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Improving the R&D process efficiency of the selective laser sintering industry through numerical thermal modeling

Carlo Martin Olivier[a, c], Gert Adriaan Oosthuizen[a], Natasha Sacks[b, c]

[a]*University of Stellenbosch, Department of Industrial Engineering, Stellenbosch 7600, South Africa*
[b]*University of the Witwatersrand, School of Chemical and Metallurgical Engineering, WITS, 2050, South Africa*
[c]*DST-NRF Centre of Excellence in Strong Materials, WITS, 2050, South Africa*

Abstract

The selective laser melting (SLS) industry is a relatively novel industry within the broad spectrum of available additive manufacturing (AM) technologies. As with most developing industries, the primary aim is to develop better quality components at reduced costs, often with a disregard towards efficiency. Resource efficiency is a key component of waste management and ties directly to sustainable manufacturing. In the SLS industry, large quantities of raw material are wasted during the machine calibration stage. Each time a new material is developed for SLS manufacturing a specific set of processing parameters need to be developed in order to ensure that high density, high strength components are produced. This paper investigates the possibility of replacing the current inefficient research and development (R&D) methods with numerical modeling. The fusion process can be simulated in a numerical thermal model using a combination of temperature dependent material properties and heat transfer principles.

Keywords: Additive manufacturing; numerical modeling; process chain; powder bed fusion; tungsten carbide.

1. Introduction

In recent years much emphasis has been placed on developing new materials for the additive manufacturing (AM) industries. Metal processing has become available to AM industry through the development of powder bed fusion (PBF) technologies such as electron beam melting, (EBM), selective laser melting (SLM) and - sintering (SLS) [1]. The development of these technologies have allowed researchers to produce fully functional components with highly complex geometries from powdered metals [2].

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However, owing to the novelty of this technology, machine specific material processing standards are still absent. Hence, manufactures and researchers need to follow a trial-and-error machine calibration process in order to identify the specific material processing parameters required to produce near full density components from novel metal powders before final production can commence [3]. This calibration process is time consuming, resource intensive and requires skilled personnel to perform the tests, which ultimately, has a negative effect on the overall process chain efficiency.

A solution to this obstacle may be to use tools such as numerical modeling in order to recreate the SLS process using known material properties and multi-physical principals in order to predict the material behavior. Numerical modeling has the advantage of providing in-situ processing information on manufacturing processes based on multi-physical phenomena [4]. Processing simulation tools have been used successfully in the past to recreate such manufacturing techniques, however the results are never fully accurate and need to be validated by experimental tests. In the future, numerical models may become sufficiently accurate to allow the machine calibration process to be omitted completely [4].

The novelty of this paper exists in using experimental tests performed by past researchers in literature and comparing them to a current numerical thermal model in an attempt to shorten the calibration step when processing novel materials in the SLS industry.

2. Background and Motivation

The SLS industry, like most industries, is faced with the challenges of globalization, climate change and social development. In order to stay competitive, all manufactures strive to improve on the Iron Triangle, shown in Figure 1, which aims at minimizing input costs/resources, reducing process time/scheduling whilst improving the final product quality [5]. These challenges can be overcome using innovation and by making good management decisions.

Efficiency has become a major aspect of manufacturing. Efficiency should not be confused with effectiveness. Effectiveness evaluates how well a process achieves its end goal, whereas efficiency evaluates the best possible process with the minimum waste of time and resources [6]. Ideally, the SLS industry wants a combination of an effective and efficient process chain, with the production of high quality (crack free, high density, etc.) components in the shortest time possible using the least amount of resources (stock powder, labor, energy, etc.).

Process chain efficiency in SLS manufacturing determines the number of components produced for the amount of resources invested. However, process efficiency varies in scale levels as seen in Figure 1. Changes to each level, affect the next level, hence it is important to strive for high efficiencies at each level [7]. Adding steps or new tools and methods to existing process chains will either have a positive or negative affect on the whole process chain system.

Fig. 1. (a) The balancing act of the Iron Triangle is used by management to make strategic business decisions. (b) Numerical modeling has a possibility of improving some of the industry's process chain efficiency levels, adjusted from [7].

