thermal cycling, rapid heating and cooling, and constrained solidification induce non-uniform strain fields. The resulting residual stresses can compromise mechanical performance,

dimensional accuracy, and reliability, especially in components manufactured from high melting point alloys such as CoCrMo. These effects are particularly important in industries like biomedical and aerospace, where structural integrity and precision are essential.

Several key parameters were highlighted as influencing the magnitude and distribution of residual stresses in SLM-fabricated components. Laser power, scanning speed, hatch spacing, and layer thickness were shown to directly impact melt pools, cooling rates, and resulting thermal gradients. Lower scanning speeds and higher energy densities were found to increase melt pool size and thermal strain, leading to higher residual stress concentrations. Additionally, scanning strategy and track length significantly affect thermal history and stress directionality. Scan patterns like Island and alternating scan patterns, for instance, have been observed to reduce anisotropy and lower peak stresses by disrupting the accumulation of directional thermal gradients. Build orientation and support structure design were also reported to influence residual stress development, with horizontal build orientations typically showing higher stresses due to more extensive support requirements and restricted heat dissipation.

To mitigate residual stresses, post-process heat treatment, such as stress-relief annealing, has been widely adopted as the preferred strategy. Literature on CoCrMo and other alloys demonstrates that heat treatment can significantly reduce residual stresses, depending on the soaking temperature, holding time, and cooling method. These studies indicate that stress-relief outcomes depend strongly on both the heat treatment temperature range and on which stress scale is evaluated. Heat treatments in the 750°C range can substantially reduce macroscopic Type I stresses, particularly near the surface, yet micro-scale stresses may remain. Higher temperatures within the γ -phase region, typically above 1000°C, promote more extensive recovery and can reduce residual stresses more consistently, with some studies indicating that full recrystallisation and reduced anisotropy require heat treatment temperatures closer to 1150°C.

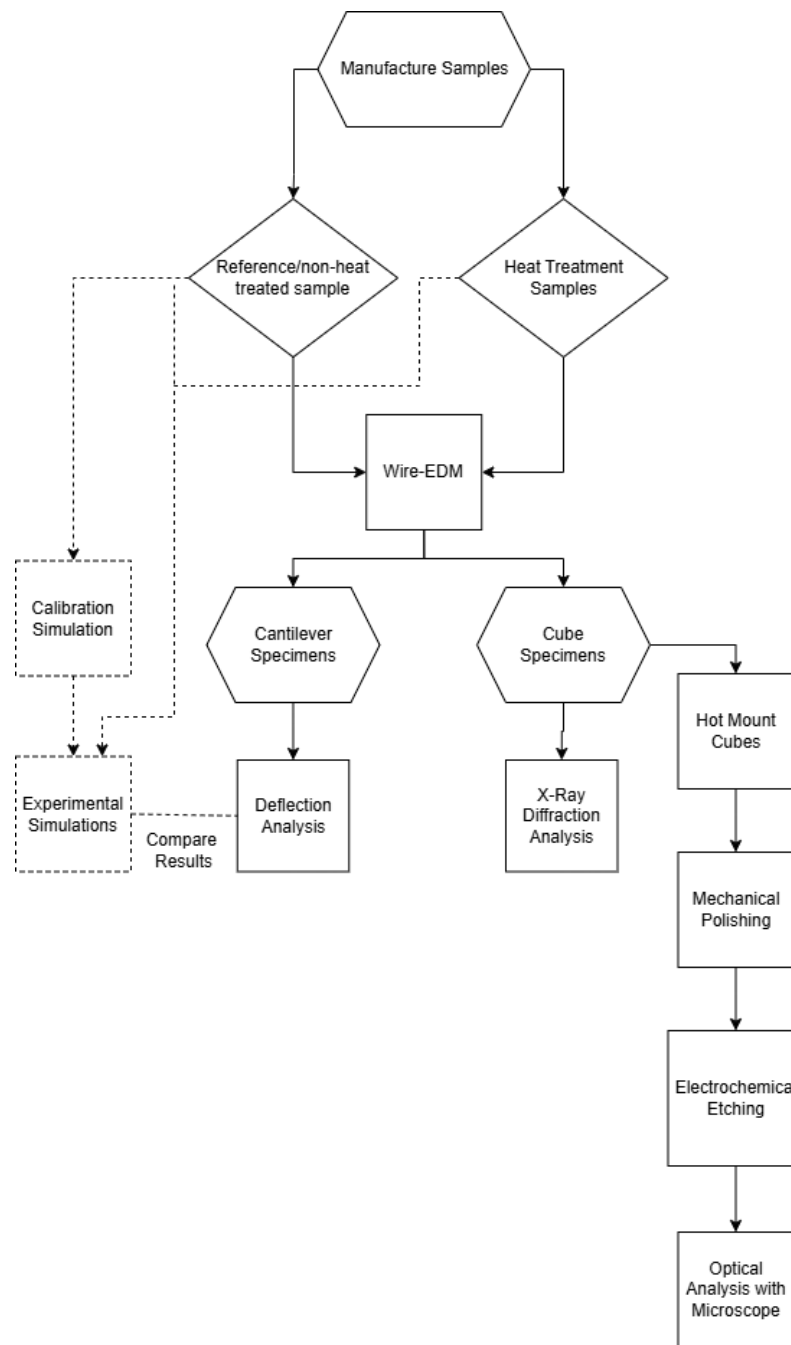
In addition to experimental mitigation strategies, numerical modelling has emerged as a critical tool for residual stress prediction. Studies have shown that ISM-based simulations, when properly calibrated using deflection data or neutron diffraction measurements, can produce highly accurate predictions of stress distributions and deformation in SLM components. Simulation tools such as Simufact Additive are increasingly used to guide process design, evaluate heat treatment strategies, and optimise support structure placement prior to physical manufacturing.

CHAPTER 3 MATERIALS & METHODS

3.1 Introduction

This chapter outlines the methodology used to predict and analyse residual stresses in CoCrMo cantilevers manufactured using SLM. The study integrates both simulation and experimental techniques to evaluate the effectiveness of heat treatment processes designed using Simufact Additive.

To improve clarity and provide a structured overview of the methodological approach, a process flow diagram is presented below. The diagram summarises the sequence of activities carried out in this study, beginning with material selection, design of the build plate layout, and sample fabrication, followed by simulation setup and calibration, and concluding with post-processing and sample analysis.



3.2 Materials

The material used in this study was TruForm™ CoCr (Co-538), a gas-atomised, medical-grade CoCrMo alloy manufactured by Praxair. The powder adheres to ASTM F75 [107] specifications, which is widely used in medical and aerospace applications as it has excellent wear resistance, corrosion resistance, and biocompatibility. The powder consists of spherical particles with a maximum particle size of 53 μm , and a chemical composition within the range stipulated by the supplier (Table 3-1).

Table 3-1: Chemical Composition of CoCrMo powder

Element	Powder Content Weight %
Aluminium	<0.01
Boron	<0.001
Carbon (Total)	0.08
Cobalt	Balance
Chromium	28.31
Iron	0.37
Manganese	0.14
Molybdenum	6.15
Nitrogen	0.10
Nickel	0.17
Oxygen	0.02
Phosphorous	<0.005
Sulphur	0.002
Silicon	0.25
Titanium	0.00
Tungsten	0.06

Manufacture of samples were carried out on a circular steel build plate with a central threaded hole for attaching to the SLM machine (Figure 3-1).



Figure 3-1: Build Plate

3.3 Sample Design

The build plate consisted of two cantilever beams and two cube specimens as shown in Figure 3-1. The cantilever beams, having dimensions of 54 mm x 9 mm x 6.75 mm and positioned orthogonally at 0° and 90° to the machine's x- and y-directions, were used for inherent strain calibration and residual stress evaluation through deflection measurement.

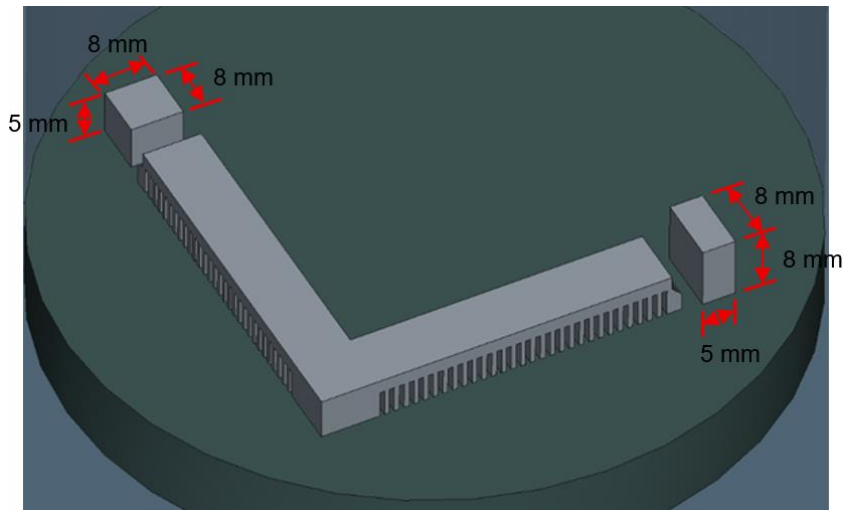


Figure 3-2: Sample Layout

On the other hand, the cubic specimens (8 mm × 8 mm × 5 mm), which were used for microstructural and phase analyses were oriented such that the 8 mm × 8 mm surface was either parallel or perpendicular to the scanning direction.

3.4 SLM Fabrication

Samples were manufactured with an ORLAS Creator SLM machine (Figure 3-3) with the processing parameters as listed in Table 3-2 that were developed in-house for high density fabrication [108].



Figure 3-3: ORLAS CREATOR

Table 3-2: Process Parameters

<i>Parameter</i>	Value
<i>Laser Power</i>	125 W
<i>Scan Speed</i>	630mm/s
<i>Hatch Overlap</i>	50%
<i>Hatch Rotation</i>	67°
<i>Spot Size</i>	120µm
<i>Contour Laser Power</i>	140 W
<i>Contour Scan Speed</i>	250mm/s
<i>Contour Spot Size</i>	40µm
<i>Layer Height</i>	25µm

The internal configuration of the ORLAS Creator build chamber (Figure 3-4) includes a powder reservoir, rotating scraper arm, central build plate, and overflow collection bin for excess powder. Before each build, the build plate was cleaned, levelled, and positioned within the chamber so that its surface projected roughly one layer height above the surrounding platform. Powder was evenly distributed across the plate using the rotating scraper arm, while excess material was recovered automatically in the overflow tank.

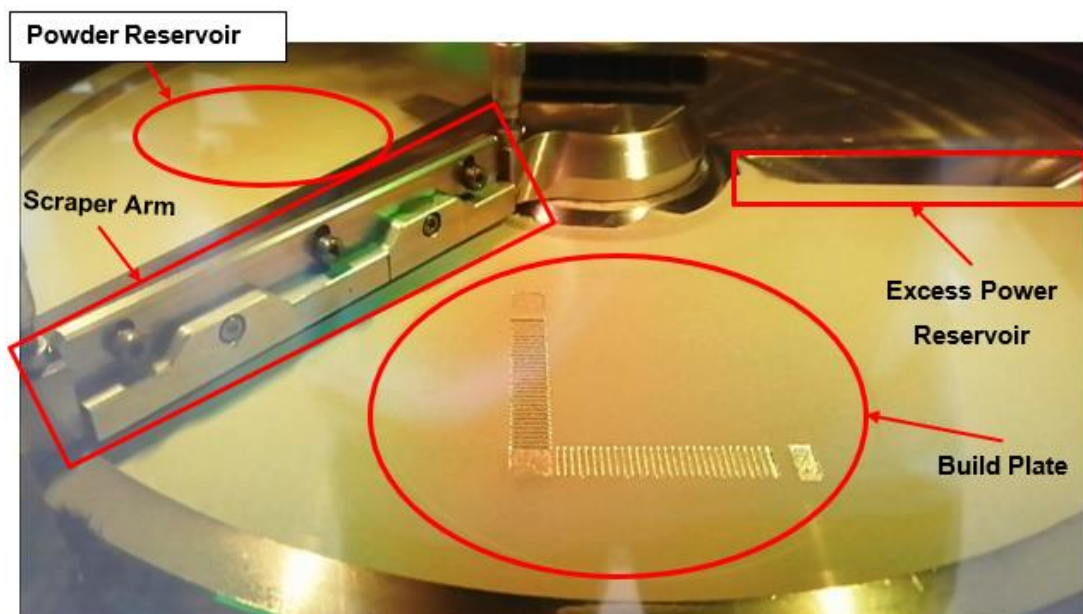


Figure 3-4: ORLAS CREATOR Build Chamber

During fabrication, the chamber atmosphere was continuously purged with nitrogen to maintain oxygen levels below 0.1 %. This inert environment is intended to prevent oxidation and ensure consistent melting behaviour. After printing, the build plate was raised, and loose powder was removed before extraction from the build chamber. Figure 3-5 shows the batch manufacture of samples directly after fabrication had been completed and build plate extraction was in progress. A total of four batches were fabricated for this study.

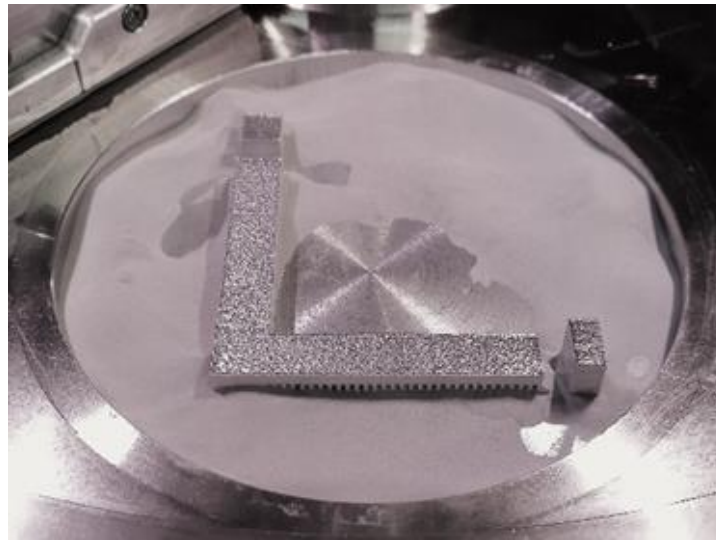


Figure 3-5: Full Build Plate Sample

3.5 Finite Element Simulation

Finite element simulations were performed using Simufact Additive to replicate the SLM process and predict residual stresses that develop during fabrication. The simulation phase consisted of two stages: calibration, used to validate the model against experimental measurements, and heat-treatment simulations, used to predict stress relaxation at various annealing temperatures. To calibrate the simulation model, wire-EDM was used to partially section the designated cantilever specimen from the build plate, and the resulting vertical deflection was measured using a micrometer screw gauge.

All model parameters, including process settings, material properties, and machine configuration, were defined to mirror the experimental setup as closely as possible. However, the simulations conducted in this study employed a purely mechanical inherent strain approach within Simufact Additive and did not include a coupled thermo-mechanical analysis. Consequently, the transient thermal history, melt pool evolution, and temperature-dependent material behaviour were not explicitly modelled. The surrounding powder bed was not represented, and effects such as powder packing density, particle size distribution, and conductive heat transfer between the

component and adjacent powder were not considered. Furthermore, metallurgical phenomena including phase transformation, diffusion-controlled recovery, and creep deformation during heat treatment were not explicitly resolved.

