Doctoral Thesis in Solid Mechanics

On the Mechanics of Sintering of Hardmetal Powders

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To my family - to those I was gifted, to the one I chose, and to the one I was blessed with.

Abstract

Powder metallurgy is used in the manufacturing of cutting tool inserts to achieve the desired material properties. Tungsten carbide, WC, mixed with a metallic binder, such as Cobalt, Co, is a common cemented carbide used for cutting tool inserts. In large scale production, the powder is pressed and sintered. During the manufacturing process, the volume of the cutting tool significantly decreases. During the sintering process, very little can be done to change the final shape, and the shrinkage during sintering must be accounted for during pressing. This thesis will investigate the mechanical modeling of shrinkage that occurs in the sintering process.

The constitutive model at issue can capture the isothermal stage in the sintering process and can be adjusted to a specific powder. To increase its usability, a sensitivity analysis was performed in **Paper A** to determine if all parameters must be determined when using a new powder mixture. It was found that some of the parameters were more sensitive than others when optimizing parameters using experimental results. The less sensitive parameters could be constant, reducing the number of necessary experiments to determine all adjustable parameters.

The different stages of sintering were also investigated in **Paper A**, where the model had difficulty describing the shrinkage both in the initial stage and in the liquid phase, where the Cobalt starts to melt. The latter was expected, since the constitutive model was explicitly developed for the solid stage of sintering.

To evaluate the model, all the experiments were performed on a specific WC-Co powder blend. For adherence to match the industrial process for cutting tools made from this powder, the debinding phase was included early in the sintering

cycle. This was not done in the previous development of the sintering model. The influence of the debinding process was experimentally investigated in **Paper B**, where it was shown that the shrinkage, as well as the final microstructure, is influenced by the exclusion of the debinding stage.

In **Paper C**, multiple dilatometer and sintering furnace experiments were performed to further develop the model. Complements to the initial stage and liquid phase were introduced, and the effect of changing the initial density, post-compaction, was investigated. Different sintering cycles were used to ensure the robustness of the constitutive parameters of the model. The deviatoric influence was tuned with bending experiments.

To verify the model, **Paper D** compares simulations to experiments. This was done using two different press dies, where the same amount of powder was pressed to different heights. The powder blanks were sintered to different maximum temperatures and measured. The compaction and sintering process was simulated and compared to the experimental values, showing that the sintering model captured the process well. A sintering furnace was used, where one of the sintering cycles was representative of the industrial production of cutting tools.

Keywords
Cemented carbide, Constitutive modelling, Sintering, Powder metallurgy

Sammanfattning

Pulvermetallurgi används vid tillverkning av vändskär för att uppnå de önskade materialegenskaperna. Volframkarbid, WC, blandat med ett metalliskt bindemedel, som exempelvis Kobolt, Co, är en vanlig hårdmetall att tillverka skär av. Vid storskalig produktion är pressning och sintring vanliga, och vid dessa tillverkningsprocesser sker en signifikant volymminskning. Under sintringssteget är möjligheten att påverka den slutgiltiga formen begränsad varför man redan vid pressning behöver ta hänsyn till den krympning som kommer att ske under sintringen. I denna avhandling kommer modellering av krympning under sintring att undersökas.

Den utvalda konstitutiva modellen kan fånga isotermiska delar av sintringsprocessen och har parametrar som går att anpassa för specifika pulversammansättningar. För att förenkla användningen av modellen utfördes en känslighetsanalys i **Artikel A**. Denna visade att när anpassningsbara parametrar ska justeras till en ny pulversammansättning kan vissa av de mindre känsliga hållas konstanta för att förenkla optimering.

Sintringens olika stadier undersöktes också i **Artikel A**. Modellen hade svårigheter att fånga krympningen både under den initiala fasen av sintring, samt i smältfassintringen. Det sistnämnda var förväntat, eftersom den konstitutiva modellen från början var specifikt utvecklad för fastfassintring.

För att begränsa osäkerheter vid modellutvärderingen utfördes alla experiment för en specifik sammansättning av WC-Co pulver. För att bättre representera det industriella förloppet vid skärtillverkning med detta pulver inkluderades även avdrivning (då pressmedlet avdunstar) i experimentet. Detta var inte inkluderat i den ursprungliga konstitutiva modellen, och effekten av avdrivningssteget i

sintringsprocessen undersöktes experimentellt i **Artikel B**. Här visades att både krympningen och den slutgiltiga mikrostrukturen påverkas av att inte inkludera avdrivningen i sintringscykeln.