Numerical modeling is good approach to use in applications with (1) a high level of uncertainty due to sparse data sets as well as (2) environments where the real-life processes are time-consuming and resource intensive [8].

Hence, it is ideal to use numerical modeling in order to predict the behavior of novel materials during SLS processing. Figure 2 provides further advantages of incorporating numerical modeling in the manufacturing technologies of the PBF industry.

This study tries to establish whether numerical modeling can be used as a R&D tool in order to improve efficiencies at the machine (calibration) and process (processing parameters) levels.

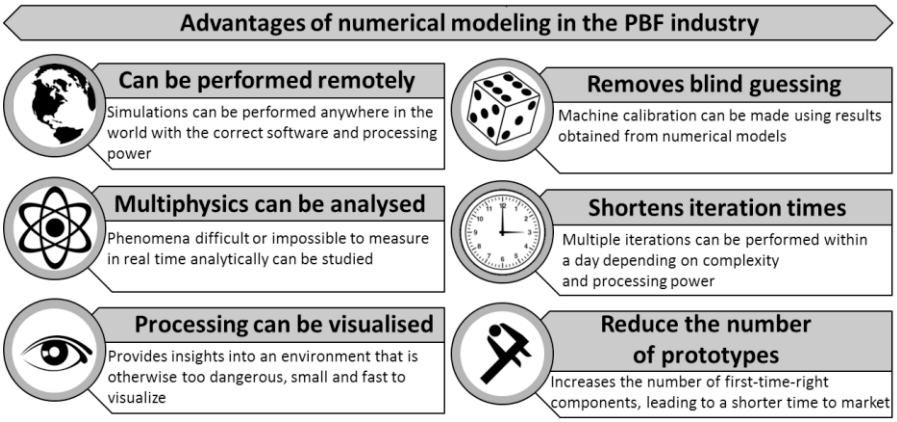


Fig. 2. Some of the main advantages of numerical modeling to the PBF industry.

3. Research Methodology

In order to ensure high accuracy, the simulated models relied on the specific input parameters listed in the past publications. Aspects of the numerical model such as geometry, material, and of course, machine input parameters had to match those applied in the experimental tests in order to reduce the final error.

As this study only tested the feasibility of comparing numerical models with experimental results obtained from past researchers in literature, only certain aspects of the process was evaluated. Therefore, certain limitations need to be set in order to reduce the scope of the simulations. SLS processing contains multi-scale, multi-physical phenomena, which need to be accounted for in order to acquire 100% accurate results [9]. However, a decision needed to be made as to the required detail of the simulations in order to provide manufactures with an adequate understanding of the material's behavior during PBF processing. The experimental process can be seen in the flow chart presented in Figure 3.

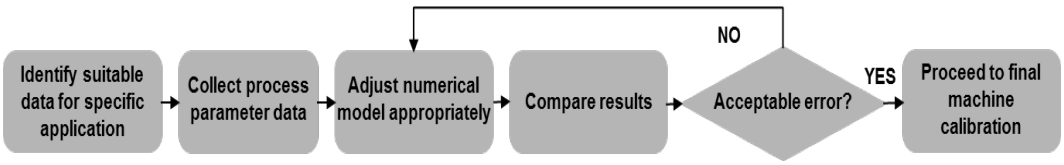


Fig. 3. Process flow chart explaining the study methodology.

The following assumptions and limitations reduce the scope of the study:

1. The laser additive manufacturing process (LAM), selective laser sintering (SLS), will be the only PBF process investigated during this study.
2. The focus spot temperature will be the physical phenomenon used to detect melting.
3. A finite element analysis (FEA) will be used to model heat transfer.
4. Model complexity will be limited to a meso-scale, single-track, single layer simulation.

Although these limits restrict some of the multi-physical phenomena (particle shape and size distribution, melt pool flow mechanics, microstructure etc.) crucial to the accuracy of the PBF process, it was argued that the results

from such an initial study may provide a close enough approximation in order to consider using numerical methods as a tool in the industry.