Instead, stress evolution was approximated through calibrated orthotropic inherent strain values applied layer-wise within a linear elastic framework. These simplifications significantly reduce computational time and enable efficient prediction of distortion trends. However, they may contribute to discrepancies between simulated and experimental results, particularly at elevated heat treatment temperatures where temperature-dependent mechanisms become more significant.

3.5.1 Simulation Calibration

The calibration procedure included both manufacturing and sectioning simulation steps. Firstly, the standard cantilever CAD model was imported and positioned centrally on the build plate. A custom CoCrMo material file was generated in the software and assigned to the geometry. Thereafter, the manufacturing and sectioning processes were simulated to induce deflection (Figure 3-6). The vertical deflection, caused by the release of residual stress, was measured experimentally and used as the maximum deflection ($Z_{\max}$) target value within Simufact.

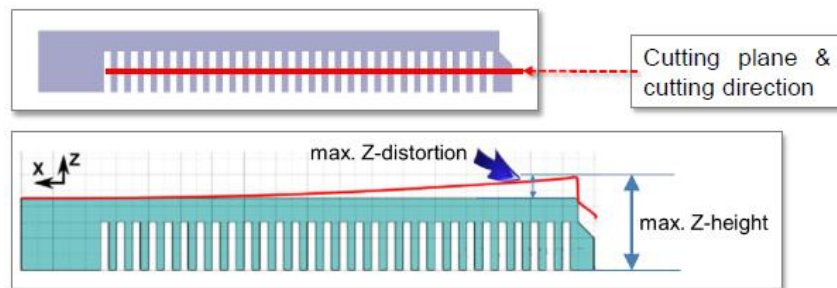


Figure 3-6: Partial Sectioning of Cantilever Beam [104]

An orthotropic strain calibration approach was employed to capture directional strain differences and improve the accuracy of predicted stress distributions. The model used a voxel-based mesh with a 0.5 mm resolution to balance computational efficiency with geometric accuracy. Layer thickness was defined as 0.025 mm, and the default inherent-strain values were used to perform the calibration (Figure 3-7).

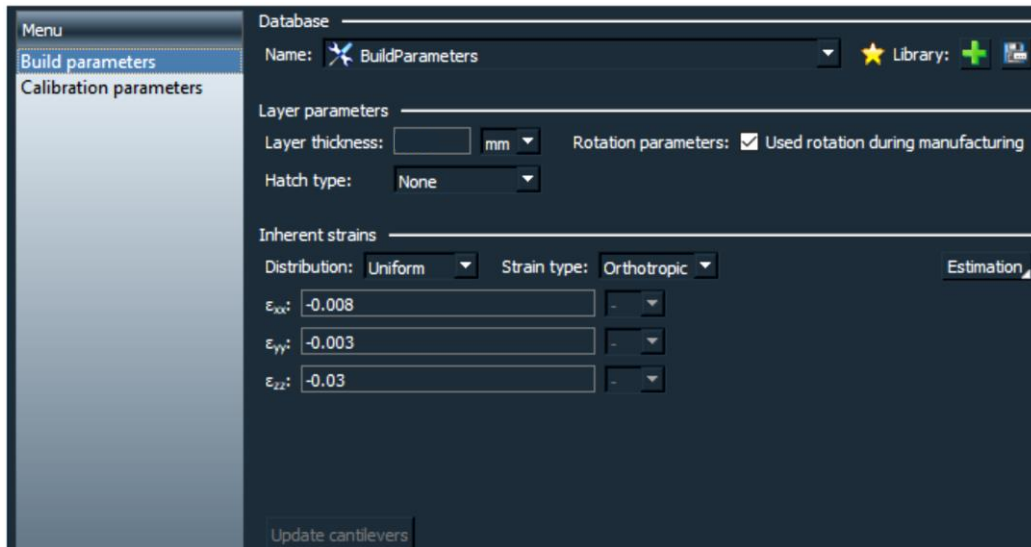


Figure 3-7: Initial Strain Parameters

Following calibration, heat treatment simulations were performed. These results were compared to the experimental deflection measurements to determine the modified inherent strain values after heat treatment.

3.6 Heat Treatment

Of the four samples, one was retained in the as-built condition to serve as a reference, while the remaining three were subjected to the stress-relief heat treatments. Literature indicates that heat treatments between 600°C and 1200°C have a significant impact on the properties of CoCrMo alloys. The heat treatments employed were selected based on previous studies that reported optimal improvements in the mechanical properties and residual stress reduction in CoCrMo alloys [91, 92]. Based on literature, 700°C and 770°C heat treatments were chosen along with a 1065°C heat treatment which was regularly used in-house and developed based on literature findings [93]. A summary of the heat treatments is provided in Table 3-3. The heat-treated samples were labelled according to their soaking temperatures, namely 700CHT, 770CHT, and 1065CHT, representing the heat treatments at 700°C, 770°C, and 1065°C respectively.

Table 3-3: Heat Treatment Procedure

Sample	700CHT	770CHT	1065CHT
<i>Soaking Temperature [°C]</i>	700	770	1065
<i>Holding time [min]</i>	60	60	30

<i>Cooling Method</i>	Forced Induction Furnace Cooling	Forced Induction Furnace Cooling	Forced Induction Furnace Cooling
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All the heat treatments were performed in a nitrogen atmosphere using a Nabertherm GmbH furnace (Figure 3-8).



Figure 3-8: Nabertherm GmbH Furnace

Upon completion of the heat treatment soaking period, the furnace was switched off and a ventilation flap located at the top of the furnace was opened. A fan positioned at the base of the furnace actively circulated ambient air into the chamber, promoting forced induction cooling. The samples were left to cool inside the closed furnace under forced air circulation overnight until ambient temperature was reached. For all three heat treatment conditions, the average cooling rate from the soaking temperature to ambient temperature was approximately 1.6°C/min. The corresponding temperature-time curves for each heat treatment are presented in Figure 3-9.

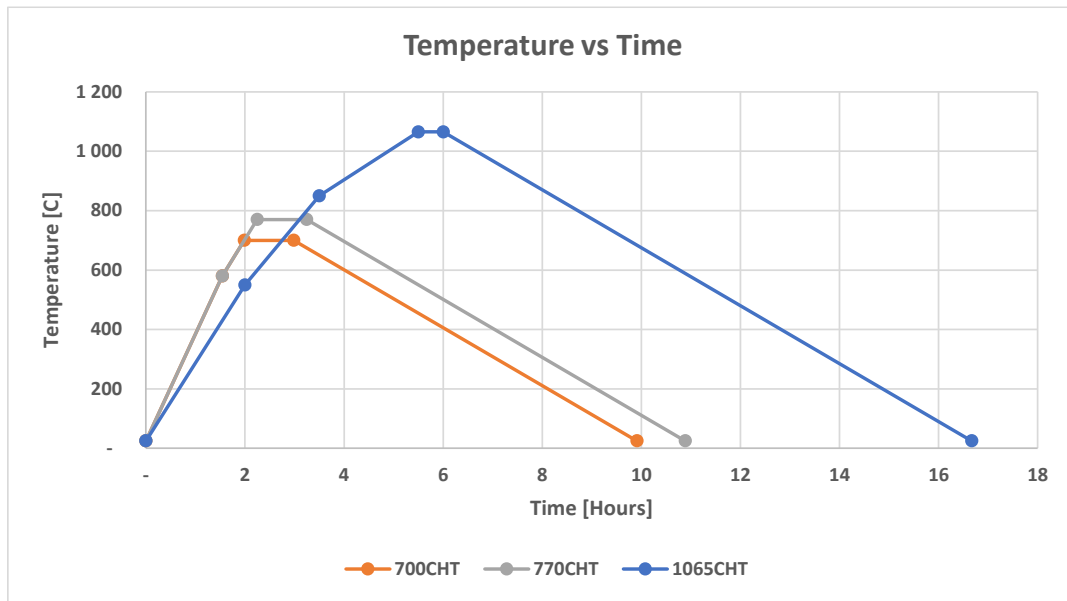


Figure 3-9: Heat Treatment Temperature vs Time Curves

3.7 Experimental Analysis

For the experimental analysis, the cube specimens were completely detached from the build plates, while the cantilevers were partially sectioned 2.2 mm above the build plate surface using a Wire Electrical Discharge Machine (EDM) (Figure 3-10).



Figure 3-10: Wire Electrical Discharge Machine

3.7.1 Cantilever Distortion Measurement

The cantilever deflection method used in this study is interpreted using classical Euler–Bernoulli beam theory under small-deflection conditions. The measured tip deflections were small relative to the cantilever length, justifying the assumption of linear elastic bending behaviour without

geometric nonlinearity. The deformation is assumed to be predominantly bending-dominated with negligible shear contribution. Uniform material properties and minimal additional stress introduction during wire-EDM cutting was also assumed. Deflection measurements were taken several days after sectioning to account for time-dependent stress relaxation, and stabilised values were used in the analysis. Opposing corner measurements were obtained to evaluate minor asymmetry and local stress redistribution within the cantilevers.

Measurements were taken from consistent reference locations at the corners of each cantilever, highlighted in Figure 3-11, to reduce measurement variability.

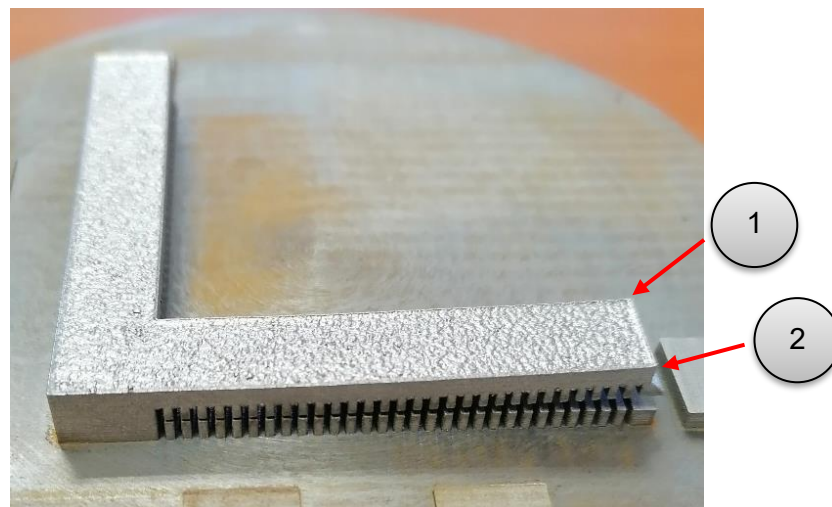


Figure 3-11: Cantilever Deflection Measurement Points

The height of each cantilever was measured using a micrometer screw gauge in conjunction with a custom-made FDM-printed jig (Figure 3-12). The jig ensured stable positioning and repeatable contact at the designated measurement points.

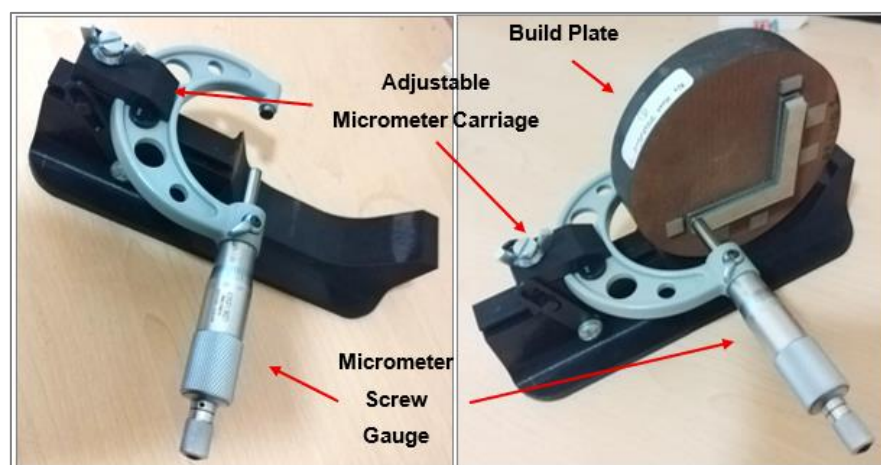


Figure 3-12: FDM Measuring Jig

The initial height of the cantilever before sectioning was measured and served as the reference point for calculating the resulting deflection. Multiple readings were averaged to compensate for surface irregularities and contact pressure variability, thereby improving measurement accuracy. The resulting deflection values were converted into equivalent strain using the inherent strain method implemented in Simufact Additive. The equivalent strain values were then used to infer changes in residual stress distribution.

3.7.2 Microstructural Analysis

The cube specimens were used to examine the microstructure of the as-builts and heat-treated samples. Each cube was labelled according to its heat treatment condition and orientation relative to the scanning direction. They were then prepared for optical microscopy through a mounting, grinding, polishing, and electrochemical etching process. The cubes were hot mounted using a hot mount press, shown in Figure 3-13. During mounting, the cubes were placed face-down in the mould cavity of the mounting press and carefully covered with ClaroFast thermoplastic powder (Figure 3-14).



Figure 3-13: Hot Mounting Press



Figure 3-14: ClaroFast Thermoplastic

After the cubes were completely covered with the thermoplastic powder, a cap and heating element were placed over the mould cavity. While heating, a constant pressure of 3 bar was applied. After 20–25 minutes of heating and cooling, the mounted cubes were removed from the press. Surface preparation was carried out using a Struers Rotopol-11 polishing system (Figure 3-15), following Akasel’s standard procedure for surface-hardened steels [109].



Figure 3-15: Struers Rotopol-11 Machine

Initially, plane grinding was carried out using Akasel Piatto 220 with water lubrication, applying a load of 35 N at a rotational speed of 300 rpm until a flat surface was achieved. This was followed by fine grinding, which employed Akasel Allegran 3 with 9 μm diamond-infused lubrication under the same 35 N load but at a reduced speed of 150 rpm for 2 minutes and 30 seconds. The next stage involved polishing using Akasel Ramda with 3 μm diamond-infused lubrication at 30 N and 150 rpm for 2 minutes. Finally, a fine polishing step was performed using Akasel Napal cloth with 1 μm diamond-infused lubrication, applying a 20 N load at 150 rpm for 30 seconds to achieve a mirror-like surface finish.

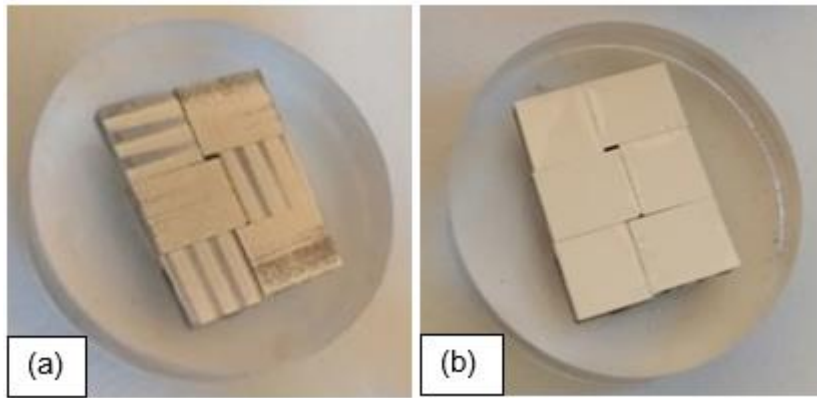


Figure 3-16: (a) Cube Samples Before Polishing and (b) Cube Samples After Polishing

Figure 3-16 shows the x and y-orientated cubes for the 700°C, 770°C, and 1065°C heat treatments both before and after grinding and polishing. After polishing, the cubes were released from their mounts by placing the samples on a cloth in a drill press, drilling through the rear of each cube and gently punching out the specimen to preserve the polished surface. After this step, the cubes were electrochemically etched using the Struers Lectropol-5 automatic electrolytic polishing and etching machine (Figure 3-17).