I **Artikel C** utfördes ytterligare experiment, både med dilatometer och i sintringsugn, för att vidareutveckla modellen. Kompletteringar gjordes både för att ta hänsyn till avdrivning i sintringens initiala fas, samt i smältfasen. Vidare undersöktes effekten av att förändra pulvrets initiala densitet, efter pressning. För att öka modellens robusthet användes olika sintringscykler vid framtagandet av modellens konstitutiva parametrar. Inflytandet av deviatorisk spänning justerades med hjälp av böjexperiment.

För verifiering av modellen jämfördes i **Artikel D** simuleringar med experiment för olika geometrier. Detta gjordes med två olika pressformar, som pressade samma mängd pulver, men till olika höjder. Dessa sintrades till olika temperaturer och mättes därefter. Kompakterings- och sintringsprocessen simulerades och jämfördes med experimentens resultat, med mycket god överensstämmelse. En sintringsugn användes, där en av sintringscyklerna efterliknande vad som används vid industriell sintring.

Nyckelord
Hårdmetall, Konstitutiv modellering, Sintring, Pulvermetallurgi

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I wish to express my warmest gratitude to my parents, Katarina and Mats, for their support and encouragement to challenge myself in life. I also want to thank all my friends for their constant support. Lastly, I would like to thank my dear husband Johannes for your constant support and for making this possible for me.

List of publications

Appended papers

***Paper A**: L. Rosenblad, H. Staf, H. Larsson and P.-L. Larsson, "Parametric Dependency of a Constitutive Model Describing Solid State Sintering of Cemented Carbides", Powder Technology, 403, 117407 (9 pp.), 2022.*

***Paper B**: L. Rosenblad, H. Staf, H. Larsson and P.-L. Larsson, "An Experimental Investigation of the Solid State Sintering of Cemented Carbides Aiming for Mechanical Constitutive Modelling", Crystals, 13, 978 (12 pp.), 2023.*

***Paper C**: L. Rosenblad, H. Staf, H. Larsson and P.-L. Larsson, "Modeling of the Mechanical Behavior during Sintering of Cemented Carbides", International Journal of Refractory Metals and Hard Materials., 133, 107356 (8 pp.), 2025.*

***Paper D**: L. Rosenblad, H. Staf and P.-L. Larsson, "An experimental and numerical investigation of a material model for predicting densification of hardmetal powders", submitted for international publication.*

Author contributions

The contributions are listed and presented according to the Contributor Roles Taxonomy (CRediT) standard for all the authors in the same manner as in the appended papers.

Paper A

Louise Rosenblad: Formal analysis, Writing – original draft, Writing – review & editing. Hjalmar Staf: Formal analysis, Writing – review & editing. Henrik Larsson: Formal analysis, Writing – review & editing. Per-Lennart Larsson: Formal analysis, Writing – original draft, Writing – review & editing.

Paper B

Louise Rosenblad: Methodology, Validation, Formal analysis, Investigation, Writing—original draft. Hjalmar Staf: Methodology, Formal analysis, Investigation, Resources, Writing—original draft. Per-Lennart Larsson: Methodology, Formal analysis, Resources, Writing—original draft, Supervision. Henrik Larsson: Methodology, Investigation, Writing—original draft.

Paper C

Louise Rosenblad: Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Hjalmar Staf: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. Henrik Larsson: Writing – original draft, Validation, Supervision, Methodology, Conceptualization. Per-Lennart Larsson: Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Paper D

Louise Rosenblad: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Hjalmar Staf: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. Per-Lennart Larsson: Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Other work not included in the thesis

In addition to the appended papers, the work has resulted in the following publications and presentations

Investigation of a constitutive model of sintering of cemented carbides

Conference, Svenska Mekanikdagar 2022, Luleå, Sweden, Oral presentation

Constitutive Modelling of Solid State Sintering of Cemented Carbides

Conference, World PM 2022 Congress, Lyon, France, Oral presentation, Proceedings, Keynote paper award.

Constitutive Modeling of Sintering of Cemented Carbide Aiming for Robustness

Conference, Euro PM 2024 Congress, Stockholm, Sweden, Poster presentation, proceedings.