The study aimed at selecting literature, which focused on developing novel material for implementation in the SLS industry. The research was also required to be recent (past 5 years) in order to ensure materials and machine settings are correct.

The study chose to focus on past research developing tungsten carbide-cobalt (WC-Co) for application in the SLS environment. WC-Co is known as a "cermet" and is used predominantly in the mining, manufacturing, and oil and gas industries [10, 11]. WC is hard and brittle with a high melting temperature, whereas Co is tough and has a low melting temperature. The WC is known as the structural component, whereas the Co acts as a binder, which is used to consolidate the unmelted carbide particles. The combination of the carbide and metal can be adjusted according to the application. A higher WC content results in a harder, more brittle component, while a greater Co content results in a tougher yet softer part [12]. Table 1 lists the past research identified as suitable to use for the numerical model comparison.

Table 1. Past research identified for the experimental comparison.

Institute	Powdered material	Abbreviation	Reference
TU Clausthal ISAF and Bremer Institut für angewandte Strahltechnik.	Praxair WC-CO 88/12	ISAF, BIAS	[13]
Lyon University	MBN Nanomaterials S.P.A WC/Co12	UDL	[14]
Moscow State Technological University, STANKIN	WC-Co 25% Co	STANKIN	[15]

4. Simulation

Abaqus/CAE 2017 was selected as the numerical software to perform the analysis. It is a finite element analysis software used for design, analysis and visualisation of mechanical components assemblies and structures. Abaqus/CAE 2017 has a wide range of multi-physics modeling capabilities such as full structural loads, dynamic vibrations, multi-body systems, impact crash, nonlinear static, thermal coupling, etc. Abaqus/CAE 2017 is used in applications for the automotive, aerospace and industrial product industries [16]. The SLS processing is simulated using an implicit uncoupled thermal heat transfer analysis.

4.1. Model characteristics

In order to reduce the computational effort required to solve the thermal fields, the model geometrical complexity was limited to a simple rectangle. The rectangle consists out of two sections, a base substrate and a powder layer. The substrate material may vary from that of the powdered layer. The powder layer thickness will depend on the thickness specified in past literature. The dimensions of the base substrate was specifically selected in order to minimize computational time, while still allowing the thermal fields to fully develop during processing. In this study the base substrate size was chosen to be 500x600x1000 µm (h x w x l). A sketch of the numerical model geometry is shown in Figure 4.

An efficient meshing strategy, requiring less computational power, was used in the model. Powder layer elements positioned 100 µm on either sides of the scan track required the highest accuracy. Fine elements of 10x10x10 µm were used for the regions closest to the laser path, while the regions further away have coarser elements assigned to them. In total the model consisted out of 5060 linear hexahedral DC3D8 thermal brick elements with one degree-of-freedom on each node.

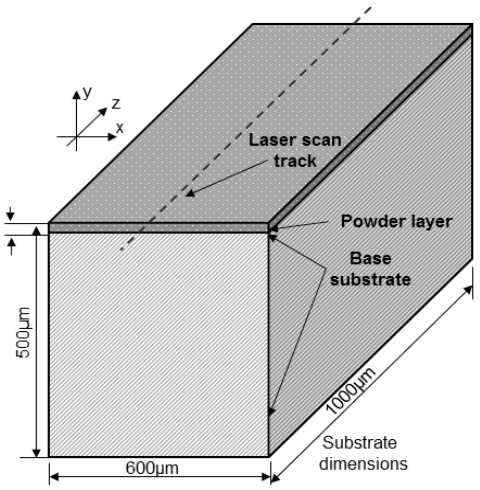


Fig. 4. The numerical model geometry used for the study of past publications.

4.2. Material assignments

During the material assignment step both the powder layer and base substrate were assigned with material properties, which vary with changes in temperature. The temperature dependent material properties taken into consideration in this study included the thermal conductivity, k, and specific heat, c_p. The temperature dependent properties of the WC-Co powder layer were calculated using the equations as specified by [8].

$$k_{WC-Co} = g_{WC}k_{WC} + g_{Co}k_{Co} \qquad \left[\frac{W}{m\ K}\right] \tag{1}$$

$$C_{WC-Co} = f_{WC}C_{WC} + f_{Co}C_{Co} \qquad \left[\frac{J}{kg\ K}\right] \tag{2}$$

Where g and f are the mass fractions of the tungsten carbide and cobalt binder particles, respectively. The material properties of the base substrates used by the past researcher can be found in the referenced literature in Table 2.