Figure 3-17: Struers Lectropol-5 Etching Machine

The electrochemical etching required a 5% hydrochloric acid solution which served as the electrolyte, to reveal the material's grain boundaries. Each cube was positioned with the polished surface facing down towards the etching region, and an electrode arm was placed on top of the cube. Optimal etching parameters for CoCrMo alloy cubes were determined as a polishing step of 3 V for 5 seconds and an etching step of 3 V for 2 seconds. This etching procedure was programmed into the etching machine to ensure consistency and visual inspections were conducted after etching to confirm that each cube had undergone the etching process as intended. Following etching, the cubes were thoroughly cleaned with water and acetone. An

optical microscope was then used to examine the etched regions and capture images of the surface of each cube for further analysis.

3.7.3 XRD Analysis

For the XRD analysis, the test samples included virgin CoCrMo powder used as a reference for comparison to the manufactured material and both heat-treated and non-heat-treated cubes. The XRD phase analysis was performed using the PANalytical X'Pert PRO XRD machine (Figure 3-18).



Figure 3-18: PANalytical X'Pert PRO X-Ray Diffraction Machine

The samples were securely mounted onto sample holders and positioned within the XRD machine for measurement. The samples were analysed, and the diffraction patterns for each sample were recorded, which was used in the material phase analysis. The XRD analysis was performed with a 2θ scan axis ranging between 4° and 120° , with a 0.017° step size.

3.8 Summary

This chapter presented the materials and methods used to investigate residual stress reduction in SLM-manufactured CoCrMo alloy components. The study used TruForm™ CoCr (Co-538) powder for manufacturing of all the experimental samples. Four samples in total were evaluated, each including two cantilever beams and two cubes.

The heat treatment procedures used in this study to investigate residual stress relief was investigated within a nitrogen atmosphere and had soaking temperatures of 700°C , 770°C , and 1065°C . These temperatures were selected based on existing literature and the regularly used

in-house heat treatment process. Forced induction cooling within the closed furnace was the cooling method used for the experiments.

Finite element simulations were performed using Simufact Additive to model the SLM and heat treatment processes and to compare the simulation results to the experimental results. For the experiments, residual stress reduction was interpreted based on cantilever deflection measurements using the inherent strain method. The XRD analysis was performed on the phase composition of virgin CoCrMo powder, the as-built cube, and heat-treated cubes. The microstructural analysis was used to evaluate the microstructures associated with different heat-treated and non-heat-treated conditions.

CHAPTER 4 RESULTS & DISCUSSION

4.1 Introduction

This chapter presents the results obtained from simulations and experimental testing, focusing on residual stress prediction and reduction in SLM-manufactured CoCrMo cantilevers. In this chapter, experimental residual stress relief is inferred from cantilever deflection after sectioning, rather than measured directly as stress. The findings from simulations, deflection measurements, microstructure analysis, and XRD are discussed and compared. Correlations between the simulation and experimental results are highlighted to evaluate the effectiveness of heat treatment in reducing residual stresses.

4.2 Simulation Results

Figure 4-1 shows the cantilever that was used for the initial calibration of the Simufact Additive simulations. The initial height of the cantilever was measured to be 8.66 mm from the build plate surface. After partial sectioning, the measurements recorded at both points 1 and 2 were 10.75 mm, resulting in deflections for each point of 2.09 mm.



Figure 4-1: Calibration Cantilever After Sectioning

After providing the displacement measurements as the target values for the calibration simulation, the simulation reached a simulated displacement of 2.07 mm and 2.08 mm, respectively. The simulated displacements were within 1% of the experimental values and resulted in orthotropic inherent strain values of -0.00295761 in the xx-direction and -0.00261896 in the yy-direction. These calibrated strain values were used as initial strain input values for the subsequent heat treatment simulations.

Figure 4-2 shows the results from the simulation for the 700°C heat treatment, which predicted an average deflection of 0.89 mm in the x-direction, and 0.78 mm in the y-direction. The resulting

strain values for the heat treatment were -0.00185288 in the xx-direction and -0.00156545 in the yy-direction.

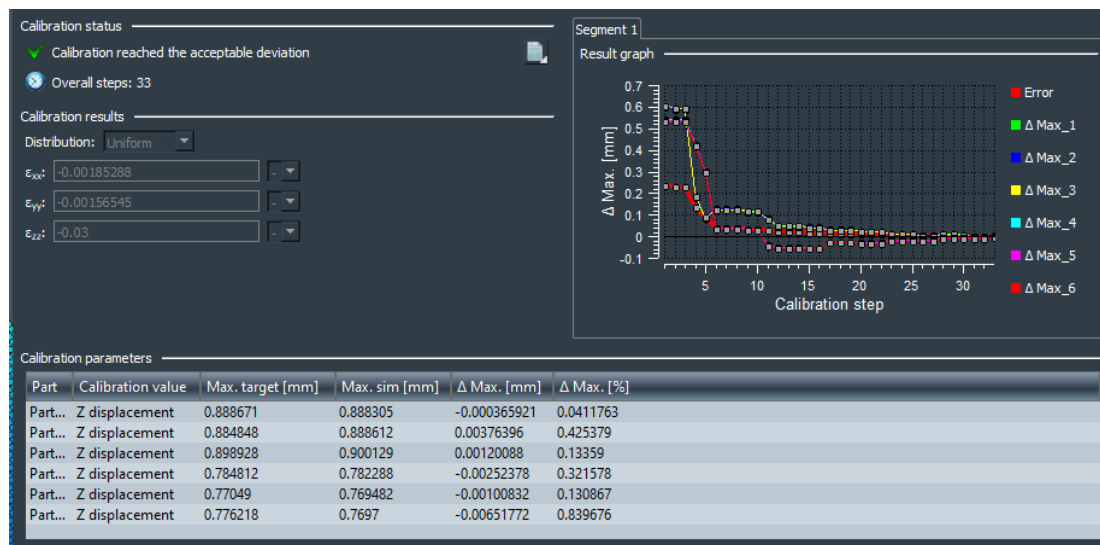


Figure 4-2: 700CHT Simulation Results

The 770°C heat treatment simulation's results are shown in Figure 4-3 and predicted an average deflection in the x-direction of 0.56 mm and 0.54 mm in the y-direction. For this heat treatment, the estimated strain values were -0.0012387 in the xx-direction and -0.00115365 in the yy-direction.

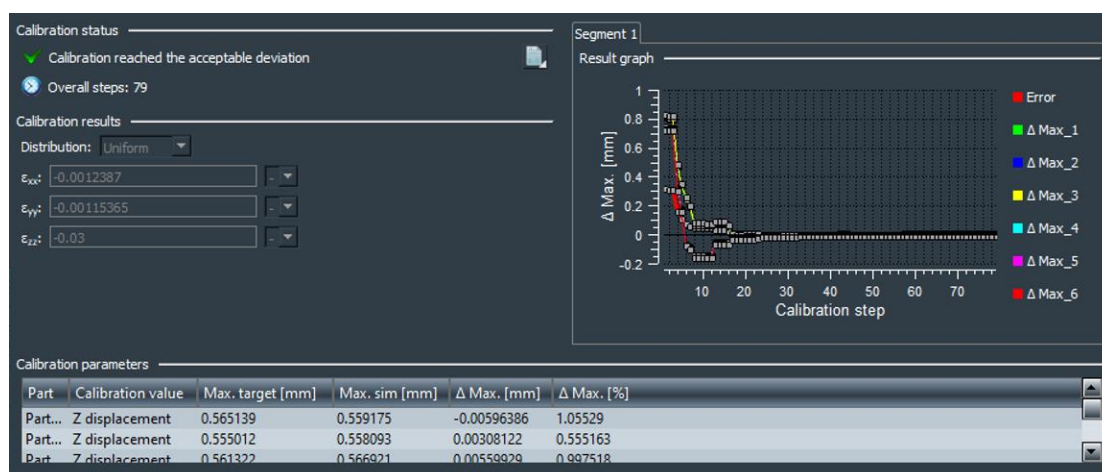


Figure 4-3: 770CHT Simulation Results

The simulation of the 1065°C heat treatment, shown in Figure 4-4, resulted in an average predicted deflection of 0.37 mm in the x-direction and 0.38 mm in the y-direction. For the simulation, the strain values were - 0.000722464 in the xx-direction and - 0.000837199 in the yy-direction. The trend in these results aligns with what was expected based on literature [91, 92, 93], where the deflection of the cantilevers decreases as heat treatment temperature increase.

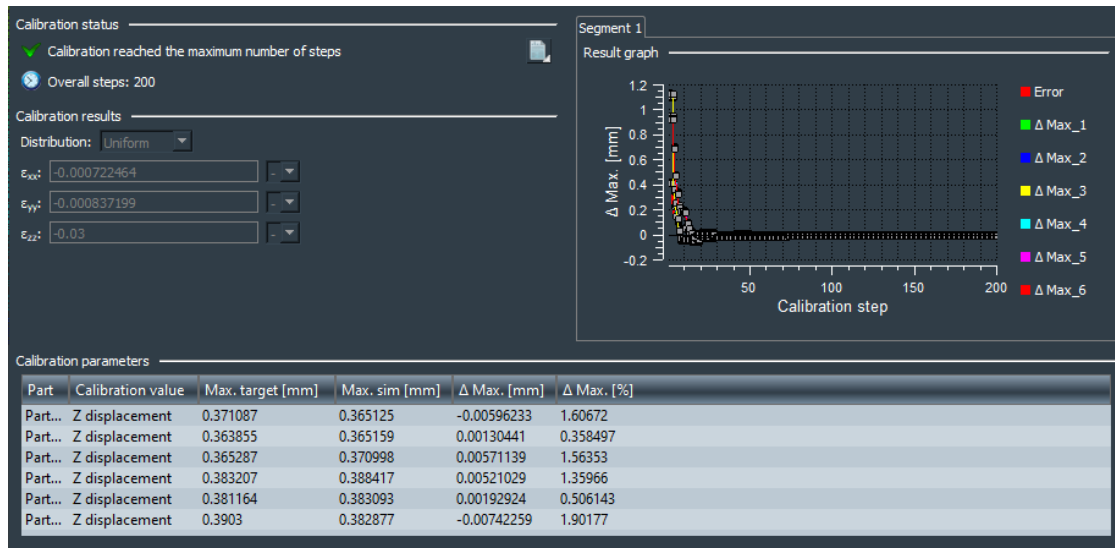


Figure 4-4: 1065CHT Simulation Results

4.3 Experimental Results

4.3.1 Cantilever Deflection

Residual stress relief in the experimental cantilevers was evaluated indirectly using cantilever deflection after sectioning, where reduced deflection is interpreted as reduced residual stress magnitude. Table 4-1 summarises the measured deflections for the as-built and heat-treated cantilevers at 700°C, 770°C, and 1065°C, showing a clear trend of progressive deflection reduction with increasing heat treatment temperature. Although slight variations were observed in the absolute values, the overall trend of decreasing deflection with increasing heat treatment temperature is consistent with simulation predictions, although discrepancies are observed in the magnitude and direction of deflection at higher temperatures.

Table 4-1: Experimental Cantilevers Deflection Results

<i>Experiment</i>	Cantilever Orientation	Deflection Measurement (± 0.01 mm)		Deflection Reduction		Average Deflection Measurement (± 0.01 mm)	Average Deflection Reduction
		Point 1	Point 2	Point 1	Point 2		
<i>As-Built</i>	X	1.50 mm	1.49 mm	N/A	N/A	1.50 mm	N/A
	Y	1.39 mm	1.41 mm	N/A	N/A	1.40 mm	N/A
<i>700CHT</i>	X	0.65 mm	0.71 mm	55.17 %	51.04 %	0.68 mm	53.11 %
	Y	0.66 mm	0.68 mm	56.00 %	54.05 %	0.67 mm	55.03 %
<i>770CHT</i>	X	0.22 mm	0.26 mm	85.67 %	82.55 %	0.24 mm	84.11 %
	Y	0.26 mm	0.18 mm	82.67 %	87.92 %	0.22 mm	85.29 %
<i>1065CHT</i>	X	-0.12 mm	0.01 mm	108.00 %	99.33 %	-0.06 mm	103.66 %
	Y	-0.02 mm	-0.04 mm	101.33 %	102.68 %	-0.03 mm	102.01 %

Reductions exceeding 100% occur where the deflection direction reverses, yielding negative deflections relative to the positive as-built reference. Figure 4-5 illustrates the corresponding deflection profiles for each build, as captured in Table 4-1, and highlights the reduction in deflection of each subsequent heat treatment. The as-built cantilevers served as a reference condition for evaluating the effectiveness of subsequent heat treatments in reducing deflection and, consequently, indicating residual stress relief. The average deflection seen in the as-built cantilever (Figure 4-5(a)) oriented along the x-direction was ± 1.50 mm, and ± 1.40 mm for the cantilever in the y-direction.

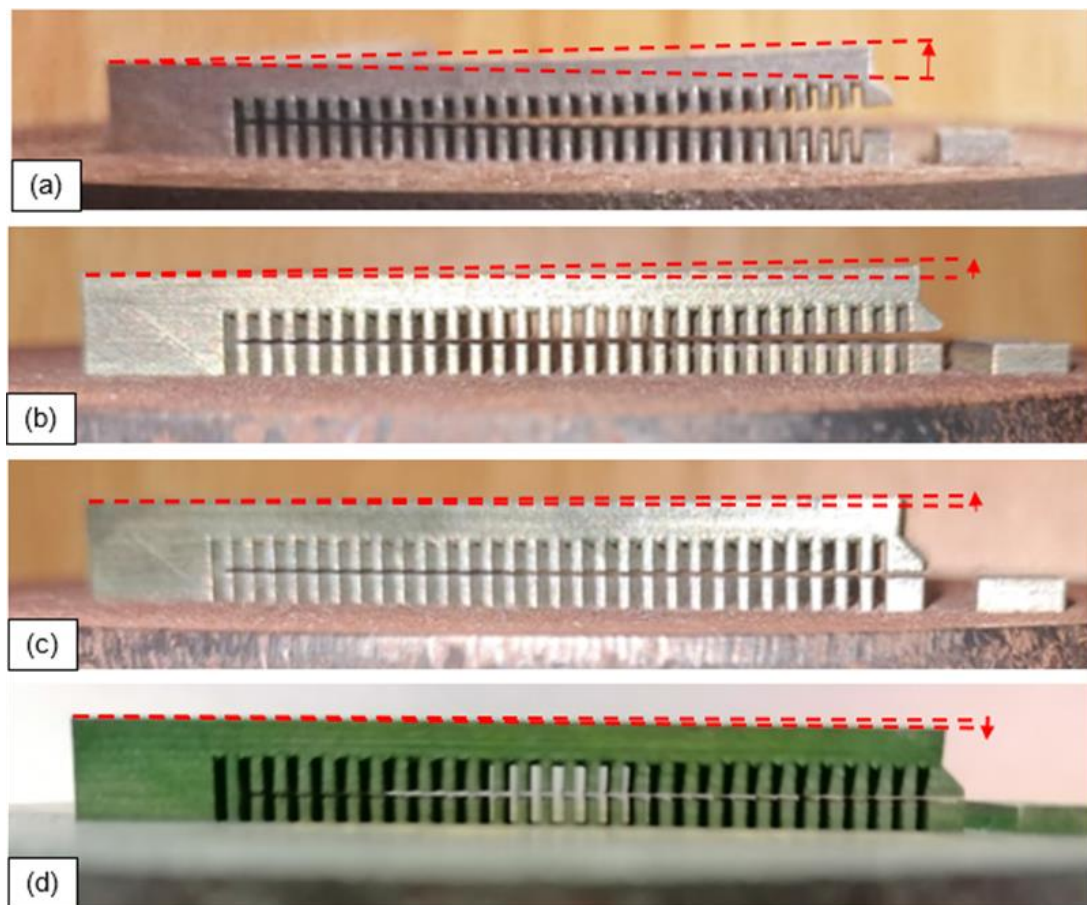


Figure 4-5: Deflection Profiles of: (a) As-Built Cantilever, (b) 700°C Heat-Treated Cantilever, (c) 770°C Heat-Treated Cantilever and (d) 1065°C Heat-Treated Cantilever

For the heat-treated cantilevers, at 700°C, the average deflection was reduced to ± 0.68 mm in the x-direction and ± 0.67 mm in the y-direction (Figure 4-5(b)), representing an average reduction of $\pm 54\%$ relative to the as-built cantilevers. These results indicate substantial stress relief occurred, as inferred from the measured reduction in deflection. When compared with the 700°C simulation, the experimental samples exhibited greater deflection reduction at approximately

$\pm 24\%$ in the x-direction and $\pm 14\%$ in the y-direction, suggesting that the actual heat treatment was slightly more effective than model predictions.

