Optimization of the pressing process of triangular shaped cutting tool inserts

Author: Mauro Milani
Supervisor LNU: Andreas Linderholt
Examiner, LNU: Andreas Linderholt
Supervisor Sandvik Coromant: Sirwan Safary

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Linnaeus University, Faculty of Technology
Abstract

Pressing of metallic powders is a manufacturing process widely investigated in the research field and in the industry. This thesis project is focused on optimizing the pressing process of cemented carbide powder utilized for the production of triangular shaped cutting tool inserts. In particular, the filling of powder into the die cavity was investigated with respect to different pressing parameters. The aim of the project was to obtain a uniform density distribution of the powder into the die cavity, and hence to reduce the variation of the height of the insert obtaining more precise dimension of the latter.

The tests were carried out at the Sandvik Coromant production department which is the creator of the project. The optimization of the pressing process was performed according to the Design of experiments theory. The dynamic of the sintering process was also investigated.

The results showed a significant improvement in the filling of the die cavity and a significant decrease of the variation of the height of the inserts. The new insert obtained has more precise dimensions and is able to meet the more demanding requirements of the customers. The results achieved are directly applicable to a larger number of products, and indicate the direction to follow for further development of the manufacturing process.

**Key words:** Powder metallurgy, Design of experiments, Cutting tool inserts, Cemented carbide.
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Mauro Milani – Master Thesis in Mechanical Engineering
1. Introduction

Cutting tool inserts are widely studied components of machine tools, they are the actual interface between the machine tool and the workpiece which has to be shaped.

Tool machining is a manufacturing process which produces high precision products, for instance a crankshaft or a gearwheel, therefore it requires high dimensional precision of the tool machine components [1]. The dimensions of the cutting tool inserts are an important factor of this manufacturing process, hence more precise dimensional tolerances of the inserts are demanded.

This study is focused on increasing the quality of the triangular shaped cutting tool inserts used in turning, and contribute to the technological development of the manufacturing process.

1.1 Background

This study focuses on the height of the cutting edges of the triangular shaped cutting tool inserts used in turning. Figure 1 shows the insert selected for this study.

![Figure 1. Triangular shaped cutting tool insert utilized in turning (TNMG) [2].](image)

Since the insert is triangular, it has three edges, and their heights have to be as equal as possible. In order to reduce the variation of the heights of the three cutting edges of the inserts, the manufacturing process in which they are produced has to be analyzed. This process consists of pressing and sintering of metallic powders, which is the process used to form solid parts from powders. In this process, firstly the metallic powders are filled in a die and pressed in a geometric form called “green compact” [3]. Then the green compact is inserted in a furnace where the sintering occurs due to the increase of temperature into a specific range for a certain amount of time.

The case of this study is focused on the pressing operation, with respect to the parameters which affect it. By changing these parameters, different density
distribution of the powder in the green compact can be obtained [4]. During sintering, shrinkage of the green compact occurs with different magnitude depending on the distribution of the density of the powder; lower density leads to greater shrinkage while higher density leads to lower shrinkage of the green compact. This difference in shrinkage leads to different dimensions of the sintered insert known as a “blank”. An issue caused by the variation of the height of the insert is related to the knowledge of the position of the contact point between the insert and the workpiece during the machining operation. Reducing the variation of the height of the insert is important in order to enhance the precision of the machining operation. Another issue caused by the variation of the height of the blank is the inaccuracy of the brushing operation to which the blank is subjected to remove the debris on the edges. The variation of the heights of the blank does not allow to achieve a uniformly brushed profile. Finally, reducing the variation of the height of the insert means enhancing the quality of the product.

1.2 Aim and Purpose

The aim of this study is to optimize the pressing operation with respect to different parameters in order to reduce the variation of the heights of the three cutting edges of the insert.

The purpose is to optimize the filling of powder into the die in the pressing process of triangular shaped inserts used in turning. “Design of experiments” (DoE) has to be used to optimize the filling and pressing parameters.

1.3 Hypothesis and Limitations

The parameter analyzed are three: the speed of the filling shoe, number of shakes of the filling shoe over the die and the die orientation with respect to the filling shoe motion. The hypothesis of this study is that optimizing the parameters selected leads to that a more uniform powder density distribution into the die cavity is obtained, which in turn leads to a reduction of the variation of the heights of the three edges of the insert.

The limitation of this study is the fact that not all the parameters affecting the pressing process are tested. Only the influences of three parameters, which affect with a higher rate the pressing process as demonstrated in previous tests carried out at Sandvik Coromant, are studied.

1.4 Reliability, validity and objectivity

The tests were carried out in the company site with the pressing machines utilized for the production of the inserts. Hence, the tests match exactly the actual production process. However, the experimental plan was performed...
following the “Design of Experiments” theory which proposes different analytical models, thus different experimental plans can be performed with the same set of parameters. In this study only one analytical model was utilized.

Furthermore, validity and reliability of the data obtained are ensured by repeating the tests with a certain combination of parameters, and guarantee the correctness of the tests procedure. All the tests were performed in the same pressing machine by the same operator in order to eliminate the variability of the process which can be generated by different pressing machines and different operators. Moreover, the reliability of the measurement system was verified performing a gage R&R analysis in order to quantify the measurement system variation.