Robustness Analysis of a Constitutive Model for Cemented Carbide Sintering

Conference, World PM 2022 Congress, Yokohama, Japan, Poster presentation, Journal of the Japan Society of Powder and Powder Metallurgy, vol. 72, s. 1569-1575, 2025, Best poster award.

List of abbreviations

PEG	Pressing agent, polyethylene glycol
PM	Powder metallurgy
FEM	Finite Element Method
wt%	Weight percentage

CONTENTS

1 Introduction

1.1 Motivation

In machining processes such as turning or milling, smaller inserts are mounted on a tool holder, as shown in Figure 1. These inserts are the cutting tools, and have an estimated global market value of $73 billion in 2023 [1]. The cutting tool inserts can be replaced when they become worn out or when switching applications. For a cutting tool to work effectively, it must be harder than the metal it is cutting. Cemented carbide is a popular choice for this purpose, as it is a cost-effective material that can be shaped into the required form with relative ease. During manufacturing, hard metal powder is pressed into powder blanks, which are then sintered. This method is an efficient way of producing large quantities of cutting tools.

Figure 1. A milling operation where the yellow cutting tool inserts are mounted on the holder. Picture taken from Sandvik Coromant webpage [2].

A significant shape change takes place during the manufacturing of cutting tool inserts. The relative density of the granulated powder, compared to a fully sintered specimen without voids, is around 25%. After compaction, the relative density is around 55% [3]. In the compaction stage, both internal friction between particles and friction between particles and the pressing die will result in an uneven distribution and a non-uniform relative density, as shown in Figure 2. This will affect the shape after sintering. Finally, considering that WC-Co powder can reach a full relative density of 100% when sintered, all of this means that, in addition to great volume change, shape distortion occurs.

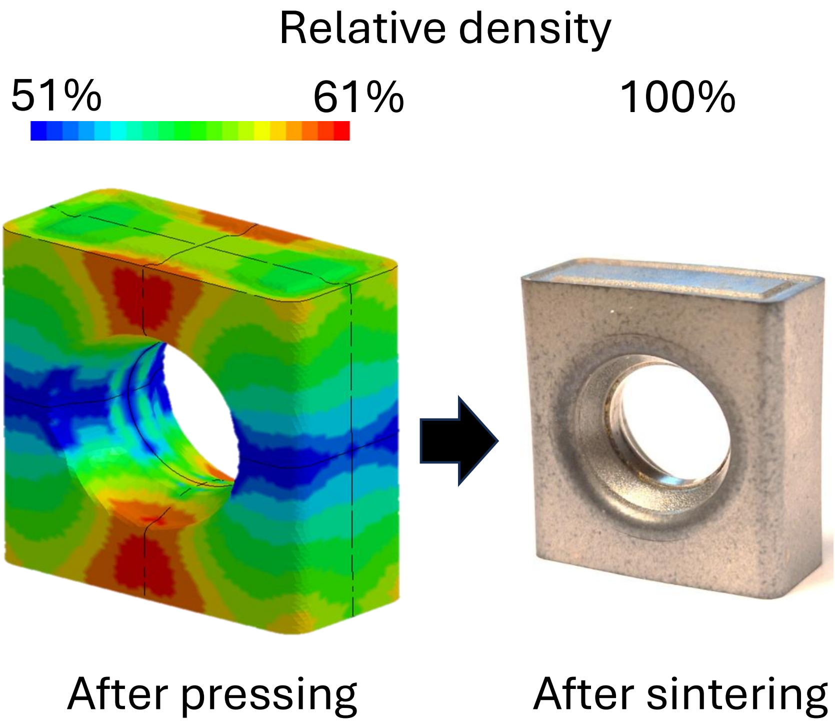

Figure 2. A cutting tool after pressing with a relative density gradient to the left and the final product of the cutting tool after sintering to the right.

The final sintered product needs to have small tolerances to be correctly mounted to the tool holder. Since alterations after sintering, such as grinding, require a harder material than the cutting tool itself, *e.g.*, diamond, this becomes costly and must be avoided if possible. The shape is defined during compaction, and little can be done afterwards to adjust the final shape. Therefore, the compaction stage must be designed to account for the shrinkage that occurs during the sintering process. To save time and resources, simulations can be used instead of extensive trial and error experimentation to find the optimal pressing tool design.