For the 770°C heat treatment (Figure 4-5(c)), further reductions were observed with average deflections of ± 0.24 mm and ± 0.22 mm for the x- and y-oriented cantilevers, respectively. The 70°C increase in soaking temperature resulted in an additional $\pm 30\%$ reduction in deflection relative to the 700°C cantilevers, yielding an overall decrease of $\pm 82\%$ compared to the as-built sample. The experimental deflections were also ± 0.32 mm smaller than the simulation results in both orientations, equivalent to approximately $\pm 57\%$ and $\pm 59\%$ lower deflections, respectively.

The 1065°C heat treatment produced unexpected results as both the x- and y-orientated cantilevers deflected downwards, opposite to the deflection direction observed in previous builds (Figure 4-5(d)). The x-oriented and y-oriented cantilevers showed negative average deflections of ± 0.05 mm and ± 0.03 mm, respectively. This downwards deflection indicates a change in the residual stress state, where tensile stresses at the top surface of the cantilever transformed into compressive stresses. Compared to the 770°C experimental results, the 1065°C treatment achieved $\pm 25\%$ more deflection reduction, and compared to the 700°C results, a further $\pm 48\%$ reduction in deflection was observed. Relative to the as-built condition, the total reduction was approximately $\pm 103\%$. However, the 1065°C simulations predicted positive deflections of ± 0.37 mm and ± 0.38 mm in the x- and y-directions, while the experimental cantilevers deflected in the opposite direction. The difference between the experimental and simulation results yielded approximately 114% in the x-direction and 108% in the y-direction, suggesting significant stress redistribution during high-temperature treatment, likely driven by temperature-dependent phase transformations not captured in the simulation model.

These discrepancies highlight the limitations of the purely mechanical inherent strain approach adopted in this study. The simulations did not incorporate coupled thermo-mechanical behaviour, phase transformation, or creep deformation during heat treatment. In addition, the surrounding powder bed and associated thermal gradients were not modelled. These simplifications likely contributed to underprediction of deflection magnitude at 700°C and 770°C , and the deflection reversal behaviour observed experimentally at 1065°C .

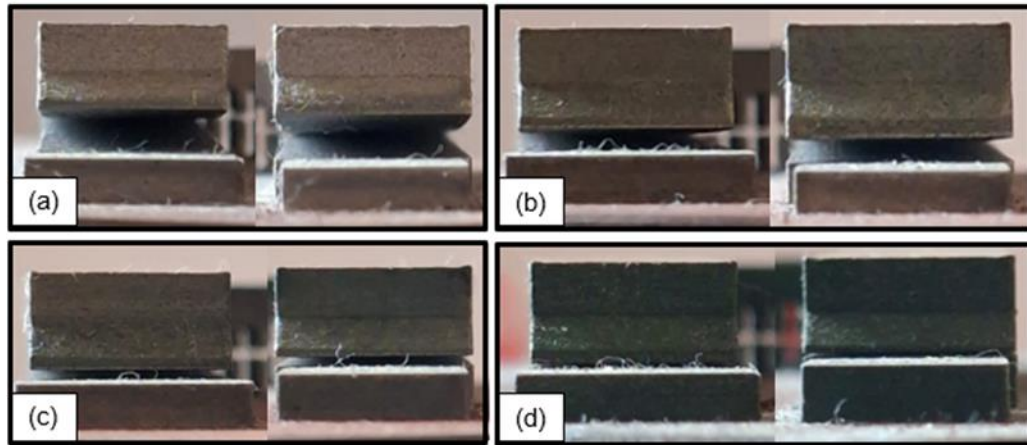


Figure 4-6: Uneven Deflections of: (a) As-Built Cantilevers, (b) 700°C Heat-Treated Cantilevers, (c) 770°C Heat-Treated Cantilevers and (d) 1065°C Heat-Treated Cantilevers

Uneven deformation was also observed between the measurement points on individual cantilevers (Figure 4-6). In the as-built condition (Figure 4-6(a)), deflection variation between points was within $\pm 1\%$ of the average in both orientations. For the 700°C heat treatment, the x-oriented cantilever showed $\pm 4\%$ variation, while the y-oriented cantilever differed by only $\pm 1.5\%$ (Figure 4-6(b)). At 770°C (Figure 4-6(c)), the y-oriented cantilever exhibited greater asymmetry, deviating by $\pm 18\%$ from the average deflection compared to $\pm 8\%$ for the x-oriented cantilever. The largest uneven deflection occurred at 1065°C (Figure 4-6(d)), where the x-oriented cantilever's two measurement points deviated by $\pm 94\%$ from the average, while the y-oriented cantilever deviated by $\pm 67\%$. The magnitude of this asymmetry increased with heat treatment temperature, indicating that stress redistribution became progressively more non-uniform at elevated temperatures.

Although average deflection values are presented to facilitate comparison between heat treatment conditions, the x- and y-oriented cantilevers were analysed independently to capture directional differences in residual stress behaviour. The slight variation between orientations in the as-built and 700°C conditions suggest relatively symmetric stress development at lower thermal exposure. However, the increased asymmetry observed at 770°C and particularly at 1065°C can be attributed to two contributing factors. First, the cantilevers were manufactured in an L-shaped configuration with a shared base, introducing mechanical coupling between the two beams. As a result, stress release during sectioning may not occur independently in each orientation, and redistribution at the junction can influence bending behaviour in both cantilevers. Second, the inherent anisotropy of the SLM process must be considered. The effective scan vector length and exposure history differ between the x- and y-oriented cantilevers, leading to variations in thermal gradient magnitude and constraint conditions. These combined geometric

and process-related effects can promote non-uniform stress redistribution during heat treatment, particularly at elevated temperatures where recovery and phase-related mechanisms become more significant.

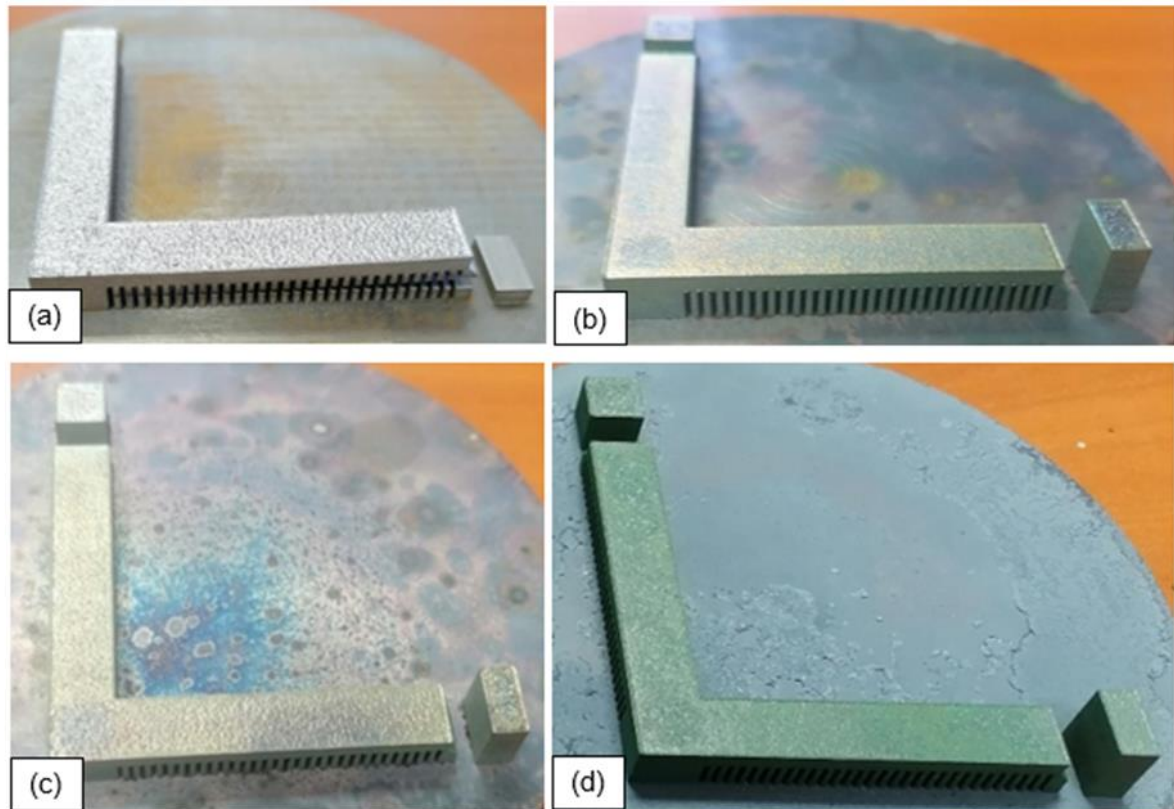


Figure 4-7: Visual Observations of: (a) As-Built Cantilevers, (b) 700°C Heat-Treated Cantilevers, (c) 770°C Heat-Treated Cantilevers and (d) 1065°C Heat-Treated Cantilevers

In addition to the measured deflection behaviour, surface changes were observed following heat treatment, providing further indication of temperature-dependent material response. Visual observations (Figure 4-7) revealed progressive surface discoloration following heat treatment. The as-built samples (Figure 4-7(a)) retained their metallic appearance, confirming that no oxidation occurred during manufacturing. The 700°C (Figure 4-7(b)) and 770°C samples (Figure 4-7(c)) exhibited a light yellow-green discoloration, while the 1065°C sample (Figure 4-7(d)) developed a deep green oxide layer. The increasing discoloration corresponds to greater oxidation at higher temperatures, forming an oxide scale on the surface that becomes more pronounced the higher the heat treatment temperatures.

To further interpret these results, microstructure and XRD analyses were performed on the cube specimens produced alongside the cantilevers. As the cubes were subjected to the same manufacturing and post-processing conditions, they provide representative insight into the

metallurgical and microstructural evolution inherent to the observed residual stress behaviour. The microstructural analysis revealed grain growth and recrystallisation trends linked to progressive stress relief, while the XRD analysis examined phase transformations associated with heat treatment.

4.3.2 Microstructure characterisation

In metallic alloys such as CoCrMo, finer microstructures generally enhance strength, hardness, and resistance to deformation, while larger grains promote ductility but reduce strength. Grain refinement also facilitates the relaxation or redistribution of residual stresses, improving overall dimensional stability. Examining the CoCrMo microstructure before and after heat treatment therefore provides valuable insight into how thermal processing affects the alloy's microstructure and residual stress state.

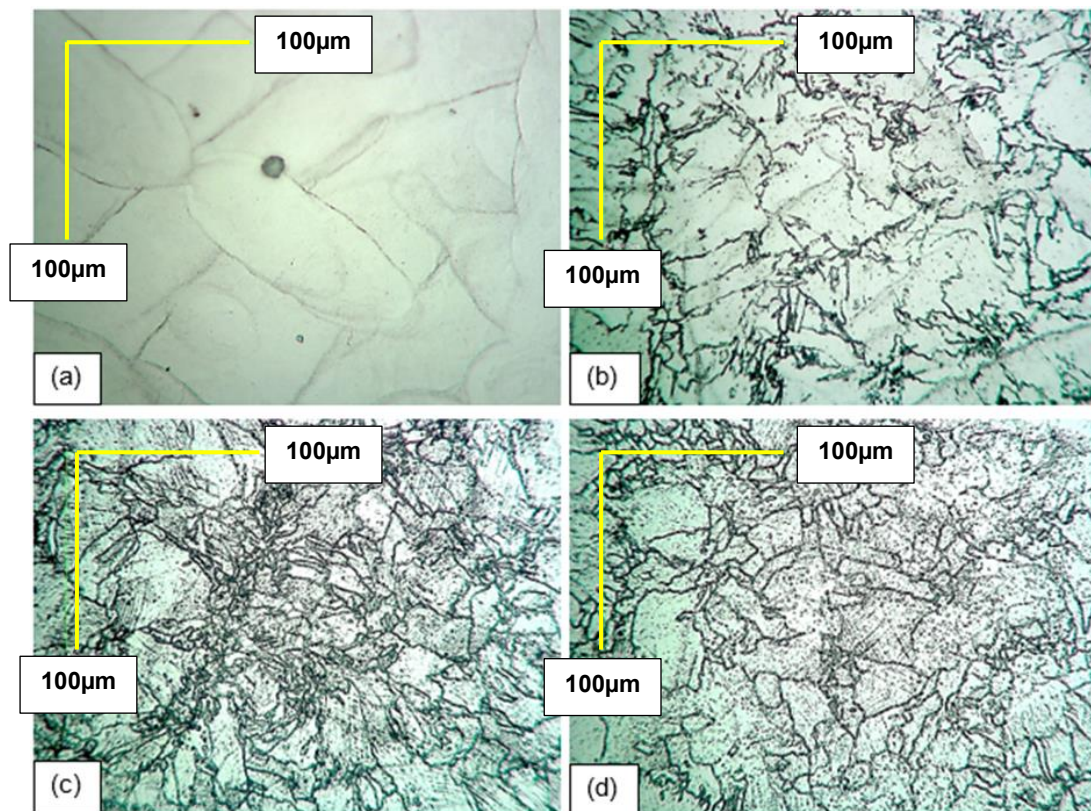


Figure 4-8: Microstructures of Cubes' Surface Parallel to Build Direction: (a) As-built, (b) 700°C Heat Treatment, (c) 770°C Heat Treatment and (d) 1065°C Heat Treatment

Figure 4-8 shows the etched microstructures of the cubes' surface parallel to the scanning direction. The as-built cube (Figure 4-8(a)) exhibits only the characteristic scanning tracks of the SLM process, with no distinct grain boundaries visible. Following heat treatment, the microstructural features highlighted distinct grain boundaries, potentially attributable to element

enrichment along the grain boundaries and a slight degree of grain growth during the heat treatment process [24].