1.5 Data confidentiality

The data presented in the results chapter are fictive because the original data were classified as confidential information of Sandvik Coromant and the publication is restricted. Furthermore, all the measurements of the inserts carried out are not reported in the appendix.
2. Theory and literature review

2.1 Cemented carbide

2.1.1 Cemented carbide characteristics

The material which constitute the cutting tool inserts studied in this project is cemented carbide. Cemented carbides constitute a class of composite materials composed of hard carbide particles bonded together by a metallic binder. The amount of carbide phase is commonly within 70-97% of the total weight of the composite and its grain size is within 0.4 µm and 10 µm. The most important characteristics of cemented carbides include:

- High compressive strength but moderate tensile strength,
- High hardness (90 to 95 HRA),
- Good hardness at elevated temperatures,
- High wear resistance,
- High thermal conductivity.

A widely used cemented carbide in the tool manufacturing industry is composed of tungsten carbide particles (WC) which constitute the hard phase, and the cobalt (Co) as a binder phase. Figure 2 shows a scanning electron microscope (SEM) micrograph of the microstructure of cemented tungsten carbide.

![Figure 2. Microstructure of cemented tungsten carbide [5].](image)

The grades with a cobalt content between 10-20% of the weight and grain sizes between 1-5 µm, are characterized by high strength and toughness, combined with good wear resistance. The grades with a cobalt content
between 3-15% and grain sizes smaller than 1 µm, are characterized by high hardness, high compressive strength, and extraordinarily high wear resistance.

The toughness of the material increases with increasing binder content (Cobalt), and with increasing of the tungsten carbide grain size. However, the toughness of this material is not as high as other metallic materials; it is comparable to hardened steel. Cemented carbide is classified as a brittle material, since almost no plastic deformation takes place before fracture. It is possible to achieve a high wear resistance only if the demand of high toughness is reduced and vice versa [6].

2.2 Powder metallurgy

The fundamental powder metallurgy technique to manufacture ceramic and metal parts include the following steps:

- Produce metallic powders,
- Mixing or blending,
- Compaction by pressing,
- Sintering.

The most important benefits of powder metallurgy are the possibility to model materials which are difficult to melt in the desired shape without melting the raw materials, and components with controlled porosity can be manufactured, for instance porous bearings. Powder metallurgy processes are efficient from the material utilization point of view (95% of the material utilized), and it consents mass production of elaborated parts such as gears or cutting tool inserts. At the moment 15% of the powder metallurgy total global market is constituted by carbides utilized to produce cutting tool inserts. However, there are some constraints of powder metallurgy, for example high cost of powders, high cost of the tools, porosity variation, and design factors such as extractability of the part from the die. Regardless these drawbacks, powder metallurgy is comparable with fabrication processes such as casting and machining with respect to part complexity and precision, and it has a growing niche market for specialized parts.

2.2.1 Powder compaction

Powder compaction enables the production of the basic shape of a part by means of partial densification of powders with an external pressure applied. Figure 3 presents two typical compaction configurations, single-action compaction, Figure 3(a), and double-action compaction, Figure 3(b). Single-action compaction is utilized for rather simple shapes and implies uniaxial
pressing of powders in a die utilizing a single punch. When using double-action compaction, the density of the compact is more uniform because two movable punches apply pressure from opposite directions. If the part has a higher complexity, additional punches can be added to obtain a more uniform density.

![Single and Double Action Compaction](image)

Figure 3. (a) Powder compaction with a single punch (b) Powder compaction with a double-action press [7].

In double-action compaction the lowest densification and lowest pressure occur at the mid-plane of the powder agglomerate and the highest densification and highest pressure at the extremity. Nevertheless, due to the friction of the particles itself and the friction with the die wall, also in double-action compaction a non-uniform density may result in the compact. Furthermore, since the central part of the compact has a higher porosity, the shrinkage is greater compared to the extremity regions and the compact can become uneven. “This variation can be reduced by utilizing the advanced net-shape powder-forming processes such as powder injection-moulding, gel-casting, hot pressing, and shock consolidation” [3].

The procedure of compaction consists of: die filling, first pressing stroke and de-airing, second pressing stroke and finally part ejection. De-airing eliminates the air which may interfere with inter-particle bonding in the second stroke, which actually generates the compact. The air entrapped in the compact increases the spring-back on the ejection of the part, enhancing the possibility of defects and cracking of the green compact. However, some spring-back will always be present due to the elastic energy stored in the powder compact which is released during the part ejection, causing a slight increase of the compact dimensions. Practically, in order to separate the part from the punch during ejection, a differential spring-back between the part and the punch is needed, usually 0.75% of the linear spring-back. Furthermore, a fast compression and a fast decompression may generate defects in the green compact. Nevertheless, a longer lapse of time at the peak compaction pressure decreases the risk of defects such as lamination because a more considerable mechanical bond formation and plastic flow occur.
The punches and the dies utilized for powder compaction are constituted of hardened tool steel, and carbide inserts are used to further reduce the wear of dies and punches. The clearance within the punch and the die is normally between 10-100 µm, and the die wall is tapered to facilitate the ejection of the part. The interval of time for pressing is in the range of a fraction of a second for smaller parts to a few minutes for bigger parts. In pressing of metallic powders a rate of production of 6 to 15 parts per minute can be applied in the industry. The range of variation of pressure is wide, usually within 20-150 MPa but it can reach 700 MPa. The life of the die is conditional to the compaction pressure, hardness of the powder and presence of lubrication, and it can be over one hundred thousand parts pressed per die.