In a previous thesis by Brandt [4], a constitutive model for compaction and sintering was formulated to describe the shape change. The constitutive models were later implemented as the 'MAT_POWDER' material card in the FEM software 'LS-Dyna' [5]. The compaction formulation was later investigated by both Andersson *et al.* [6] and Staf *et al.* [7]. This sintering model has therefore been the focus of this thesis.

1.2 Research objectives

The main objective of the thesis is to predict the final shape of a blank used for cutting tool inserts and, more specifically, model the shrinkage during sintering. To do so, several objectives have been investigated.

- The debinding stage, where the PEG is removed, has been performed differently in experiments described in the literature. It is therefore of interest to understand whether having the debinding stage as a separate process or not would influence the densification during sintering as well as the final product.
- The original constitutive model uses adjustable parameters, which need to be determined for a particular powder mix. Reducing the number of powder-specific parameters would decrease the number of experiments needed to determine them.
- There are factors that can influence the sintering conditions, such as temperature variation in the furnace or slower heating and cooling conditions. To be able to account for all relevant factors, it is of interest to develop a robust model, that is able to produce accurate results even when the simulated sintering cycle is changed.
- In a pressed powder blank, the density distribution can be uneven. If complete densification after sintering is not achieved, the model must be able to capture the intermediate results correctly.

2 Background

2.1 Powder Metallurgy

We encounter powder every day, in spices when cooking, the coffee we drink, and sugar and flour when baking. Breaking down the material to powder form increases its range of applications.

The usage of metallic powder can be traced back to as early as 3000 B.C. in Egypt [8]. Early findings of sponge iron weapons and tools have been made in India and Africa. Over the years, powder metallurgy has undergone significant improvements, and by 1900, notable progress had been made in both manufacturing and research. The introduction of cemented carbides for cutting tools in the 1920s greatly expanded capabilities in the industry. Several powder processes, including hot isostatic pressing, spray forming, and binder jetting, were developed. At the turn of the century, additive manufacturing processes began to evolve and eventually became suitable for commercial use. These technological improvements also enabled the production of more complex designs.

Powder metallurgy is used to enhance the material properties, giving better control of the distribution of alloying elements, and accelerating the reaction between constituents due to the large surface area of powders. In production, the usage of powder allows for the direct creation of precise shapes at lower temperature requirements than, for example, casting, reducing both waste and energy usage [9]. It is widely used not only in the automotive industry [10], but also in the MedTech and aerospace industries [11]. For some materials, such as hard metals, melting is not practical since, in addition to being very costly, the high temperatures would also damage the desired microstructure.

There is a distinct difference between the compaction and sintering of steel and of cemented carbide. During the sintering of cemented carbide, the metallic binder is wetting the carbides. The sintering temperature is also often above the melt temperature of the binder, including a liquid phase sintering stage. As the temperature increases, rearrangement and diffusion make the powder blanks shrink significantly, and theoretically, full density can be reached to achieve the best quality product. In steel sintering, there is no binder, and in the compaction stage, the powder blank can reach a higher relative density, but the volume change during sintering is not as significant [12].

2.2 Cutting tools

Cemented carbides, or as more specifically used in this thesis, Tungsten carbide with Cobalt, are typically used for cutting tool inserts. The very hard carbide enables it to cut through softer working materials, while the tough Cobalt makes it harder for cracks to initiate and grow, increasing the life span. Depending on the applications, the amount of binder and/or the grain size of the carbide, the material can be tougher or harder [13]. During sintering, the Cobalt wets the Tungsten carbide and sinters together, resulting in significant shrinkage of the tool. After sintering, the cutting tool is often blasted and coated to increase its life span and hardness. The shape of the cutting tool varies considerably depending on the application. It is therefore necessary to have a large variation of cutting tool geometries to optimize both machining performance and the life expectancy of the tool, depending on the operation [14].