The 700°C heat-treated cube (Figure 4-8(b)) displayed irregularly shaped grains of relatively equal size. At 770°C (Figure 4-8(c)), the grains become more irregular in both shape and size, indicating structural rearrangement and partial recrystallisation within the material. At the highest heat treatment temperature of 1065°C (Figure 4-8 (d)), the grains appear more refined overall, although slight coarsening is visible in some areas (Figure 4-9). A wider size distribution and signs of boundary migration are also observed with advanced grain growth.

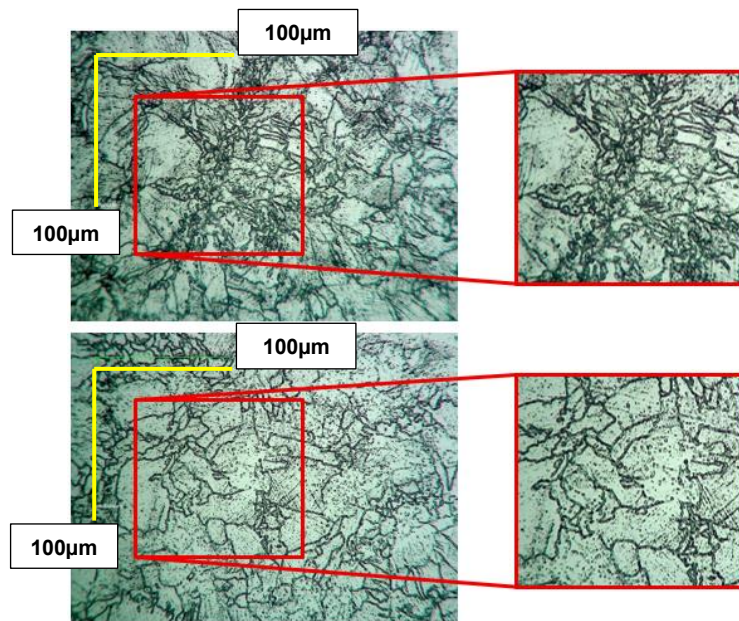


Figure 4-9: Grain Coarsening From 770°C to 1065°C Heat Treatments

Figure 4-10 presents the grain morphologies on the cubes' surface perpendicular to the scanning direction. In this orientation, the grain growth is columnar, extending through multiple build layers. The as-built cube (Figure 4-10(a)), although also showing no distinct grain boundaries, displayed deep layer penetration across multiple deposited layers, which is evidence of the development of high thermal gradients during solidification.

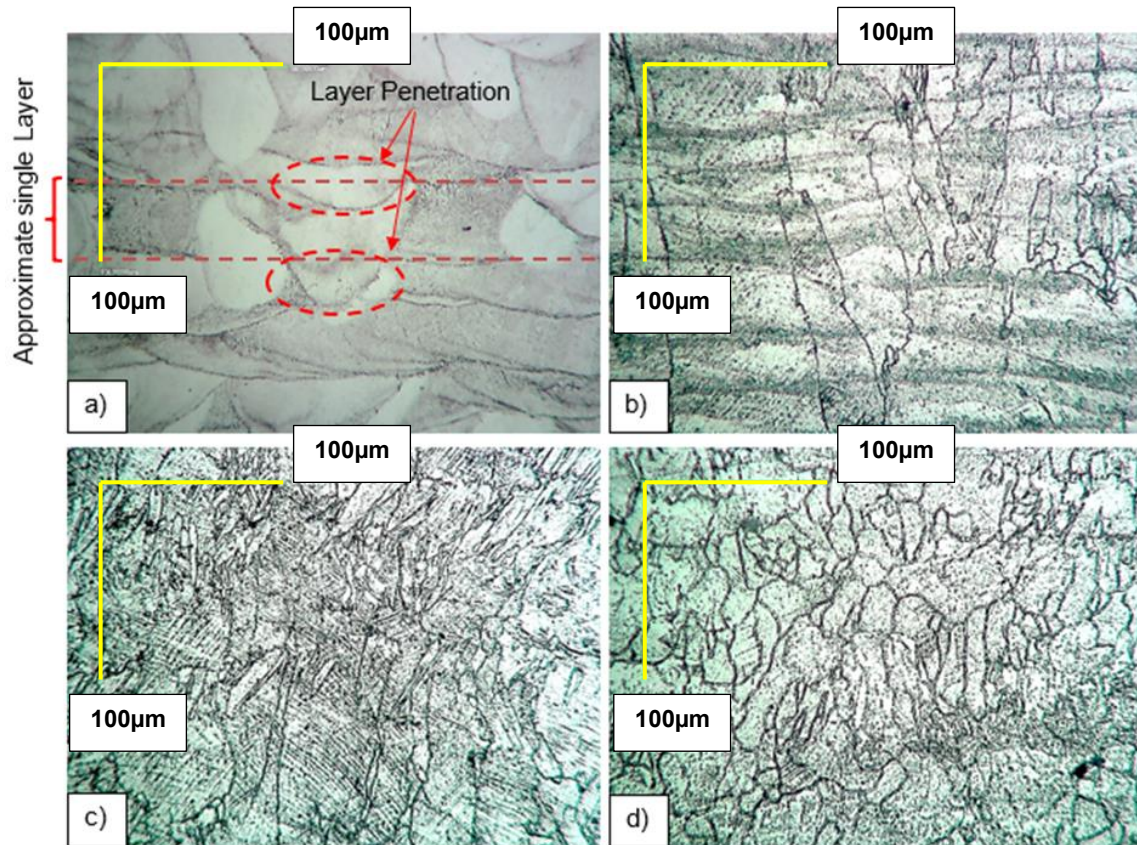


Figure 4-10: Microstructures of Cubes' Surface Perpendicular to Build Direction: (a) As-built, (b) 700°C Heat Treatment, (c) 770°C Heat Treatment and (d) 1065°C Heat Treatment

After heat treatment at 700°C (Figure 4-10(b)), columnar grain development is prominent and can be seen to stretch across multiple manufacturing layers. The elongated shapes of the grains promote anisotropic behaviour and local stress concentration at grain intersections or terminations [110, 61]. The 770°C heat treatment (Figure 4-10(c)) revealed partial dissolution of the columnar grains and the formation of smaller, irregular grains between existing boundaries. This mixed morphology changes the stress distribution within the material, creating regions of both stress relaxation and localised concentration. Irregular grain boundaries may restrict boundary sliding, thereby reducing the material's capacity for uniform stress relief.

At 1065°C (Figure 4-10(d)), the columnar grains have largely dissolved, giving rise to smaller, more mixed elongated and equiaxed grains. Similar to the 770°C heat treatment results, the mixed grain morphology induces both stress relaxation and localised stress concentration. The formation of new grain boundaries also increases resistance to dislocation movement, enhancing strain hardening and improving dimensional stability. The reduced grain anisotropy and more homogeneous structure indicate significant stress relaxation, consistent with the downward deflection behaviour observed experimentally.

When comparing the 770°C and 1065°C heat treatments with the 700°C condition, the micrographs in Figure 4-8 and Figure 4-10 shows finer grain sizes at the higher temperatures, suggesting progressive grain refinement with increasing temperature. The grain boundaries also become less distinct between layers at higher temperatures, implying a reduction in anisotropy and improved mechanical properties. The apparent refinement observed at 1065°C is consistent with enhanced recrystallisation and may contribute to more uniform stress redistribution, although this was not quantified.

Overall, the microstructure analysis confirms that heat treatment significantly modifies the CoCrMo microstructure. The transformation from elongated columnar grains in the as-built state to finer, more equiaxed grains at elevated temperatures corresponds with the measured reduction in cantilever deflection and inferred residual stress. Grain boundary migration, partial recrystallisation, and eventual grain refinement at 1065°C are consistent with thermal recovery processes and inferred stress redistribution. These findings establish a clear microstructural basis for the improved dimensional stability and mechanical performance achieved through progressive heat treatment of SLM-manufactured CoCrMo components.

4.3.3 XRD Analysis

The XRD analysis performed on the cube samples revealed clear diffraction peaks, each representing specific crystallographic planes within the CoCrMo alloy. These peaks were used to identify the crystalline phases present and to assess changes in the material's structure resulting from the SLM process and subsequent heat treatments.

Evaluating the XRD results (Figure 4-11) shows that the peaks in each graph correspond closely to the same 2θ position, although some displayed slight shifts, broadening, or variations in intensity. This indicates that the crystal lattice spacing and atomic arrangement within the material remained largely unchanged despite the different post-processing methods applied.

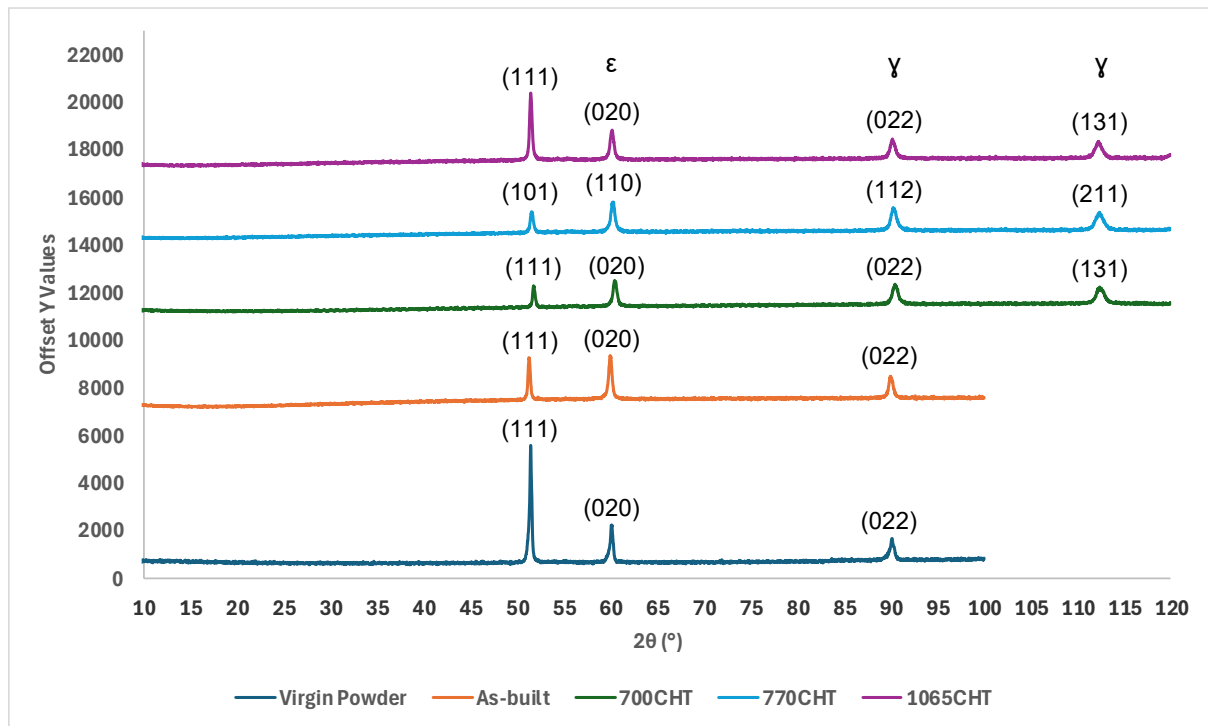


Figure 4-11: X-Ray Diffraction Graphs

This observation is significant as it demonstrates that the basic features of the material's crystal structure remained the same. It also suggests that the atomic arrangement and bonding within the alloy were not substantially altered by post-processing. However, variations in peak intensity indicate changes in the relative concentration of specific phases or crystallographic planes within the material [111].

The virgin CoCrMo powder exhibited three prominent peaks at diffraction angles (2θ) of 51.36° , 60.05° , and 90.06° , corresponding to the crystallographic planes (111), (020), and (022), respectively. These peaks align with previous studies [24, 112], which identify the presence of multiple phases in CoCrMo alloys. The first and third peaks, at 51.36° and 90.06° , can be attributed to the gamma phase (γ -phase) with a face-centred cubic (FCC) structure, while the second peak at 60.05° corresponds to the epsilon phase (ϵ -phase) with a hexagonal close-packed (HCP) structure [112]. The dominance of the first peak confirms that the γ -phase is the primary phase in the virgin CoCrMo powder. The presence of the ϵ -phase suggests partial transformation from the γ -phase during powder production, likely due to the thermal and mechanical conditions experienced during atomisation.

For the as-built cube, three peaks were observed at 51.23° , 59.91° , and 89.92° , corresponding to the same crystallographic planes as those in the virgin powder. The similarity in peak positions confirms that the same γ - and ϵ -phases are present after the SLM process. However, a notable

reduction in peak intensities was recorded, with the first, second, and third peaks decreasing from 3031.68 to 1559.01, 1334.73 to 687.32, and 713.37 to 368.82, respectively. These reductions suggest that the high thermal gradients and rapid solidification inherent to SLM influence the material's microstructure, potentially contributing to lower crystallinity and the development of residual stresses.

The heat-treated cubes exhibited an additional diffraction peak, signifying the formation of a new phase resulting from the applied higher temperature heat treatments. The first three peaks in the 700°C, 770°C, and 1065°C cubes closely correspond to those of the virgin and as-built samples, with 2θ positions of approximately $51.59^\circ \pm 0.16$ and $90.3^\circ \pm 0.16$, along with a new peak around 112.4° . The 700°C and 1065°C heat-treated cubes retained the same crystallographic planes as the virgin powder and as-built cube of (111), (020), and (022), while introducing an additional (131) plane. In contrast, the 770°C cube displayed a different set of indexed reflections was identified as (101), (110), (112), and (211), suggesting a change in the dominant phase at this temperature. Table 4-2 presents the peak positions and intensities for each heat-treated cube.

Table 4-2: Heat-Treated Samples' XRD Results - Peak Identification

<i>Experimental Set</i>		2θ Angle	Intensity	Miller Indices
<i>700CHT</i>	Peak 1	51.73°	837.04	(111)
	Peak 2	60.42°	374.56	(020)
	Peak 3	90.44°	211.91	(022)
	Peak 4	112.50°	315.63	(131)
<i>770CHT</i>	Peak 1	51.59°	982.56	(101)
	Peak 2	60.32°	290.37	(110)
	Peak 3	90.3°	160.5	(112)
	Peak 4	112.46°	235.05	(211)
<i>1065CHT</i>	Peak 1	51.41°	1827.75	(111)
	Peak 2	60.1°	804.87	(020)
	Peak 3	90.12°	430.69	(022)
	Peak 4	112.18°	618.71	(131)

Comparing the 700°C XRD results to the as-built shows that peak intensities approximately halved, with the first, second, and third peaks, decreasing to 837.04, 374.56, and 211.91, respectively. A new peak appeared at 112.5° , indicating a structural transformation linked to the heat treatment. However, the 1065°C results displayed a significant increase in all peak

intensities, more than doubling relative to the 700°C results, suggesting improved crystallinity and stress relief at higher temperature.