Powder metallurgy process has some advantages compare to other processes such as die-casting and stamping. The thickness of parts made of metal powder can vary while the thickness of the sheet metal is constant. Furthermore, during the design phase, the weight of parts made of powder metal can be reduced without decreasing part functionality.

2.2.2 Dynamics of powder densification

When an external pressure is applied to a powder compound, its density increases by means of particle deformation and fracture. However, the density of the compacted part is smaller than the theoretical density of the material with no porosity, and a certain level of porosity is still present in the structure. This porosity decreases due to sintering, leading to almost fully dense material [8]. Experimental data of the influence of compaction pressure on the density of the green compact of alumina are shown in Figure 4.

Figure 4. Semi-logarithmic plot of percent compact density as a function of punch pressure during uniaxial compaction of alumina showing three distinct stages of powder compaction [3].
The data of the pressure on the x-axis are plotted in a logarithmic scale. It is possible to identify three stages of compaction. In stage I the pressure is small and due to sliding and reordering of particles, a small densification takes place. In stage II the pressure is increased and the particles in the powder undergo deformation and fracture, leading the porosity to decrease and the density to increase. The density of the compact $\rho_c$ becomes greater, linearly, with the logarithm of the pressure ratio $P_a/P_y$, as stated by the following equation:

$$\rho_c = \rho_f + n \ln \left(\frac{P_a}{P_y}\right) \quad (I)$$

where $\rho_f$ is the density before the compaction (fill density), $P_a$ is the pressure applied, $P_y$ is the yield strength of the powder material and $n$ is a compaction constant. The density of the powder material before the compaction determine the volume occupied by a certain quantity of powder in the die. When the fill density is high, the green compact is characterized by high density, no defects, and high sintered density. The ratio $\rho_f/\rho_c$ is defined as the compact ratio. The logarithmic component lead to a linear relationship of the compact density $\rho_c$ as a function of $\ln (P_a)$ which is a feature of the stage II of compaction. In stage III the pressure increase largely, leading to a significant decrease of the porosity, but with further increase of the pressure applied, the compact density does not increase and settle to constant trend. Figure 5 shows the three different compaction stages of the powder.

![Diagram of compaction stages](https://example.com/diagram.png)

**Figure 5.** “Behaviour of powders during compaction in the three stages displayed in Figure 4 [3].

During stage I, at low pressure, there is an insignificant increase in density due to the rearrangement of the powders. During stage II, at middle pressures,
the powders deform and fracture leading to a linear increase in the density with pressure, and the porosity between the particles decreases as well as the porosity within single particles. During stage III the porosity does not decrease anymore, and significantly fine pores are present in the compact, which are mostly eliminated during sintering. The densification is dependent to the hardness of the powder material when the pressure applied is constant. Several empirical equations were formulated in order to determine the effect of compaction pressure on the characteristics of powder compacts [3]. For instance, the influence of the pressure applied on the green compact density, strength and porosity is given by:

\[ \ln \varepsilon = B - CP \]  \hspace{1cm} (2)  
\[ \sigma = B' \sigma_0 P = KP \]  \hspace{1cm} (3)  
\[ \sigma = \sigma_0 \rho^m \]  \hspace{1cm} (4)

Here, \( \rho \) is the fraction density, \( \varepsilon \) is the fraction porosity, \( \sigma \) is the strength of the green compact, \( P \) is the compaction pressure, \( \sigma_0 \) is the strength of wrought material, and \( C, K, B, B', m \) are experimental constants. Equation (2), (3) and (4) can be rearranged in a linear form in order to determine the empirical constants. For instance, equation (2) becomes:

\[ \ln(1 - \rho) = B - CP \]  \hspace{1cm} (5)

Which is a linear relationship of \( \ln(1 - \rho) \) and the pressure applied, \( P \). In the same way, equation (4) becomes:

\[ \ln \sigma = \ln \sigma_0 + m \ln \rho \]  \hspace{1cm} (6)

The transmission of pressure through powder layers was studied utilizing beads. As Asthana, Kumar & Dahotre state: “Model studies using compaction of glass beads have demonstrated that small granules experience a higher level of stress during compaction and break down at a lower stress than large granules. As a result, large granules tend to persist in the compact even at high applied pressures” [3].

Furthermore, the pressure transmitted from the punch to the powder compact, is influenced by the friction between the particles and the friction at the die wall. Moreover, they affect the pressure necessary to eject the compact from the die, but this pressure can be controlled with the aid of lubricants. Figure 6 shows the plot of the shear force generated by the ejection of the part in lubricated and un lubricated die. Under lubrication conditions the pressure necessary to eject the part from the die decreases, and the stick-slip motion is prevented which avoid significant force variations and risk of surface cracking.

The surface roughness of the particles during sliding generates a resistant force which opposes to the sliding motion and to the redistribution of the powders. Nevertheless, rolling and group movement of the particles decrease the resistance to compaction.
The magnitude of shear force as a function of die displacement during ejection of pressed alumina compacts from lubricated and unlubricated dies [3].

The surface roughness of the powder depends on the type of the material and from the fabrication method of the powder. For instance, layered silicate minerals have low surface roughness, smaller than 100 nm, while crushed ceramic minerals have high roughness, bigger than 1 µm. In the same manner, atomized metal droplets are subjected to rapid cooling and solidification, and have surface dendritic morphology which enhance surface roughness.