2.3 Material and powder compaction

The powder used in this thesis is 10 wt.% of Co, 0.5 wt.% of Cr, 2 wt.% of PEG, and the rest, 88 wt.% WC, which is ball-milled together to achieve a mean grain size of 1 μm. Multiple studies have investigated the manufacturing of WC-Co powders and their effect on shrinkage during sintering. The surface energy acts as the driving force, meaning that smaller powder particles will accelerate the sintering process [8]. Besides particle size, the distribution of particle sizes also affects shrinkage [15]. The ball-milling process can influence sintering through various factors, including whether WC and Co particles are milled together [16], the type of milling [17], milling speed, and the presence or absence of a liquid [18]. The manufacturing of WC grains also influences the grain shape and strain rate during sintering [19]. During compaction, both the friction between powder particles and between the press die and the powder will affect the density gradient after compaction. The powder is mixed with a pressing agent, PEG, which influences powder formation [20]. The mixture is then spray-dried into granules of 100 μm. The properties of the powder are affected by humidity and the time since the powder blank was created, and incorrectly storing the powder over time can influence the Carbon level in the final product. In paper **B**, it is shown how PEG protects the powder from these environmental effects.

Different pressing techniques can be used depending on the purpose. In this thesis, the following methods were used.

- Isostatic pressing, where a larger mass of powder is pressured simultaneously and equally in all directions [21]. This reduces the density gradients since there is no friction from a pressing die. Under most circumstances, the mass needs to be cut to the desired shape after pressing, which could be a risk with the sensitive powder blank.
- Single and double action pressing, which is illustrated in Figure 3. When pressing, there is an upper and a lower punch that can both move, along with a fixed wall die. In single action pressing, only one of the two punches moves, while in double action pressing, both the upper and the lower punches are moving. Single action pressing leads to a higher relative density variation in the sample than if double action pressing were used [8]. An asymmetrical movement in double action pressing can also be used to correct the distortion effect from sintering.

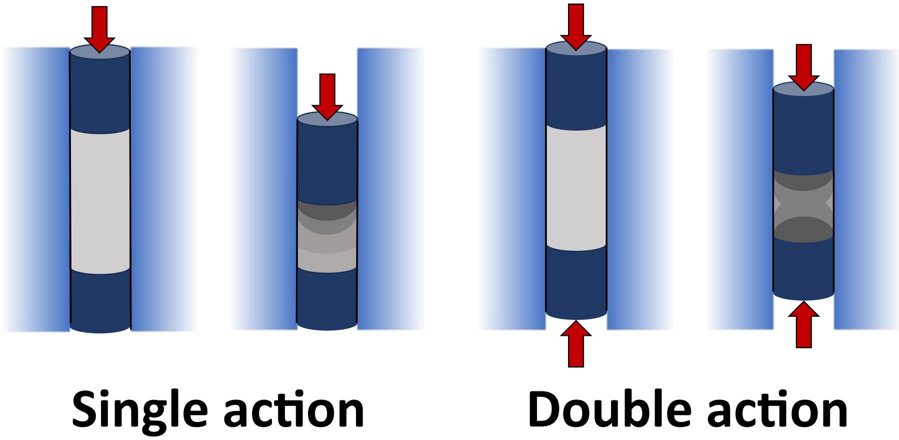

Figure 3. Illustration of single and double action pressing.

2.4 Sintering

Sintering occurs when the powder blank is heated, and the powder particles fuse together. With an increase in temperature, the atoms will move and bond the particles to reduce the total surface energy. Higher temperatures increase movement, accelerating the sintering process. The sintering process can vary depending on the material, temperature, and different environmental aspects. The schematic of the microstructure of WC-Co powder during sintering is illustrated in Figure 4, and the various stages are described as follows:

- The heating starts, and the PEG begins to evaporate. To successfully remove all PEG during sintering, which otherwise would be trapped and affect the quality of the cutting tool, a debinding stage is used. The PEG evaporates in stages and is presumed to be gone at around 300 °C. During the debinding stage, a small flow of hydrogen is used, and an isothermal holding is performed before increasing the temperature in vacuum.
- In the early stage of sintering, the densification is relatively low. Cobalt is wetting the Tungsten carbide and building bonds with other Cobalt particles. The main driving forces are surface diffusion and particle rearrangement.
- Around 1100-1300 °C, volume diffusion of Cobalt and rearrangement will contribute to a significant amount of densification. Cobalt has not melted but is softer and moves around with the Tungsten carbide to dissipate

surface energy. The mean grain size starts to increase, first from the dissolution of fine WC in the binder, and at higher temperatures, by grain growth [22].

- The liquid phase appears around 1300-1350 °C for WC-Co powder, when the Cobalt starts to melt. Now, the main part of the densification has already occurred, and Cobalt is filling the last voids. A longer time at this stage will result in significant grain growth, which will influence material properties.