Based on peak identification of the 770°C heat treatment, the peaks at approximately $51.59 \pm 0.16^\circ$, $90.3 \pm 0.16^\circ$ and $112.46 \pm 0.16^\circ$ can be attributed to the γ -phase, while the peak at $60.3 \pm 0.16^\circ$ indicates the presence of an ϵ -phase. This confirms that the γ -phase is the dominant phase present in the material, even after heat treatment. The 770°C XRD results showed an increase of about 17% in the intensity of the first peak of the 700°C heat treatment (from 837.04 to 982.56), while subsequent peaks decreased slightly. Compared to the 1065°C heat treatment XRD results, it also displayed a significant increase in all peak intensities relative to the 770°C results.

The observed variations in intensities, peak positions, crystallographic planes and the development of an additional phase in the heat-treated samples highlight the influence heat treatment has on the material's microstructure. The introduction of a new (131) plane, together with shifts in existing peaks, indicates lattice relaxation and phase transformation induced by heat treatment. Notably, the distinct set of Miller indices observed for the 770°C cube suggests that this temperature induces a unique crystallographic reorientation within the material.

On closer examination, the individual peaks revealed noticeable changes where some of the peaks tend to shift to the left or right of the initial positions when compared to the virgin powder and the as-built cube. Figure 4-12 provides detailed views of the peaks and highlights their positions relative to the virgin powder and as-built cube peaks.

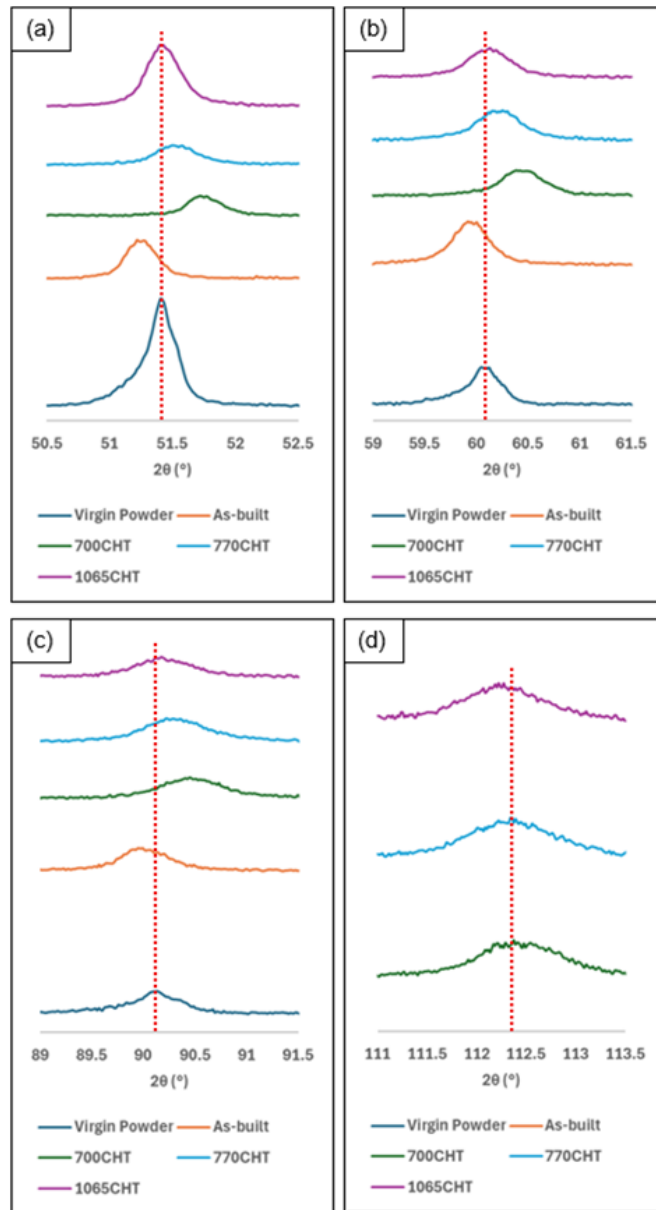


Figure 4-12: XRD Peak Shifting at 2θ Position: (a) $51.4^\circ \pm 0.3$, (b) $60.1^\circ \pm 0.2$, (c) $90.2^\circ \pm 0.2$ and (d) $112.3^\circ \pm 0.1$

Comparing the as-built and virgin powder peaks, Figure 4-12(a)-(c) shows that the as-built peaks shift towards lower diffraction angles (to the left), indicating increased interplanar spacing and the presence of tensile residual stresses introduced by the SLM process. It should be noted that residual stresses were not directly quantified using XRD stress analysis methods such as the $\sin^2\psi$ technique; therefore, peak shifts are interpreted qualitatively in terms of relative lattice strain. Slight peak broadening, seen in Figure 4-12(b) & (c), suggests lattice distortion caused by rapid solidification and thermal gradients induced during manufacturing.

After heat treating at 700°C, the peaks shift to higher angles, indicating a reduction in interplanar spacing, and may reflect partial relaxation of tensile stresses and possible development of compressive stresses. With the 770°C heat treatment, the peaks again shift slightly to the right, though less than at 700°C heat treatment, consistent with the reductions in residual stress inferred from the deflection results. The new fourth peak (Figure 4-12(d)) observed in the 700°C, 770°C, and 1065°C heat-treated cubes remain relatively unchanged in position, although it can be seen that the 1065°C peak appears shifted to the left. The 1065°C peak also appears slightly sharper than the 700°C and 770°C peaks, which may suggest grain growth and reduced residual micro-strain.

Overall, the XRD results suggest that progressive heat treatment increases stress relaxation and improve crystallographic recovery in the CoCrMo alloy, as inferred from the relative peak position and intensity changes. The shifts in peak position, changes in peak intensity, and broadening of the peaks demonstrate the evolution of the material's microstructure. Further characterisation through microstructure analysis was conducted to complement these findings and to provide deeper insight into the influence of heat treatment on the alloy's microstructural behaviour.

4.4 Summary

This chapter presented a comprehensive evaluation of the simulation and experimental findings related to residual stress reduction in SLM-manufactured CoCrMo cantilevers. The main observations made during testing included a sharp decrease in cantilever deflection after heat treating at 700°C, indicating that most stress relief occurs at this temperature. The 700°C treatment achieved an average deflection reduction of approximately 54% relative to the as-built cantilevers, while the 770°C treatment further reduced deflection by roughly 82%. At 1065°C, the heat-treated cantilevers deflected in the opposite direction, potentially signifying stress redistribution rather than further relaxation.

The comparison between simulated and experimental results showed good correlation in trend but highlighted that simulations underpredicted the degree of stress reduction, suggesting the influence of additional physical mechanisms, possibly linked to phase transformations, that were not fully captured in the numerical model.

XRD analysis revealed that all samples retained the primary γ -phase (FCC) and ϵ -phase (HCP) crystal structures, though heat treatment induced notable intensity changes and the formation of an additional diffraction peak. Peak shifts toward higher diffraction angles are consistent with a reduction in tensile stresses and possible development of compressive stresses following heat treatment, based on qualitative comparisons of peak positions. Peak broadening is commonly

associated with lattice distortion and strain relaxation, which is interpreted qualitatively in this study as indicative of strain evolution. The 770°C heat treatment produced the most distinct crystallographic rearrangement, corresponding to the temperature range where the greatest deflection reduction, and therefore inferred residual stress relief, was observed experimentally.

Microstructure analysis showed predominantly columnar grain structures on surfaces parallel to the build direction, promoting anisotropy and residual stress retention. Heat treatment at 700°C caused the grain boundaries to be distinct but irregular columnar grains, while at 770°C, partial recrystallisation introduced fine equiaxed grains, and at 1065°C the columnar grains dissolved into smaller, more homogeneous grains. The transition from elongated to more equiaxed grains suggests reduced anisotropy and possible recrystallisation, which may contribute to redistribution of internal stresses and consistent with the measured deflection reductions.

CHAPTER 5 CONCLUSION

This study aimed to evaluate the effect of heat treatment on residual stress reduction in SLM CoCrMo components by integrating experimental measurements and calibrated FEA simulations. The findings demonstrate that, within the investigated temperature range and for the cantilever geometry studied, post-processing heat treatments provide a practical and effective pathway to reduce deflection and therefore infer a reduction in residual stresses in SLM-manufactured CoCrMo components.

The initial step of the study involved validating the effectiveness of FEA simulations for predicting residual stress-induced distortion in SLM CoCrMo alloys. The results indicate that Objective 1 was partially achieved, as the calibrated inherent strain model predicted distortion trends within 1% of the experimental deflection measurements in the as-built condition. The Simufact Additive simulations successfully reproduced the expected trend of decreasing inherent strain magnitude with increasing heat treatment temperature. However, the model did not predict the potential stress redistribution and deflection reversal observed experimentally at 1065°C. This discrepancy is likely attributable to the exclusion of phase transformation and temperature-dependent metallurgical mechanisms. These findings suggest that while the simulations provide reliable trend prediction, they represent idealised scenarios and may not fully capture complex high-temperature behaviour. This study also found that simulations, when calibrated with experimental data, can serve as a powerful tool for guiding the design of heat treatments for residual stress reduction in SLM components. While simulations offer a cost-effective way to narrow the range of experimental testing, they cannot fully replace physical validation due to the complexities introduced by real-world conditions. By integrating simulations and experiments, manufacturers can streamline the development of heat treatment processes, reduce time and cost while improving part reliability. For applications requiring strict dimensional accuracy, this approach provides a structured pathway to manage residual stresses more effectively.

Quantifying the influence of heat treatment temperature on residual stress reduction formed the core experimental objective. Objective 2 was achieved, as cantilever deflection measurements established a clear relationship between soaking temperature and inferred residual stress reduction, with 770°C demonstrating the most favourable balance between stress relief and dimensional stability within the investigated range. Three heat treatments were applied at 700°C, 770°C, and 1065°C, based on literature and established in-house practice. The 700°C heat treatment reduced deflection by approximately 54% relative to the as-built condition, indicating substantial residual stress relaxation. Increasing the soaking temperature to 770°C further

reduced deflection by approximately 82% relative to the as-built condition, representing an additional reduction of approximately 30% compared to the 700°C heat treatment. At 1065°C, the deflection change exceeded 100% relative to the as-built condition due to deflection reversal, indicating residual stress redistribution rather than continued relaxation. While this suggests internal stress rebalancing, the associated distortion may compromise dimensional accuracy and stability.

Metallurgical characterisation provided further insight into the mechanisms responsible for these temperature-dependent behaviours. Objective 3 was achieved, as phase evolution and microstructural changes were systematically examined using XRD and optical microscopy, and their qualitative relationship to deflection behaviours was established. For the 700°C heat treatment, the XRD analysis indicated changes in lattice spacing consistent with partial stress relaxation, while microstructural analysis revealed irregular grain morphologies that may promote anisotropic behaviour and local stress concentration at grain intersections.

At 770°C heat treatment, a distinct set of indexed reflections, suggesting crystallographic reorientation, and microstructural observations indicated structural rearrangement and partial recrystallisation including partial dissolution of columnar grains and formation of smaller irregular grains between existing boundaries. These mixed microstructures likely change the stress distribution, creating regions of both stress relaxation and localised concentration with irregular grain boundaries restricting boundary sliding and reducing the capacity for uniform stress relief.

The XRD results of the 1065°C heat treatment showed higher peak intensities and sharper diffraction profiles. The microstructural analysis also showed that the columnar grains developed during the heating ramp to the 1065°C soaking temperature transformed into finer mixed grain structure having both elongated and equiaxed shapes. Similar to the 770°C heat treatment, the 1065°C heat treatment also indicated mixed microstructure development. The refinement of grains and the formation of new grain boundaries also increase the material's resistance to dislocation movement, which may contribute to stress redistribution and relaxation.

Within the investigated temperature range, increasing soaking temperature resulted in progressively greater deflection reduction until possible stress redistribution and deflection reversal occurred at 1065°C. Accordingly, Objective 4 was achieved within the scope of the investigated conditions. Although 1065°C produced the greatest deflection change, the reversal behaviour indicates redistribution rather than purely beneficial relaxation. An intermediate soaking temperature between 770°C and 1065°C may be sufficient to achieve effective residual stress reduction without inducing stress reversal. The 700°C heat treatment reduced deflection by 54%, indicating substantial residual stress reduction, and the 770°C heat treatment reduced deflection

by 82%, relative to the as-built condition. Within the tested range, 770°C demonstrated a desirable balance between substantial deflection reduction, dimensional stability, and reduced post-processing time. Based on cantilever deflection as an indirect indicator of residual stress reduction, this temperature is recommended as the most suitable stress-relief temperature for the investigated geometry and processing conditions.

5.1 Future Work & Recommendations

Future work should focus on refining simulation algorithms to better account for environmental and material variability, as well as exploring the applicability of this approach to other materials and component geometries. Based on the findings, the following recommendations are made:

1. **Simulation Calibration:** Future studies should focus on expanding calibration datasets to improve the predictive accuracy of simulation software. This includes capturing material-specific behaviours and environmental influences.
2. **Material and Process Optimisation:** The relationship between process parameters and heat treatment should be explored further to optimise residual stress management across a broader range of materials and geometries.
3. **Hybrid Approaches:** Combining simulations with real-time monitoring technologies, such as in-situ thermal imaging, could enhance the feedback loop between prediction and validation, reducing trial-and-error iterations in heat treatment design.
4. **Further Studies on Mid-Range Heat Treatments Temperatures:** Additional research is needed to understand the behaviour of CoCrMo alloys at elevated heat treatment temperatures between 770°C and 1065°C, to identify more effective soaking temperatures and holding times for stress relief.
5. **Advanced Residual Stress and Microstructural Characterisation:** Future investigations should incorporate direct residual stress measurement techniques such as $\sin^2\psi$ XRD analysis or neutron diffraction to quantitatively determine residual stress magnitudes and distributions. Electron Backscatter Diffraction (EBSD) could also be employed to quantify grain size and recrystallisation behaviour for improved evaluation of the relationship between heat treatment temperature, microstructural evolution, and residual stress reduction.

REFERENCES

- [1] M. Mehrpouya, A. Dehghanghadikolaei, B. Fotovvati, A. Vosooghnia, S. S. Emamian and A. Gisario, "The Potential of Additive Manufacturnig in the Smart Factory Industry 4.0: A Review," *Applied Sciences*, vol. 9, no. 3856, pp. 1-34, 2019.
- [2] S. Jung, L. B. Kara, Z. Nie, T. W. Simpson and K. S. Whitefoot, "Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production?," *Environmental Science & Technology*, vol. 57, pp. 6373-6386, 2023.
- [3] B. Blakey-Milner, P. Gradl, G. Snedden, M. Brooks, J. Pitot, E. Lopez, M. Leary, F. Berto and A. Du Plessis, "Metal additive manufacturing in aerospace: A review," *Materials & Design*, vol. 209, 2021.
- [4] M. Langelaar, "Integrated component-support topology optimization for additive manufacturing with post-machining," *Rapid Prototyping Journal*, vol. 25, no. doi: 10.1108/RPJ-12-2017-0246, 2018.
- [5] K. Carpenter and A. Tabei, "On Residual Stress Development, Prevention, and Compensation in Metal Additive Manufacturing," *Materials*, vol. 13, no. 2, 2020.
- [6] K. V. Wong and A. Hernandez, "A Review of Additive Manufacturing," *ISRN Mechanical Engineering*, vol. 2012, pp. 1-10, 2012.
- [7] L. Chen, G. Bi, X. Yao, J. Su, C. Tan, W. Feng, M. Benakis, Y. Chew and S. K. Moon, "In-situ process monitoring and adaptive quality enhancement in laser additive manufacturing: A critical review," *Journal of Manufacturing Systems*, vol. 74, pp. 527-574, 2024.
- [8] M. Perez, D. R. E. M. Carou and R. Teti, "Current advances in additive manufacturing," *Procedia CIRP*, vol. 88, pp. 439-444, 2020.
- [9] ISO and ASTM, "International Organization for Standardization," November 2021. [Online]. Available: <https://www.iso.org/standard/74514.html?browse=tc>. [Accessed 16 June 2024].