Table 2. References listing the temperature dependent properties for the substrate material used in each of the past publications.

Institute	Substrate/base plate material	Temperature dependent properties reference
ISAF, BIAS	AISI H11 Tool Steel	[17]
UDL	Stainless steel 304L	[18]
STANKIN	Sintered WC-Co	[10]

4.3. Loads and boundary conditions

Heat transfer loads and boundary conditions produce the SLS thermal field. For the input loads, the moving heat volumetric heat flux was described using the user specified subroutine known as DFLUX. The laser intensity distribution, q, is described using the Gaussian distribution.

$$q(x,y,z,t) = \frac{6\sqrt{3}\alpha P}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3[z+vt]^2/c^2} \qquad \left[\frac{W}{m^3}\right] \tag{3}$$

,where P is the laser power (W), α is the material's absorptivity taken as 0.82 [20][21], a, b and c are spot geometry specifics and x, y and z are the current beam coordinates.

Boundary conditions included a uniform initial temperature as specified in the considered literature. Heat conduction accounted for the heat transfer between the powder surface and the surrounding powder as well as the base substrate. Finally, radiation and film convection was added to the top surface of the powder layer.

5. Validation

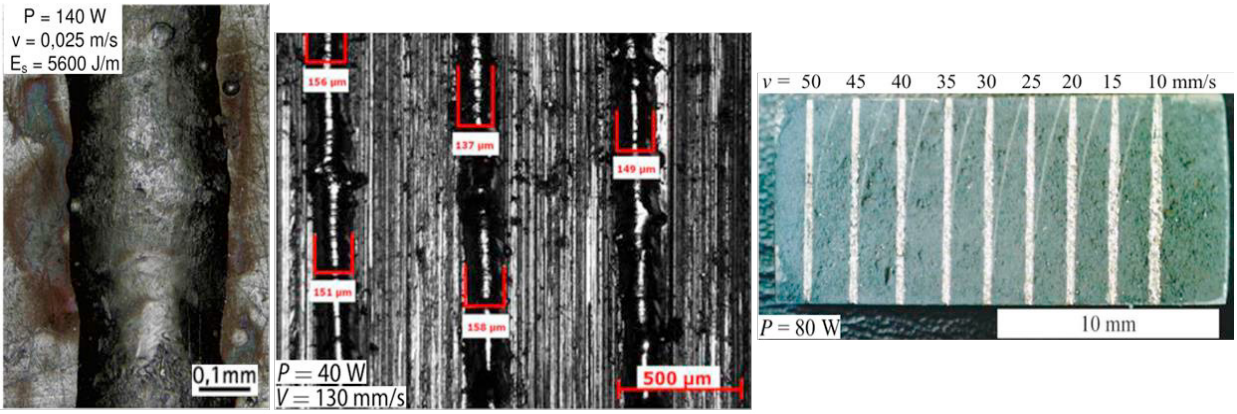
After selecting publications, which qualify from the set criteria, the experimental information was extracted. The most important process parameter information needed for the numerical thermal analysis is shown in Table 3. These parameters are then used in the numerical model in order to test the feasibility of constructing a numerical model using past results.

Table 3. Parameters used for the experimental testing in past literature.

	Publication		
Parameters	ISAF, BIAS	UDL	STANKIN
Powder layer thickness [µm]	Assume 50	40	100
Spot size, diameter [µm]	200	70	100
Laser power [W]	110 and 140	40	80
Scanning speed [mm/s]	250	130	10 to 50

The parameters used in past literature included a wide variety of capable machine parameters, which create unique combinations for processing WC-Co. This parameter variation tested the rigidity of the numerical model and provided insight to its accuracy.