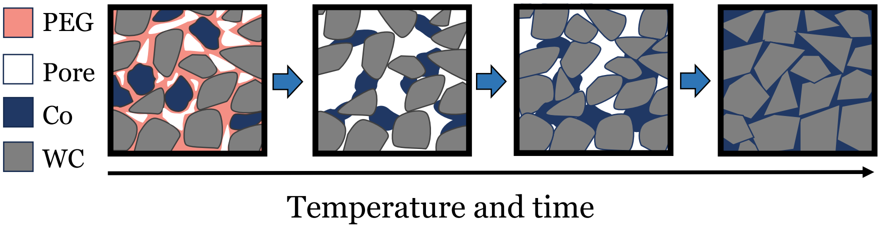

Figure 4. Schematic illustration of the microstructure of WC-Co sintering.

3 Experimental methods

3.1 Dilatometer

A dilatometer is, in essence, a small sintering furnace where shrinkage during sintering can be measured. This is typically done by placing the specimen between the wall and a rod. A small force is then applied to the rod, which follows the expansion and shrinkage during the heating cycle. The size of the specimen is limited, and only a certain interval of shrinkage can be captured. Because of the small size of the specimen, the gravitational effect is negligible compared to the sintering stress. Since the specimen is pinned by the push rod, frictional effects are also minimal. Therefore, the only considerable external force that can influence the shrinkage during sintering is the pinning force. The dilatometer experiments used in Papers **A** and **B** use a force of 0.45 N, and in Paper **C,** it was lowered to 0.2 N. There was no noticeable difference between the experimental results, meaning that the dilatometer force does not influence the shrinkage of the powder used. During the dilatometer experiment, the rod movement is registered, and the temperature is measured. Figure 5 shows the results from a typical dilatometer experiment. Thermal expansion will take place in the experiment and should be subtracted from the measured results to retrieve the relative density.