- [10] D. Mahmoud, M. Magolon, J. Boer, M. Elbestawi and M. G. Mohammadi, "Applications of Machine Learning in Process Monitoring and Controls of L-PBF Additive Manufacturing: A Review," *Applied Sciences*, vol. 11, no. 24, 2021.
- [11] S. Sun, M. Brandt and M. Easton, "Powder bed fusion processes: an overview," *Laser Additive Manufacturing*, pp. 55-77, 2017.
- [12] P. Gokuldoss, S. Kolla and J. Eckert, "Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting, Binder Jetting - Selection Guidelines," *Materials (Basel)*, vol. 10 (672), no. doi: 10.3390/ma10060672, p. 12, 2017.
- [13] C. Yap, C. Chua, Z. Dong, Z. Liu, D. Zhang, L. Loh and S. Sing, "Review of Selective Laser Melting: Materials and Applications," *Appl. Phys. Rev*, vol. 2 (4), no. doi: 10.1063/1.4935926, 2015.
- [14] A. Khorasani, I. Gibson, J. K. Veetil and A. H. Ghasemi, "A review of technological improvements in laser-based powder bed fusion of metal printers," *The International Journal of Advanced Manufacturing Technology*, pp. 1-19, 2020.
- [15] M. Revilla-Leon and M. Ozcan, "Additive manufacturing technologies used for 3D metal printing in dentistry," *Curr. Oral Heal. Reports*, vol. 4(3), no. doi: 10.1007/s40496-017-0152-0, pp. 201-208, 2017.
- [16] D. Xie, F. Lv, Y. Yang, L. Shen, Z. Tian, C. Shuai, B. Chen and J. Zhao, "A Review on Distortion and Residual Stress in Additive Manufacturing," *Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers*, vol. 1, no. 3, 2022.
- [17] A. Edelmann, M. Dubis and R. Hellmann, "Selective Laser Melting of Patient Individualized Osteosynthesis Plates - Digital to Physical Process Chain," *Materials*, vol. 13, no. 24, pp. 1-13, 2020.
- [18] B. Konieczny, A. Szczisio-Włodarczyk, J. Sokolowski and K. Bociog, "Challenges of Co-Cr Alloy Additive Manufacturing Methods in Dentistry - The current State of Knowledge (Systematic Review)," *Materials (Basel)*, vol. 13 (16), no. doi: 10.3390/MA13163524, pp. 1-16, 2020.

- [19] C. Song, M. Zhang, Y. Yang, D. Wang and Y. Jia-Kuo, "Morphology and Properties CoCrMo Parts Fabricated by Selective Laser Melting," *Master. Sci. Eng. A*, vol. 713, no. doi: 10.1016/j.msea.2017.12.035, pp. 206-213, 2018.
- [20] K. Kulcsar and J. Konya, "The Influence if Heat Treatment on the Mechanical Properties of 3D-Printed Cobalt-Chrome Alloy used in Dental Laboratory Practice," *Acta mater. Transilv*, vol. 1 (2), no. doi: 10.2478/amt-2018-0036, pp. 97-100, 2019.
- [21] H. H. Wai Cho, A. Takaichi, Y. Kajima, H. L. Htat, N. Kittikundecha, T. Hanawa and N. Wakabayashi, "Effect of Post-Heat Treatment Cooling on Microstructures and Fatigue Properties of Cobalt Chromiun Molybdenum Alloy Fabricated through Selective Laser Melting," *Metals*, vol. 11, no. 7, 2021.
- [22] D. Dimitrov, T. Becker, I. Yadroitsev and G. Booyesen, "On the Impact of Different System Strategies on the Material Performance of Selective Laser Melting Manufactured Ti6Al4V Components," *South African Journal of Industrial Engineering*, vol. 27, no. 3, pp. 184-191, 2016.
- [23] T.-N. Lam, K.-M. T. C.-H. Chen, P.-I. Tsai, M.-H. Wu, C.-C. Hsu, J. Jain and E.-W. Huang, "Effect of Porosity and Heat Treatment on Mechanical Properties of Additive Manufactured CoCrMo Alloy," *Materials*, vol. 16, no. 751, pp. 1-17, 2023.
- [24] L. Haoqing, W. Ming, L. Dianjun, X. Weilong and F. Xiaoying, "Microstructural features of biomedical cobalt–chromium–molybdenum (CoCrMo) alloy from powder bed fusion to aging heat treatment," *Journal of Materials Science & Technology*, vol. 45, pp. 146-156, 15 May 2020.
- [25] L. Mugwagwa, D. Dimitrov, S. Matope and I. Yadroitsev, "Investigation of the Effect of Scan Vector Length on Residual Stresses in Selective Laser Melting of Maraging Steel 300," *South African Journal of Industrial Engineering*, vol. 30, no. 4, pp. 60-70, 2019.
- [26] T. Becker, M. Van Rooyen and D. Dimitrov, "Heat treatment of Ti-6Al-4V produced by lasercusing," *South African Journal of Industrial Engineering*, vol. 26, no. 2, pp. 93-103, 2015.

- [27] N. Bastola, M. P. Jahan, N. Rangasamy and C. S. Rakurty, "A Review of the Residual Stress Generation in Metal Additive Manufacturing: Analysis of Cause, Measurement, Effect and Prevention," *Micomachines*, vol. 14, no. 7, 2023.
- [28] K. Moore, D. Kouprianoff, D. Louw, I. Yadroitsava and I. Yadroitsev, "Monitoring for Cracks in Metal L-PBF Using Gas-Borne Acoustic Emission," *South African Journal of Industrial Engineering*, vol. 34, no. 4, pp. 147-154, 2023.
- [29] X. Lu, M. Cervera, M. Chiumenti and X. Lin, "Residual Stresses Control in Additive Manufacturing," *Journal of Manufacturing and Materials Processing*, vol. 5, no. 4, 2021.
- [30] S.-g. Chen, H.-j. Gao, Y.-d. Zhang, Q. Wu, Z.-h. Gao and X. Zhou, "Review on residual stresses in metal additive manufacturing: formation mechanisms, parameter dependencies, prediction and control approaches," *Journal of Materials research and Technology*, vol. 17, pp. 2950-2974, 2022.
- [31] Z. Fang, Z. Wu, C. Huang and C. Wu, "Review on Residual Stress in Selective Laser Melting Additive Manufacturing of Alloy Parts," *Opt. Laser Techno.*, vol. 129 (15), no. doi: 10.1016/j.optlastec.2020.106283, 2020.
- [32] P. Krakhmalev, I. Yadroitsava, G. Fredriksson and I. Yadroitsev, "Microstructural and Thermal Stability of Selective Laser Melted 316L Stainless Steel Single Tracks," *South African Journal of Industrial Engineering*, vol. 28, no. 1, pp. 12-19, 2017.
- [33] S. Bazri, C. Mapelli, S. Barella, A. Gruttadauria, D. Mombelli, R. Nemfardi, R. Bedini and G. Zucchelli, "Microstructural, textural, and residual stress evolution alongside the magnetic properties through isothermal static recrystallization of cold-drawn Fe-Cr-Si-S-C ferritic high-alloy stainless steel and by JMAK modelling," *Journal of Materials Research and Technology*, vol. 23, pp. 3091-3118, 2023.
- [34] Y. Kajima, A. Takaichi, H. L. Htata, T. Hanawa and N. Wakabayashi, "Recrystallization behavior of selective laser melted Co–Cr–Mo alloys with several heat treatment times," *Materials Science and Engineering: A*, vol. 856, 2022.
- [35] C. Li, Z. Liu, X. Fang and Y. Guo, "Residual Stress in Metal Additive Manufacturing," *Procedia CIRP*, vol. 71, no. doi: 10.1016/j.procir.2018.05.039, pp. 348-353, 2018.

- [36] S. Leuders, M. Thöne, A. Riemer, T. Niendorf, T. Tröster, H. Richard and H. Maier, "On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance," *International Journal of Fatigue*, vol. 48, pp. 300-307, 2013.
- [37] K.-H. Ko, H.-G. Kang, Y.-H. Huh, C.-J. Park and L.-R. Cho, "Effects of heat treatment on the microstructure, residual stress, and mechanical properties of Co-Cr alloy fabricated by selective laser melting," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 126, 2022.
- [38] L. Zhou, J. Miller, J. Vezza, M. Mayster, M. Raffay, Q. Justice, Z. Al Tamimi, G. Hansotte, L. D. Sunara and J. Bernat, "Additive Manufacturing: A Comprehensive Review," *Sensors*, vol. 24, pp. 1-44, 2024.
- [39] M. Armstrong, H. Mehrabi and N. Naveed, "An overview of modern metal additive manufacturing technology," *Journal of Manufacturing Processes*, vol. 84, pp. 1001-1029, 2022.
- [40] S. Rouf, A. Malik, N. Singh, A. Raina, N. Naveed, M. I. H. Siddiqui and M. I. U. Haq, "Additive manufacturing technologies: Industrial and medical applications," *Sustainable Operations and Computers*, vol. 3, pp. 258-274, 2022.
- [41] M. Q. Zafar, R. Sajjad, M. T. Anwar, M. S. Mustafa, N. Husnain, A. B. Aqeel and M. B. Khan, "A Review on Metal Additive Manufacturing - Types, Applications and Future Trends," *Recent Progress in Materials*, vol. 7, no. 1, pp. 1-38, 2025.
- [42] G. Liu, X. Zhang, X. Chen, Y. He, L. Cheng, M. Huo, J. Yin, F. Hao, S. Chen, P. Wang, S. Yi, L. Wan, Z. Mao, Z. Chen, X. Wang, Z. Cao and J. Lu, "Additive Manufacturing of Structural Materials," *Materials Science & Engineering R*, vol. 145, pp. 1-67, 2021.
- [43] J. W. Nicholson, "Titanium Alloys for Dental Implants: A Review," *Prosthesis*, vol. 2, no. 2, pp. 100-116, 2020.
- [44] Y. Liu, Y. Yang and D. Wang, "A Study on the Residual Stress During Selective Laser Melting (SLM) on Metallic Powder," *Int. J. Adv. Manuf. Technol.*, vol. 87, no. doi: 10.1007/s00170-016-8466-y, pp. 647-656, 2016.

- [45] M. Brennan, J. Keist and T. Palmer, "Defects in Metal Additive Manufacturing Processes," *J Mater Eng. Perform*, vol. 30(7), no. doi: 10.1007/s11665-021-05919-6, pp. 4808-4818, 2021.
- [46] S. Cooke, K. Ahmadi, S. Willerth and R. Herring, "Metal additive manufacturing: Technology, metallurgy and modelling," *Journal of Manufacturing Processes*, vol. 57, pp. 978-1003, 2020.
- [47] T. DebRoy, H. Wei, J. Zuback, T. Mukherjee, J. Elmer, J. Milewski, A. Beese, A. Wilson-Heid, A. De and W. Zhang, "Additive manufacturing of metallic components – process, structure and properties," *Progress in Materials Science*, vol. 92, pp. 112-224, 2018.
- [48] C. Wensrich, V. Luzin, J. Hendriks, P. Pant and A. Gregg, "Residual Stress in additive manufactured Inconel cubes; Selective Laser Melting versus Electron Beam Melting and a comparison of modelling techniques," *Materials & Design*, vol. 244, pp. 1-15, 2024.
- [49] P. Zhu, X. He, H. Guan, Z. Zhang, T. Zhang and X. Qu, "Investigation on the Attainment of High-Density 316L Stainless Steel with Selective Laser Sintering," *Materials*, vol. 17, no. 1, 2023.
- [50] Y. Adungna, A. Akessa and H. Lemu, "Overview study on challenges of additive manufacturing for a healthcare application," *Materials Science and Engineering*, vol. 1201, no. 1, pp. 1-13, 2021.
- [51] A. Kiran, J. VELURU, S. Merum, A. Radhamani, M. Doble, T. Kumar and S. Ramakrishna, "Additive Manufacturing Technologies: An Overview of Challenges and Perspective of using Electrospraying," *Nanocomposites*, vol. 4(4), no. doi: 10.1080/20550324.218.1558499, pp. 190-214, 2018.
- [52] A. Bandyopadhyay, K. D. Traxel, M. Lang, M. Juhasz, N. Eliaz and S. Bose, "Alloy design via additive manufacturing: Advantages, challenges, applications and perspectives," *Materials Today*, vol. 52, pp. 207-224, 2022.
- [53] A. Ladewig, G. Schlick, M. Fisser, S. Volker and U. Glatzel, "Influence of the shielding gas flow on the removal of process by-products in the selective laser melting process," *Additive Manufacturing*, vol. 10, pp. 1-9, 2016.

- [54] T. G. Spears and S. A. Gold, "In-process sensing in selective laser melting (SLM) additive manufacturing," *Integrating Materials and Manufacturing Innovation*, vol. 5, no. 2, pp. 1-25, 2016.
- [55] S. Adjamskiy, K. G. R. Podolskyi and S. Baduk, "Studying the Influence of Orientation and Layer Thickness on the Physico-Mechanical Properties of Co-Cr-Mo Alloy Manufactured by the SLM Method," *Science and Innovation*, vol. 18, no. 5, pp. 85-94, 2022.
- [56] A. Vafadar, F. Guzzomi, A. Rassau and K. Hayward, "Advances in Metal Additive Manufacturing: A Review of Common Processes, Industrial Applications, and Current Challenges".
- [57] R. Nandhakumar and K. Venkatesan, "A process parameters review on selective laser melting-based additive manufacturing of single and multi-material: Microstructure, physical properties, tribological, and surface roughness," *Materials Today Communications*, vol. 35, 2023.
- [58] F. Kandil, J. Lord, A. Fry and P. Grant, "A Review of Residual Stress Measurement Methods - A Guide to Technique Selection," National Physical Laboratory, Teddington, 2001.
- [59] L. Mugwagwa, I. Yadroitsava, W. Makoana and I. Yadroitsev, "9 - Residual Stress in Laser Powder Bed Fusion," in *Fundamentals of Laser Powder Bed Fusion of Metals*, Elsevier, 2021, pp. 245-276.
- [60] K. Kempen, L. Thijs, B. Vrancken, S. Bols, J. Van Humbeeck and J.-P. Kruth, "Producing crack-free, high density M2 HSS parts by Selective Laser Melting: Pre-heating the baseplate," pp. 1-10, 2013.
- [61] J. L. Bartlett and X. Li, "An Overview of residual stresses in metal powder bed fusion," *Additive Manufacturing*, vol. 27, pp. 131-149, 2019.
- [62] F. Schmeser, E. Krohmer, N. Schell, E. Uhlmann and W. Reimers, "Experimental observation of stress formation during selective laser melting using in situ X-ray diffraction," *Additive Manufacturing*, vol. 32, 2020.