The transmitted pressure is decreased by the formation of agglomerated powder particles which thus reduce the densification rate. Fine powders agglomerates rapidly due to the electrostatic forces generated from absorbed surface ions and due to the presence of the weak Van der Waals forces. Moreover, strong forces between the particles due to the capillary forces of a wetting liquid, called binder, contribute as well to the powder agglomeration.

2.2.3 Analysis of pressure distribution in uniaxial compaction

The force of friction acts against the transmission of the applied pressure and this interaction determines the rate of densification of the compacted powders. The pressure distribution in a cylindrical die during uniaxial compaction, considering as only resisting force the friction at the die wall, was analyzed by Asthana, Kumar & Dahotre [3] as follows. Figure 7 shows a schematization of the forces acting on an infinitesimal element of compressed powders subjected to the pressure $P_a$. The difference of pressure along the disc of thickness $dH$ situated at a depth $h$ is $dP = P - P_b$, where $P$ and $P_b$ corresponds to the pressures at the top and the bottom surfaces of the element. The friction force is $F_f = \mu F_n$, where $F_n$ is the force normal to the die wall, and $\mu$ is the friction coefficient between the powders and the die wall.
The static equilibrium of the forces along the cylinder axis results in:

\[ \Sigma F = 0 = AdP + \mu F_n \quad \text{or} \quad dP = -\frac{\mu F_n}{A} \quad (7) \]

where \( A \) is the cross sectional area of the die \( A = \pi D^2/4 \) and \( D \) is the diameter of the die. Previous studies [3] revealed that the pressure normal to the die wall is a constant fraction of the pressure along the axis of the cylinder at any plane, and the ratio is called \( Z \). Furthermore, \( F_n = \pi D dH Z P \) \( (8) \)

Hence, \( F_f = \mu F_n = \mu \pi D dH Z P \) \( (9) \)

By substituting equation (9) in equation (7), the result is:

\[ dP = -\frac{4\mu \pi D dH Z P}{\pi D^2} = -\frac{4\mu Z P dH}{D} \quad (10) \]

Equation (10) is integrated over the interval \( P = P_a \) at \( h = 0 \), and \( P = P_x \) at \( h = x \), thus

\[ \int_{P_a}^{P_x} \frac{dP}{P} = -\frac{4\mu Z}{D} \int_0^x dH \quad (11) \]

Therefore,

\[ \ln \left( \frac{P_x}{P_a} \right) = -\frac{4\mu Z x}{D} \quad (12) \]

or,

\[ P_x = P_a e^{x \left( -\frac{4\mu Z x}{D} \right)} \quad (13) \]

Hence, the pressure transferred within the powder layer decreases exponentially with increasing depth. Furthermore, \( P_x \rightarrow 0 \) as \( x \rightarrow \infty \), which is
due to the fact that the assumption made during the derivation carried out above consider an infinite cylinder with negligible end effects. In the case of double-action compaction, equation (13) is still applicable, and the distance \( x \) is the distance of the nearest punch across the midplane. In Figure 8 it is possible to see the trend of the transmitted pressure into the compact in the case of single-action compaction and double-action compaction.

**Figure 8.** Calculated pressure transmission ratio \((P_x / P_a)\) during uniaxial powder compaction using single- and double-action press. The calculations are based on the friction coefficient, \( \mu = 0.2 \), and the radial-to-axial pressure ratio, \( Z = 0.4 \) [3].

### 2.2.4 Pressure distribution in an annular cylinder

The analysis of the pressure distribution can be carried out also for the case of an annular cylinder, constituted by the outer diameter \( D \), and the inner diameter \( d \). In this case, the die wall friction must be recalculated considering that it acts over two curved surfaces. The force normal to the die wall is:

\[
F_n = \pi D d H Z P + d \pi d H Z P = (D + d) \pi d H Z P \quad (14)
\]

Therefore, the friction force at the die wall is:

\[
F_f = \mu F_n = \mu (D + d) \pi d H Z P \quad (15)
\]

The static equilibrium of the forces along the axial direction gives:

\[
dP = -\frac{F_f}{A} \quad (16)
\]

Substituting equation (15) in equation (16) gives:

\[
dP = -\frac{4\mu \pi (D + d)d H Z P}{\pi D^2 - \pi d^2} = -\frac{4\mu Z P d H}{D - d} \quad (17)
\]

Equation (17) is integrated over the interval \( P = P_a \) at \( x = 0 \), and \( P = P_x \) at \( x = x \), thus:
\[ \int_{P_a}^{P_x} \frac{dP}{P} = -\frac{4\mu Z}{D-d} \int_0^x dH \]  

(18)

By performing the integration and rearranging,

\[ P_x = P_a \exp \left( -\frac{4\mu Z x}{D-d} \right) \]  

(19)

In the case of a thin ring of powder the pressure decreases faster than in a thick ring of powder, thus when the thickness of compact wall decreases, the pressure transferred decreases as well. Furthermore, in the case of double-action compaction, equation (19) is still applicable, and the distance \( x \) is the distance of the nearest punch across the midplane in the powder layer.

### 2.2.5 Die filling

In the production of powder compacts, a uniformly distributed bulk density of the powder into the die is a desirable condition. Inhomogeneity may generate problems such as distortion, cracking, strength decreasing and non-uniform shrinkage within the part, which may generate the dimension of the part to exceed the dimensional tolerances.