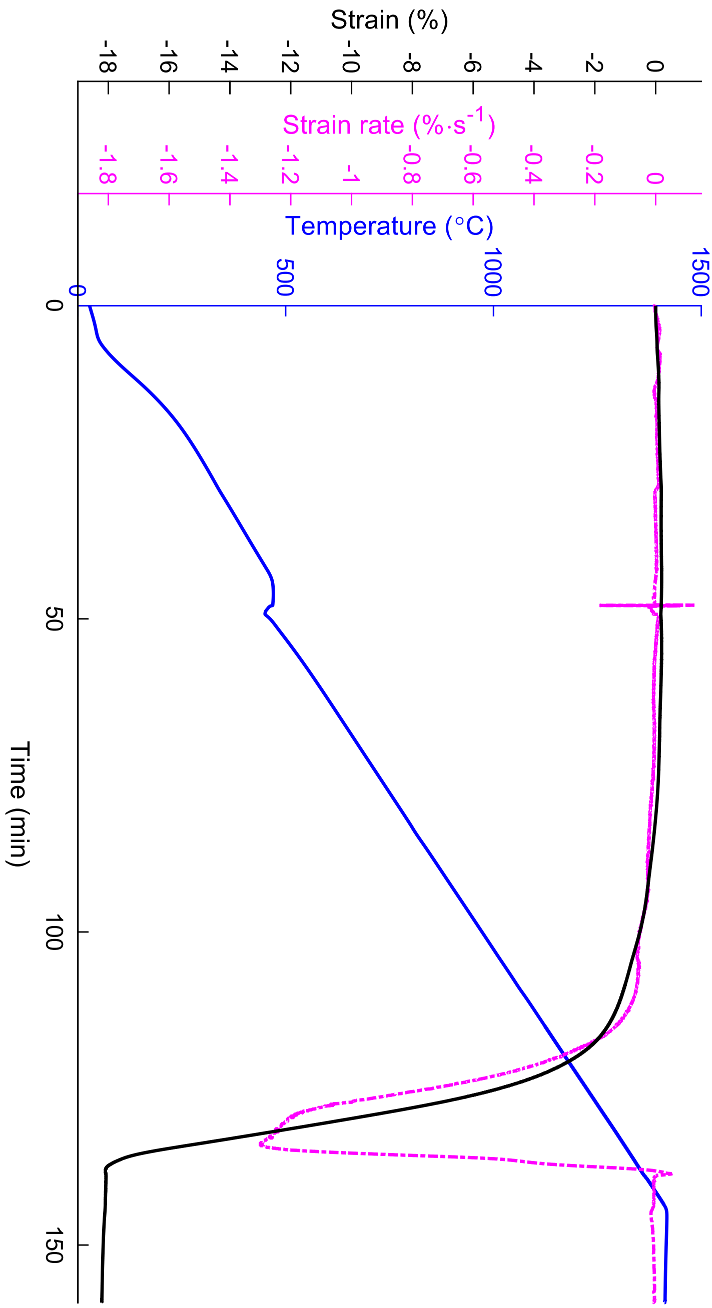

Figure 5. Strain, strain rate and temperature measured in the dilatometer.

The dilatometer used in all experiments is a Netzsch DIL 402C, and can be seen in Figure 6. The chamber is a small compartment where hydrogen is used to remove the evaporated PEG during the debinding stage. Here, the Carbon level is not controlled, and because of the small volume of the chamber, the environment is assumed to be homogeneous during the sintering cycle.

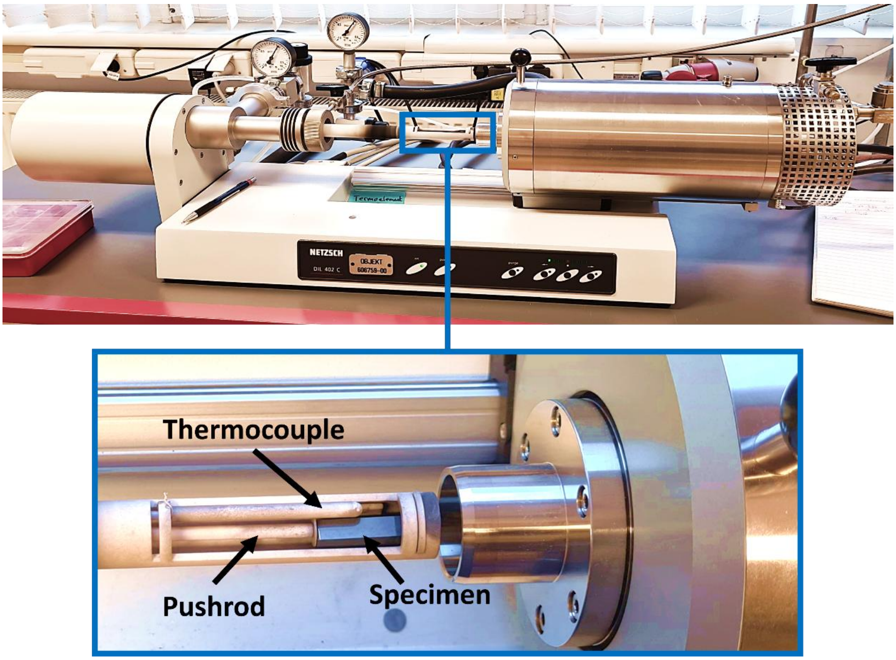

Figure 6. Overview and details of the Netzsch DIL 402C dilatometer used in this thesis.

3.2 Sintering furnace

Similar to the dilatometer, the sintering furnace operates in a vacuum atmosphere with a hydrogen flow during the debinding process. The furnace is considerably larger than the dilatometer chamber, which causes temperature changes to take more time. It is crucial to ensure that the entire furnace reaches a certain temperature or condition. Therefore, the typical sintering cycle is longer than what is needed in a dilatometer. There could also be fluctuations within the furnace, and conditions may vary depending on the specimen's placement, such as whether it is on the top or bottom. Additional Carbon can be used if necessary. In the sintering furnace, the powder blanks are placed on sintering plates, and the friction between the plates and specimens may influence the final sintered product.

A large number of samples can, of course, be sintered at the same time in the sintering furnace with less restriction on size and shape than the dilatometer has. The temperature is registered during the sintering cycle to ensure the right conditions, but the shrinkage cannot be measured. Therefore, the experiments can only be evaluated after the cycle is completed, using essentially finalized products.

4 Constitutive modeling

4.1 Sintering of cemented carbide

Simulation of the sintering process can provide information on how the shape changes occur during the sintering cycle and what effect alterations to the cycle might have. It is difficult to predict the behavior of a single particle, but a mass of particles tends to behave more uniformly. The constitutive model used in this thesis treats the powder as a continuum, and by employing a viscous model, it captures the effects of temperature and time in the sintering simulation.