The measurement of success in this study is the measured error between the experimental melt tracks dimensions compared to the dimensions obtained in the numerical study. The selected publications provided information regarding the scan track width (w). The exact dimensions of the melt tracks were obtained using the scale bar provided on each of the micrographs. Figure 5 displays the various experimental scans produced in order to determine the correct processing parameters for the new material. These single track scans were recreated using the numerical model thereafter and measured in order to determine the numerical model's accuracy.



(a) (b) (c)

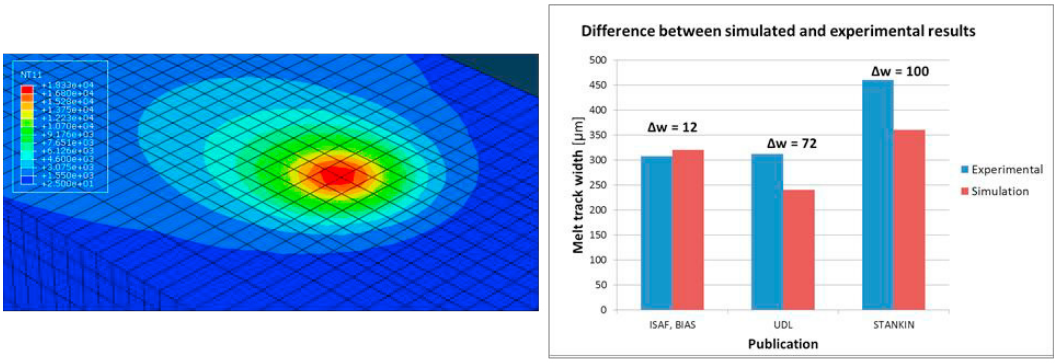
Fig. 5. Single track experimental results produced by (a) ISAF, BIAS [13], (b) UDL [14] and (c) STANKIN [15].

6. Results

The numerical results were analysed once the computer had solved the thermal fields of the scan tracks. In order

for liquid phase sintering to occur, the temperature of the powder mixture needed to exceed that of the melting temperature of the metal binder [2]. In the case of WC-Co, the Co will melt at temperatures exceeding 1495℃ [14]. Hence, from the numerical simulation the melting tracks can be approximated using the temperatures surrounding the laser spot.

A positive sign from initial observation of the results in the visualisation window were that all of scans resulted in temperatures exceeding the melting temperature of the cobalt binder, which indicated that sintering had occurred. It is also important to note that maximum temperatures do not exceed the evaporation temperature of the binder as this will lead to model inaccuracy [22]. For Co the evaporation temperature is approximately 2900 ℃ [23]. Figure 6(a) displays the thermal distribution caused by the laser on the top surface of the powder layer.



(a) (b)

Fig. 6. (a) Results showing the thermal field as predicted by the numerical model. (b) The comparison between the numerical and experimental results, with the error shown in terms of the absolute value of the difference in width.

After recreating the sintering circumstances described in each of the past publications and accepting that the initial overview seemed to provide reasonable results, the scan track dimensions were measured and compared to the experimental results. The differences between the experimental and simulated melt track widths (Δw) were plotted in Figure 6(b).

The comparison revealed a set of mixed of results. The ISAF, BIAS simulation predicted the scan track width with excellent accuracy, with only a 12 μm error. However, the results of the UDL and STANKIN simulation proved to be less accurate with errors of 72 μm and 100 μm, respectively. This inaccuracy may be due to a variety of factors, as SLS is a multi-physical which was only partially included in this numerical model.

7. Conclusion

The study investigated whether the results from a numerical SLS thermal model can be used to predict material behavior during the R&D development of novel powdered materials such as WC-Co. Ideally, numerical models can be used to improve the process efficiency by alleviating the need for the resource and time intensive machine calibration process required in order to find the optimal machine parameters before processing novel materials.

Although the success from the literature comparison produced a mixed set of results, it still proved to be a valuable technique to calibrate the numerical models even before any experimental validation scans are performed. Better and more refined numerical models, which include more of the multi-physical phenomena in the simulations, may lead to more consistent and accurate results.

8. Acknowledgement

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