The general system utilized for die filling consists of a bottomless box feed shoe which is pressed onto the die plate and slides over the open die, and a hopper from which the powder is fed by means of the gravity into the feed shoe. Once the die is filled, the feed shoe is pulled back to the starting position. The feed shoe and tool movements can be controlled to realize two different methods of die filling: “gravity filling” and “suction filling”. These two methods are shown in Figure 9.

![Figure 9. Die filling methods used in axial powder pressing: (a) suction filling (b) gravity filling [7].](image-url)
Furthermore, filling depends on the filling shoe velocity, with a critical fill shoe velocity \( v_{\text{crit}} \) determined experimentally for each type of powder, for instance hard-metal and ceramic [7]. At velocities lower than \( v_{\text{crit}} \), the die is completely filled, while at velocities higher than \( v_{\text{crit}} \) the filling is incomplete. Figure 10(a) shows the relationship between the feed shoe velocity and die filling.

![Graph showing fill ratio vs shoe velocity](image)

Figure 10. (a) Critical fill shoe velocity for iron powder (b) Schematic representation of nose flow and bulk flow [9].

At low velocity of the feed shoe, the so-called “nose flow” (Figure 10(b)) occurs and the die cavity will be filled mostly with powder from the top of the feed shoe. At high velocity or with small die opening, the powder drops from the bottom of the feed shoe by “bulk flow”. In the case of nose flow, when the tip of the nose passes the cavity, the latter is entirely covered and the air inside the cavity can escape only by penetrating through the powder. This generates a pressure which opposes the powder flow, in particular for fine and low-density powders. Before the tip of the nose passes the cavity, the air inside the die can exit from the opening ahead of the nose.

Critical velocities are notably higher in air than in vacuum, due to the air flow effects generated by entrapped air which influence the filling. Air entrapped in the die may generate low-density areas in the green compact. Particles on the surface of the nose, flow down in the cavity easily, while it is difficult for particles to detach from the bulk of the powder agglomerate because of interlocking between each other, which is enhanced when the feed shoe accelerates. However, the advantages of nose flow have to be balanced with bulk flow because only a small part of the die opening is utilized [4].

The uniformity of the deposition is conditioned by the filling conditions such as filling method and rate, feed shoe speed and acceleration, number of shakes of the feed shoe above the die cavity, powder level on the hopper as demonstrated in previous studies [10]. Furthermore, the powder feed system design has an influence, which includes the hopper size and the slope angle, tube size, feed shoe size and geometry; the die geometric characteristic are also important, for instance a triangular die cavity can be rotated with respect
to the direction of motion of the feed shoe leading to different powder flow in the die cavity and different density distribution.

Particle deposition in the die can be distinguished in three regions as shown in Figure 11.

![Figure 11. Three regions formed during particle deposition [4].](image)

The top region, i.e. the rolling region, is dragged by the feed shoe during the backward stroke and moves horizontally to the right side while the sliding region slides diagonally. The moving distances are the greatest in the center region of the die. The non-sliding region at the bottom of the die does not move.

The fill density at higher feed shoe speed is greater than at lower speed. Increasing the number of strokes of the feed shoes is of significance at high feed shoe speed since the holding time of the latter over the die has an important influence [11]. The die filling rate slightly decreases when the feed shoe velocity increases, due to the limited nose flow and more enhanced powder cohesion because of a longer acceleration period.

2.3 The sintering process

Sintering is a manufacturing process utilized to produce materials and parts with a controlled density from metal powders by applying thermal energy. Sintering is achieving more and more importance as new materials with increased properties are required by the market, and the science related to material processing is constantly developing.

2.3.1 Sintering introduction

Sintering has been studied scientifically starting from the mid-nineteenth century, leading to the fabrication of all types of components. The fabrication procedure of sintered parts is shown in Figure 12. In contradistinction of other manufacturing processes, different variables have to be considered for the realization of such parts.
For instance, in the step which involves shaping, it is possible to use die compaction, injection molding, slip casting or isostatic pressing etc., with respect to the shape and characteristics needed for the final product. Depending upon the shaping techniques adopted, also the sintered properties can differ significantly, leading to variations in the sintered microstructure [12].

The general aim of sintering is to produce components with repeatable and designed microstructure by controlling sintering variables, which means controlling grain size, distribution of phases and sintered density. A completely dense body with a fine grain microstructure is often desired.

2.3.2 Driving force and basic phenomena

The driving force which allows sintering to occur is the reduction of the total surface energy $\gamma A$, where $A$ is the total surface area of the compact and $\gamma$ is the specific surface energy. The equation of the reduction of the total energy can be expressed as:

$$\Delta (\gamma A) = \Delta \gamma A + \gamma \Delta A$$

The change in superficial energy ($\Delta \gamma$) occurs because of the densification, and the variation in interfacial area is attributable to grain coarsening. In solid state sintering, the superficial energy is associated to the substitution of solid-vapor interfaces by solid-solid interfaces. Figure 13 shows a schematization of the sintering phenomena, which consist of reduction of the total superficial energy through densification and grain growth. Traditionally, the total surface energy of the powder for sintering is 0.5-500 J/mole, and the powders size is within 0.1 and 100 µm. The surface energy of the powder is very small compared with the energy variation generated by oxide formation which is normally within 300-1500 kJ/mole. If this small quantity of energy has to be utilized to obtain the demanded microstructure, it is required to control the variables implicated in the sintering process.
2.3.3 Sintering variables

The most important variables which affect the attitude of a powder compact to be sintered and the sintered microstructure can be divided into two categories: process variables, related to the sintering conditions, and material variables, related to raw materials. This classification is shown in Table 1.