Ideally, there should be a constitutive model for which adjustable parameters can be calculated, requiring very few experiments. However, relating constitutive formulations to specific physical properties of the powder mixtures is challenging and requires numerous experiments.

Multiple constitutive models have been derived to describe shrinkage during sintering of hard metals [23-28]. Brandt's phenomenological model [26] was used as a base to model sintering. Without external loading, the plastic strain rate is formulated as $\dot{\varepsilon}_m^s = \frac{-\sigma^s}{3K^v}$. Here, the sintering stress is the driving mechanism of densification, which depends on the surface energy, the particle size, and the relative density. When the sintering stress goes to zero, the pores vanish. The viscous bulk modulus, K^v, increase with higher density and includes factors such as diffusion and particle rearrangement.

4.2 Reverse engineering

During the sintering process, many factors coincide, and the influence each factor has is hard to predict. Therefore, a reverse engineering approach has been used. Thus, the material parameters can include multiple factors, and fewer experiments are needed to characterize the full model.

The sensitivity analysis is done by allowing a variation of the adjustable parameters and using the Monte-Carlo method [29] to retrieve a random distribution. By analyzing the simulation with the Sobol method [30], the sensitivity of the parameters can be evaluated both overall and for a specific phase of the sintering process. In other words, the parameters for which small changes influence the shrinkage curve will have a higher Sobol index and need to be carefully fitted, while a parameter with a lower Sobol index can remain constant.

In the different stages of sintering, certain parameters will be dominant and therefore easier to match. The sintering process for WC-Co is complex, and history effects, such as heating rate, will influence the densification during isothermal holding [31]. To make the cycle robust to changes in the sintering cycle, multiple variations of heating and isothermal holding are needed to determine the constitutive parameters.

5 Key results and conclusions

5.1 Paper A - Sensitivity analysis

A sensitivity analysis has been conducted for the full Brandt model. Several of the adjustable parameters have very small Sobol indices, meaning that the value can change without influencing the densification process.

The sensitivity was also evaluated at different stages of sintering to understand the importance of not only obtaining a correct final result but also gaining insight into the sintering process. The model does not have the ability to capture the initial stage of sintering or the liquid phase with high accuracy.

5.2 Paper B - Debinding analysis

The debinding step was investigated, and the effect of having the debinding step separated from the sintering cycle was tested. When PEG is preserved in the powder blank, the specimen is more shielded from environmental effects. When the PEG is removed and not directly sintered, the Carbon level decreases, affecting both the shrinkage during sintering and the final microstructure.

5.3 Paper C - Full Constitutive model

The full sintering model is evaluated with experiments in both the sintering furnace and the dilatometer. With a few experiments using different sintering cycles, the constitutive parameters were determined in a robust way to be able to account for changes in the heating cycle. The method of determining the parameters from experiments is also described. The initial relative density before sintering influences the early shrinkage. Even before sintering starts, some thermal particle movements occur in the lower initial density specimens, and in the initial stage of sintering, early rearrangement occurs. When the Cobalt starts to melt, an additional diffusion mechanism is introduced, which describes the accelerated shrinkage occurring. The deviatoric influence was investigated and compared to bending experiments, which could be captured well with a simple description of the viscous Poisson’s ratio.

5.4 Paper D - Simulations and experiments on cutting tools

To validate the model, simulations of the compaction and sintering were paired together and compared to experiments. The density gradient and the mean initial density before sintering varied with different press heights. The sintering model could reliably capture the shape change and densification during sintering with different temperature cycles and with different maximum temperatures.

6 Points of perspective

Coupling the compaction and sintering steps is effective, and the developed model accurately predicts the final product. In order to further enhance accuracy, especially in predicting distortion, optimization can be carried out on both processes together, examining the effect of the friction coefficient during compaction on distortion after sintering.

It is difficult to evaluate the compaction and sintering simulations separately. To get an understanding of the density distribution in the samples, 3D neutron imaging can be used, as done by Staf *et al.* [32], to confirm intermediate results before and after sintering to different densities.

Through further experiments, such as altering the powder size and the amount of binder, the constitutive parameters can be linked to physical factors. Variations such as the location in the furnace or in material composition within the part, for example, functional grading [33], can then be estimated through simulation. This would assist in future cutting tool development and could also be utilized to improve product quality.

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