- [63] R. Magana-Carranza, C. Sutcliffe and E. Patterson, "The effect of processing parameters and material properties on residual forces induced in Laser Powder Bed Fusion (L-PBF)," *Additive Manufacturing*, vol. 46, 2021.
- [64] N. Dejene and H. Lemu, "Current Status and Challenges of Powder Bed Fusion-Based Metal Additive Manufacturing: Literature Review," *Metals*, vol. 13, no. 424, pp. 1-22, 2023.
- [65] H.-G. Kang, "Dental Co-Cr alloys fabricated by selective laser melting: A review article," *Journal of Korean Academy of Prosthodontics*, vol. 59, no. 2, 2021.
- [66] L. Parry, I. Ashcroft and R. Wildman, "Understanding the effect of laser scan strategy on residual stress in selective laser melting through thermo-mechanical simulation," *Additive Manufacturing*, vol. 12, pp. 1-15, 2016.
- [67] W. Sames, F. List, S. Pannala, R. Dehoff and S. Babu, "The Metallurgy and Processing Science of Metal Additive Manufacturing," *International Materials Reviews*, vol. 61(5), no. doi: 10.1080/09506608.2015.1116649, pp. 315-360, 2016.
- [68] B. Vrancken, "Study of Residual Stresses in Selective Laser Melting," June 2016.
[Online]. Available:
https://lirias.kuleuven.be/bitstream/123456789/542751/1/thesis+Bey+Vrancken+v01-06-2016+FINAL_compressed.pdf. [Accessed 4 November 2022].
- [69] J. H. Robinson, I. R. T. Ashton, E. Jones, P. Fox and C. Sutcliffe, "The effect of hatch angle rotation on parts manufactured using selective laser melting," *Rapid Prototyping Journal*, vol. 25, no. 2, pp. 289-298, 2019.
- [70] Z. Yan, K. Wu, Z. Xiao, J. Hui and L. Jingxiang, "The Effect of Scanning Strategy on the Thermal Behavior and Residual Stress Distribution of Damping Alloys during Selective Laser Melting," *Materials*, vol. 17, no. 12, 2024.
- [71] H. Ali, H. Ghadbeigi and K. Mumtaz, "Effect of scanning strategies on residual stress and mechanical properties of Selective Laser Melted Ti6Al4V," *Material Science & Engineering A*, vol. 712, pp. 175-187, 2018.

- [72] J. Robinson, I. Ashton, P. Fox, E. Jones and C. Sutcliffe, "Determination of the effect of scan strategy on residual stress in laser powder bed fusion additive manufacturing," *Additive Manufacturing*, vol. 23, pp. 13-24, 2018.
- [73] P. R. Zagade, B. Gautham, A. De and T. DebRoy, "Analytical modelling of scanning strategy effect on temperature field and melt track dimensions in laser powder bed fusion," *Additive Manufacturing*, vol. 82, 2024.
- [74] M. Nematollahi, S. E. Saghaian, K. Safaei, P. Bayati, P. Bassani, C. Biffi, A. Tuissi, H. Karaca and M. Elahinia, "Building orientation-structure-property in laser powder bed fusion of NiTi shape memory alloy," *Journal of Alloys and Compounds*, vol. 873, 2021.
- [75] L. Cheng and A. To, "Part-scale build orientation optimization for minimizing residual stress and support volume for metal additive manufacturing: Theory and experimental validation," *Computer-Aided Design*, vol. 113, pp. 1-23, 2019.
- [76] E. Arabul and A. J. G. Lunt, "A Novel Low-Cost DIC-Based Residual Stress Measurement Device," *Applied Sciences*, vol. 12, no. 14, 2022.
- [77] P. Pant, "4.3 Measurement of residual stress," in *Residual Stress Distributions in Additively Manufactured Parts - Effect of Build Orientation*, Linköping, Sweden, Linköping University, 2020, pp. 21-22.
- [78] D. Boruah, N. Dewagtere, B. Ahmad, R. Nunes, J. Tacq, X. Zhang, H. Guo, W. Verlinde and W. De Waele, "Digital Image Correlation for Measuring Full-Field Residual Stresses in Wire and Arc Additive Manufactured Components," *Materials*, vol. 16, no. 4, 2023.
- [79] A. Ben-Artzy, K. Demir, J. Peterson, S. Maloy, G. X. Gu and P. Hosemann, "Residual Stress Measurement Techniques for Additive Manufacturing Applications," *Journal of Materials Science and Engineering A*, vol. 12, pp. 1-12, 2022.
- [80] V. P. Group, "Measurement of Residual Stresses by the Hole-Drilling Strain-Gage Method, Tech. Note TN-503," 1993.
- [81] X. Li, J. Liu, H. Wu, K. Miao, H. Wu, R. Li, C. Liu, W. Fang and G. Fan, "Research progress of residual stress measurement methods," *Heliyon*, vol. 10, pp. 1-25, 2024.

- [82] C. Chua, Y. Liu, R. J. Williams, C. K. Chua and S. L. Sing, "In-process and post-process strategies for part quality assessment in metal powder bed fusion: A review," *Journal of Manufacturing Systems*, vol. 73, pp. 75-105, 2024.
- [83] Z. Shao, C. Zhang, Y. Li, H. Shen, D. Zhang, X. Yu and Y. Zhang, "A Review of Non-Destructive Evaluation (NDE) Techniques for Residual Stress Profiling of Metallic Components in Aircraft Engines," *Aerospace*, vol. 9, no. 10, 2022.
- [84] S. Breumier, A. Villani, C. Maurice, M. Levesque and G. Kermouche, "Effect of crystal orientation on indentation-induced residual stress field: Simulation and experimental validation," *Materials & Design*, vol. 169, 2019.
- [85] A. Hollmann, M. Meixner, M. Klaus and C. Genzel, "Concepts for nondestructive and depth-resolved X-ray residual stress analysis in the near-surface region of nearly single crystalline materials with mosaic structure," *Journal of Applied Crystallography*, vol. 54, pp. 22-31, 2021.
- [86] S. Goel, M. Neikter, J. Capek, E. Polatidis, M. Colliander, S. Joshi and R. Pederson, "Residual stress determination by neutron diffraction in powder bed fusion-built Alloy 718: Influence of process parameters and post-treatment," *Materials and Design*, vol. 195, pp. 1-12, 2020.
- [87] W. Gale and T. Totemeier, "29 - Heat Treatment," in *Smithells Metals Reference Book (Eighth Edition)*, Butterworth-Heinemann, 2004, pp. 29-1 - 29-83.
- [88] T. Mishurova, S. Cabeza, K. Artzt, J. Haubrich, M. Klaus, C. Genzel, G. Requena and G. Bruno, "An Assessment of Subsurface Residual Stress Analysis in SLM Ti-6Al-4V," *Materials*, vol. 10, no. 4, 2017.
- [89] A. Paraschiv, G. Matache and M. Vladut, "Assessment of Residual Stresses in Laser Powder Bed Fusion Manufactured IN 625," *Materials*, vol. 17, no. 2, 2024.
- [90] K. Dimitriadis, A. G. Lekatou, A. K. Sfikas, M. Roumpi, S. Tsouli, A. Galiatsatos and S. & Agathopoulos, "Influence of Heat-Treatment Cycles on the Microstructure, Mechanical Properties, and Corrosion Resistance of Co-Cr Dental Alloys Fabricated," *Journal of Materials Engineering and Performance*, vol. 30, no. 3, pp. 1-24, 2021.

- [91] M. Shiomi, K. Osakada, K. Nakamura, T. Yamashita and F. Abe, "Residual Stress within Metallic Model Made by Selective Laser Melting Process," *CIRP Annals*, vol. 53, no. 1, pp. 195-198, 2004.
- [92] Z. Guoqing, L. Junxin, Z. Xiaoyu, L. Jin and W. Anmin, "Effects of Heat Treatment on the Properties of CoCrMo Alloy Manufactured by Selective Laser Melting," *J Mater Eng Perform*, vol. 27, no. 5, pp. 2281-2287, 2018.
- [93] G. Rousseau, J. Fourie, C. Kloppers and D. Marais, "Effect of stress-relief anneal time on residual stress of Co-Cr-Mo parts manufactured with selective laser melting," in *2022 RAPDASA-RobMech-PRASA-CoSAAMI Conference*, Stellenbosch, 2022.
- [94] L. Dai, C. Song, H. Fu, H. Chen, Z. Yan, Z. Liu, R. Li, A. Wang, Y. Yang and J.-K. Yu, "Recrystallization induced by heat treatment regulates the anisotropic behavior of CoCrMo alloys fabricated by laser powder bed fusion," *Materials Futures*, vol. 4, pp. 1-19, 2025.
- [95] A. Takaichi, Y. Kajima, N. Kittikundecha, H. L. Htat, H. H. Wai Cho, T. Hanawa, T. Yoneyama and N. Wakabayashi, "Effect of heat treatment on the anisotropic microstructural and mechanical properties of Co-Cr-Mo alloys produced by selective laser melting," *Journal of the Mechanical Behaviour of Biomedical Materials*, vol. 102, no. 103496, 2020.
- [96] H. Alzyod and P. Ficzer, "Finite Element Modeling of Additive Manufacturing in Case of Metal Parts," *Periodica Polytechnica Transportation Engineering*, vol. 50, no. 4, pp. 330-335, 2022.
- [97] J. Robertson and S. Webstre, "Simufact Additive: Accelerating the metal Binder Jetting workflow with sintering simulation," *Metal AM*, vol. 7, no. 3, pp. 165-172, 2021.
- [98] H. Mohammadtaheri, R. Sedaghati and M. Molavi-Zarandi, "Inherent strain approach to estimate residual stress and deformation in the laser powder bed fusion process for metal additive manufacturing - a state-of-the-art review," *The International Journal of Additive Manufacturing Technology*, vol. 122, pp. 2187-2202, 2022.
- [99] Z.-D. Zhang, O. Ibhade, S. I. Shahabad, X.-Y. Zhai, D.-Y. Yu, T. Gao, J.-H. Zhu and W.-H. Zhang, "High-resolution inherent strain method using actual layer thickness in laser

powder bed fusion additive manufacturing with experimental validation,” *Journal of Materials Research and Technology*, vol. 30, pp. 6576-6595, 2024.

- [100] B. Ahmad, S. O. Van der Veen, M. E. Fitzpatrick and H. Guo, “Residual stress evaluation in selective-laser-melting additively manufactured titanium (Ti-6Al-4V) and inconel 718 using the contour method and numerical simulation,” *Additive Manufacturing*, vol. 22, pp. 571-582, 2018.
- [101] M. Siewert, F. Neugebauer, J. Epp and V. Ploshikhin, “Validation of Mechanical Layer Equivalent Method for simulation of residual stresses in additive manufactured components,” *Computers & Mathematics with Applications*, vol. 78, no. 7, pp. 2407-2416, 2019.
- [102] I. Setien, M. Chiumenti, S. Van der Veen, M. San Sebastian, F. Garciandia and A. Echeverria, “Empirical methodology to determine inherent strains in additive manufacturing,” *Computers & Mathematics with Applications*, vol. 78, no. 7, pp. 2282-2295, 2019.
- [103] S. Weber, J. Montero, M. Bleckmann and K. Paetzold, “A Comparison of Layered Tetrahedral and Cartesian meshing in additive Manufacturing Simulation,” *Procedia CIRP*, vol. 91, pp. 522-527, 2020.
- [104] Hexagon, “Hexagon - SimuFact Additive Tutorial,” 11 May 2022. [Online]. Available: https://help.hexagonmi.com/bundle/Simufact_Additive_2022_Introducing_Simufact_Additive/resource/Simufact_Additive_2022_Introducing_Simufact_Additive.pdf. [Accessed June 2022].
- [105] T. Taufek, Y. H. Manurung, S. Lüder, M. Graf and F. M. Salleh, “Distortion Analysis of SLM Product of SS316L using Inherent Strain Method,” *IOP Conference Series: Materials Science and Engineering*, vol. 834, no. 1, pp. 1-15, 2020.
- [106] X. Laing, L. Cheng, Q. Chen, Q. Yang and A. To, “A modified method for estimating inherent strains from detailed process simulation for fast residual distortion prediction of single-walled structures fabricated by directed energy deposition,” *Additive Manufacturing*, vol. 23, pp. 471-486, 2018.

- [107] A. International, "Advancing Standards Transforming Markets International," 4 5 2023. [Online]. Available: <https://store.astm.org/f0075-23.html>. [Accessed September 2023].
- [108] S. Papworth, A. Bayode, J. Fourie and C. Kloppers, "Selective laser melting of CoCrMo: an evaluation of part density distribution across the built plate," *2022 RAPDASA-RobMech-PRASA-CoSAAMI Conference*, vol. 370, 2022.
- [109] AKASEL, "AKASEL," 2021. [Online]. Available: https://www.akasel.com/wp-content/uploads/2021/01/aka-brief-2021_18_uk5_web.pdf. [Accessed November 2022].
- [110] N. Mistry, L. Hitzlet, A. Biswas, C. Krempaszky and E. Werner, "Predicting anisotropic behavior of textured PBF-LB materials via microstructural modeling," *Continuum Mechanics and Thermodynamics*, vol. 35, no. 8, 2023.
- [111] P. B. Raja, K. R. Munusamy, V. Perumal and M. N. M. Ibrahim, "Characterization of nanomaterial used in nanobioremediation," in *Nano-Bioremediation: Fundamentals and Applications*, Elsevier Inc., 2022, pp. 57-83.
- [112] Z. Wang, Y. Yan and L. Qiao, "Effect of deformed subsurface on the corrosion resistance of biomedical CoCrMo alloy in simulated physiological solution," *Journal of Materials Science*, vol. 55, 2020.
- [113] H. Albayrak, M. Ayata and B. Demirel, "Recycling selective laser melting alloy powder on cobalt chromium-to-ceramic bond strength," *The Journal of Prosthetic Dentistry*, vol. 130, no. 5, pp. 786.e1-786.e7, 2023.
- [114] O. Ekren and Y. Ucar, "The Effect of Reuseing Cobalt-Chromium Alloy Powder on Its Mechanical Properties and Grain Size: An In Vitro Study," *The International Journal of Prosthodontics*, vol. 37, pp. s187-s193, 2024.

ANNEXTURE A: ADDITIONAL INFORMATION ON METHODS

Powder Preparation

Used powder can be reused multiple times during part manufacturing to reduce material waste and cost. However, studies indicate that excessive reuse may degrade material performance. Some studies recommend limiting reuse to approximately 30 cycles [113], while others report that high recycling rates increase the release of Co and Cr ions, potentially leading to cytotoxic effects, and therefore advise restricting reuse to fewer than 13 cycles to preserve desirable mechanical properties and biocompatibility [114]. After manufacturing was completed, the excess powder in the build chamber was carefully brushed into the excess powder reservoir inside the machine. Excess powder collected after manufacturing was sieved through the sieve stack shown in Figure A-1.



Figure A-1: Powder Sieves

The collected powder was sieved through several sieves with decreasing aperture size, namely 212 µm, 150 µm, 106 µm, and finally 53 µm, to remove any spatter, contaminants, and large particles from the powder. After sieving, the powder was placed inside a furnace to dry at 120 °C for one hour, as the powder can contain moisture resulting from exposure to the ambient air. Once the powder had been dried, it can be placed back into the powder reservoir inside the machine and virgin powder can also be added to this when necessary to ensure the reservoir is completely full before manufacturing commences.