<table>
<thead>
<tr>
<th>Material variables</th>
<th>Process variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder:</td>
<td>Time, pressure, temperature, heating and cooling rate, etc.</td>
</tr>
<tr>
<td>Size, size distribution, shape, mixedness, agglomeration, etc.</td>
<td></td>
</tr>
<tr>
<td>Chemistry:</td>
<td></td>
</tr>
<tr>
<td>Homogeneity, impurity, composition, non-stoichiometry, etc.</td>
<td></td>
</tr>
</tbody>
</table>

The material variables include powder size distribution, powder size, powder shape, chemical composition of the powder compact, etc. These variables affect the powder sinterability and compressibility, and for powder compact containing at least three kinds of powders, the homogeneity is of primary
importance. The remaining variables are thermodynamic variables, as time, temperature, atmosphere, heating-cooling rate and pressure. However, in the actual process, pressure and sintering atmosphere are more important variables.

2.4 Design of experiments (DoE)

Experiments in manufacturing companies are carried out to improve the understanding and knowledge of different manufacturing processes. The experiments are often performed in a series of tests or trials which provide quantifiable outcomes. Understanding the process mechanism, the size of variability and its influence on the process is fundamental to continuously improve the quality of the process. In an engineering approach, experiments are often performed in order to explore, estimate or confirm. Exploration means comprehend the data from the process, estimation means determine how the process variables affect the output performance characteristic, and confirmation refers to verifying the predicted results achieved from the experiment.

A basic alternative approach to DoE is the One-Variable-At-a-Time (OVAT), where one variable at a time is varied while keeping all other variables in the experiment constant. This approach depends on guesswork, experience luck and intuition for its success. Furthermore, this method of experimentation implies the use of a large amount of resources to achieve a limited amount of data about the process. One-Variable-At-a-Time experiments may be inefficient, unreliable, consuming large amount of time and may lead to wrong optimum conditions for the process.

2.4.1 Introduction to DoE

Statistical methods are important in planning, performing and analysing data from engineering experiments. The Design of Experiment approach plays an important role when many variables affect a certain characteristic of a product, it allows to perform experiments which produce valid and reliable results in an efficient and economic manner. In a designed experiment, the process variables are changed in order to determine how the output performance is affected. The process variables affect the output performance with different magnitudes, some may have a strong influence while other may not have any influence at all. Thus, the aim of a planned design of experiment is to determine which set of variables in a process affect the output most, and determine the best levels for these variables to achieve the required output performance, as demonstrated in previous studies [13]. In real processes, some of the process variables can be governed without large difficulty but some of them are more difficult or expensive to control during standard production. Figure 14 shows the general model of a process or system.
In the scheme illustrated in Figure 14, the outputs are characteristics which are measured to evaluate the process and product performance. The controllable variables or factors denoted by $X_n$ can be varied without difficulty during an experiment and they have a key importance in the process characterization. Uncontrollable variables denoted by $Z_n$ are more arduous to control during an experiment, and they induce variability in the product performance.

### 2.4.2 Factorial design

Experiments often include the study of two or more factors, generally factorial designs are the most proficient for this type of experiments. In the factorial design, each trial or replication consist of all possible combinations of the levels of the factors under study. For instance, if factor $A$ has $a$ levels, and factor $B$ has $b$ levels, each replicate includes all $ab$ combinations. The effect of a factor is defined as the variation in response induced by a change in the level of a factor. This is usually called “main effect” because is generated by the primary factors of interests in the experiment. A complete replicate of a design with $k$ factors, each at two levels, is called a “$2^k$ factorial design”. A design with three factors, $A$, $B$, and $C$ each at two levels is called a “$2^3$ factorial design”. The eight experiment combinations can be geometrically arranged as a cube, are shown in Figure 15(a). Each factor has two levels “+“ and “−“, and an average value indicated with zero. The design consist of eleven runs as shown in the design matrix in Figure 15(b). The first eight are all the combinations of the three different factors at two levels, and the last three runs, located in the center point of the cube, are performed in order to determine the variance of the process.

![Figure 14. General model of process/system [14].](image)
2.4.3 Optimization: Response surface methodology

Response surface methodology (RSM), is a set of mathematical and statistical techniques adopted for the modeling and analysis of problems in which a response is influenced by many variables, and the aim is to optimize this response. For instance, suppose the aim of a study is to determine the levels of two variables, $x_1$ and $x_2$, which maximize the response $y$. The process is a function of the levels of the two variables:

$$y = f(x_1, x_2) + \epsilon \quad (21)$$

where $\epsilon$ corresponds to the noise or error observed in the response $y$. The expected response is denoted by $E(y) = f(x_1, x_2) = \eta$, thus the surface is represented by

$$\eta = f(x_1, x_2) \quad (22)$$

which is called “response surface”, and it can be represented graphically as shown in Figure 16, where $\eta$ is plotted versus the levels of $x_1$ and $x_2$. In order to assist the visualization of the shape of the response surface, the contours of the surface response are plotted. In the contour plot, lines of constant response are outlined in the $x_1 - x_2$ plane, and each contours coincide with a particular height of the response surface.

In many cases where response surface methodology is adopted, the form of the relationship between the independent variables and the response is unknown, hence the first step in RSM is to determine an acceptable approximation for the functional relationship between the independent variables and the response $y$. 

![Figure 15. 2^3 factorial design: (a) Geometric view (b) Design matrix](image)
Often in optimization, a second order polynomial in some region of the independent variables is used, represented by the following model:

\[
y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \tag{23}
\]

The eventual aim of RSM is to determine the optimum operating conditions, or to identify a region of the factor space in which operating requirements are fulfilled. Furthermore, the response surface analysis is carried out using a fitted surface, and if the latter is an adequate approximation of the response function, the analysis of the fitted surface will be roughly equivalent to the analysis of the actual system. The parameters of the model can be determined most efficiently if specific experimental designs are utilized to achieve the data. One experimental design commonly used for this purpose is the “face-centered central composite design (CCF)” shown in Figure 17. It consists of a \(2^k \) factorial with \(n_f\) runs, \(2k\) axial or star runs, and \(n_c\) center runs. The axial runs are added to incorporate the quadratic terms into the model and they are located on the centers of the faces of the cube. This type of composite design has been used in previous studies [16] in order to optimize the parameters affecting a manufacturing process.
2.5 Measurement system analysis: gage R&R analysis

Gage R&R (Gage repeatability and reproducibility) is the amount of measurement variation generated by a measurement system, which is composed of the measuring instrument itself and the operators using the instrument. A gage R&R study quantifies three factors:

- **Repeatability**: the ability of an operator to consistently repeat the same measurement of the same part, using the same measuring instrument, under the same condition;

- **Reproducibility**: the ability of a measuring instrument, used by multiple operators, to consistently reproduce the same measurement of the same part, under the same condition;

- **Overall gage R&R**: the combined effect of repeatability and reproducibility;

A gage R&R analysis is useful in order to investigate three main concepts, whether the system variability is small compared to the process variability, how much variability in the measurement system is caused by differences between operators, and whether the measurement system is capable of discriminating between parts [18]. In common gage R&R studies, ten parts are measured two times by three different operators. The analysis of variance (ANOVA) allows to identify the individual source of variation such as the part-to-part variation, the repeatability of the measurement, the variation caused by different operators and the variation due to part by operator interaction. The calculation of variance components and standard deviations using ANOVA is equivalent to computing variance and standard deviation for a single variable, but it allows multiple sources of variation to be singly quantified which are simultaneously affecting a single data set. When the variance components are calculated, the sums of the squared differences are computed for measurements of the same part, by the same operator etc. The
sums of squared differences for the part ($SS_{Part}$), the operator ($SS_{Op}$), repeatability ($SS_{Rep}$) and total variation ($SS_{Total}$) are given in equations (24-27):

$$SS_{Part} = n_{Op} \cdot n_{Rep} + \sum (\bar{x}_i - \bar{x})^2$$ (24)

$$SS_{Op} = n_{Part} \cdot n_{Rep} + \sum (\bar{x}_j - \bar{x})^2$$ (25)

$$SS_{Rep} = \sum \sum \sum (\bar{x}_{ijk} - \bar{x}_{ij})^2$$ (26)

$$SS_{Total} = \sum \sum \sum (\bar{x}_{ijk} - \bar{x})^2$$ (27)

Where $n_{Op}$ is the number of operators, $n_{Rep}$ is the number of replicate measurement of each part by each operator, $n_{Part}$ is the number of parts, $\bar{x}$ is the grand mean, $\bar{x}_i$ is the mean of each part, $\bar{x}_j$ is the mean for each operator, $\bar{x}_{ij}$ is the mean for each factor level, $\bar{x}_{ijk}$ is each observation.

The sum of squared differences for part by operator interaction ($SS_{Part*Op}$) is the residual variation given by equation (28):

$$SS_{Part*Op} = SS_{Total} - SS_{Part} - SS_{Op} - SS_{Rep}$$ (28)

In order to understand whether the measurement system variation is acceptable, the process’s variation has to be evaluated according to the guidelines given in Table 2.

<table>
<thead>
<tr>
<th>Percentage of process variation</th>
<th>Acceptability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 10%</td>
<td>The measurement is acceptable</td>
</tr>
<tr>
<td>Between 10% and 30%</td>
<td>The measurement system is acceptable depending on the application, the cost of the measuring device or other factors.</td>
</tr>
<tr>
<td>Greater than 30%</td>
<td>The measurement system is not acceptable and should be improved.</td>
</tr>
</tbody>
</table>

The classification shown in Table 2 gives the criterion to verify the reliability of measurement system with respect to a specific application.
3. Method

In this chapter the equipment used for the tests is described. The experimental technique and the procedure is explained for each type of test carried out. The method of optimization based on the DoE theory was adopted because of its efficacy in reducing the number of runs needed with the pressing machine, which means saving time and resources in the production department. Furthermore, the method of analysis of the output response, Response surface methodology, is an appropriate scientific approach for the optimization of a specific set of data, and is able to provide a precise optimal combination of parameters which can be utilized in the pressing process.

3.1 Experimental equipment

The cutting tool inserts produced for this study were pressed using a hydraulic standard pressing machine, designed for the compaction of metallic powders. The main technical data of the hydraulic pressing machine are presented in Table 3.

<table>
<thead>
<tr>
<th>Technical data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>120 kN</td>
</tr>
<tr>
<td>Parts per minute</td>
<td>23 (maximum)</td>
</tr>
<tr>
<td>Repeatability</td>
<td>Less than +/− 1.5 μm</td>
</tr>
<tr>
<td>Punches positioning in the die</td>
<td>Less than +/− 3.0 μm</td>
</tr>
</tbody>
</table>

The measurements of the inserts were carried out using the Mitutoyo digital gauge “Digimatic Indicator ID-H Series 543”, shown in Figure 18. This digital gauge was used to measure the height of three edges of the inserts. The main technical data are shown in Table 4.
Figure 18. Mitutoyo digital gauge “Digimatic Indicator ID-H Series 543” used for the measurements of the inserts [20].

Table 4. Technical data of the Mitutoyo digital gauge “Digimatic Indicator ID-H Series 543” [20].

<table>
<thead>
<tr>
<th>Technical data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>0 – 30.4 mm</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.0015 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.0005 mm</td>
</tr>
</tbody>
</table>

3.2 Experimental technique

3.2.1 Gage R&R analysis

The gage R&R analysis was performed by means of a commercial software which is widely used for statistical and process quality studies. The measurements were carried out according to the parameters shown in Table 5. In the gage R&R analysis, the twelve parts consist of the three edges of four blanks. The operators who carried out the measurements were two operators of the blanks inspection department at Sandvik Coromant and the author.
Table 5. Parameters used for the Gage R&R analysis.

<table>
<thead>
<tr>
<th>N° of parts</th>
<th>N° of operators</th>
<th>N° of replicates</th>
<th>Total measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 (4 inserts)</td>
<td>3</td>
<td>2</td>
<td>72</td>
</tr>
</tbody>
</table>

3.2.2 Measurements of the green compacts

The measurements on the green compacts were carried out for two reasons. Firstly, in order to estimate the variation of the heights of the edges of the inserts before the sintering process, secondly to estimate the misalignment of the top and bottom punches mounted on the pressing machine. When the bottom punch is mounted in the pressing machine, the bottom surface of the punch lays on the surface of the housing in the pressing machine. These two surfaces in contact are not perfectly flat and this may cause the punch leaning with respect to the vertical axis of the machine. This misalignment can generate a variation in the dimensions of the green compact during the pressing process. The same concept is valid for the top punch. In order to estimate the misalignment of the punches mounted in the pressing machine, three runs were pressed. The top and bottom punches were rotated together 120° degrees between each run, and the variation of the heights of the three edges of the green compact was analyzed between each run. The rotation of the punches was carried out in order to emphasize the eventual inclination of the surfaces in contact of the punch with the housing of the pressing machine. The die was kept fixed on its position during the whole three runs. Nevertheless, this study is primarily focused on the optimization of the filling operation of the die.

3.2.3 Optimization of the pressing process

The optimization of the pressing process was carried out according to the Design of Experiments method. In order to apply this method, the software “MODDE Pro” was used; it is a dedicated software for design of experiments and optimization which contains a specific toolbox for experimental planning. The optimization of the pressing process was performed with respect to three parameters, the speed of the filling shoe, the number of shakes of the filling shoe over the die, and the orientation of the die. Three different values were set for each parameter. The die can be rotated with respect to the filling shoe motion. The three different orientations of the die utilized are respectively named (a), (b) and (c). They cannot be shown because they are confidential information.

The experimental plan for the pressing process tests was generated by the software “MODDE” according to the CCF design. Hence, the experimental
plan consists of seventeen runs, each of them with a different combination of the parameters considered. In each run, 78 inserts were pressed (one tray), but only 20 were selected for the measurements in order to spend a reasonable time for the measurements, but at the same time to have a proper amount of data for the estimation of the response. The response considered for the optimization is $\Delta H$, given by the following equation:

$$\Delta H = \text{Max edge height} - \text{Min edge height}$$  (29)

where $\Delta H$ is the difference between the maximum edge height and the minimum edge height within one blank. The height of the edge in between the maximum and the minimum was not considered for the analysis of the data. This value of $\Delta H$ was calculated for the 20 blanks within one run and the average was then calculated. This procedure was carried out for the whole 17 runs.

The measurements of the heights of the three edges of the blanks were carried out only on one face of the insert. The face of the insert which was in contact with the tray during sintering has a greater roughness due to the friction with the tray caused by shrinkage, hence that face was facing upwards during the measurement so the smoother face was in contact with the support plane of the digital gage.

3.3 Experimental procedure

The experimental work was carried out in four main steps. Firstly, the inserts were pressed in the pressing machine, secondly they were sintered in a furnace. After this two steps, the inserts were brushed in a brushing machine in order to eliminate the debris on the edges, and finally the measurements were carried out. Figure 19 illustrates the experimental procedure adopted.

![Figure 19. Schematization of the experimental procedure performed in the tests.](image)

Moreover, within the tests concerning the optimization of the pressing process, the measurements of the height of the three edges of the blanks were performed with the digital gauge in the points highlighted in Figure 20. In the case of the green compacts, the total height was measured instead of the height of the edges because of the brittleness of the green compact. The measurements were carried out in the points highlighted in Figure 21. Furthermore, the green compacts were measured right after pressing, then they were however sintered and brushed.
Furthermore, three marks are present on the insert which are part of the surface texture, one for each edge, and they are named respectively “08”, “MM” and “2”. This marks were utilized to identify the edges of the insert (see appendix A).

Only one type of powder was utilized for all the tests in order to exclude the variability of the process caused by different types of powder. Moreover, in order to evaluate the dimensional changes of the blank during the optimization of the pressing process, the lengths of the blanks were measured three times for each blank, one with respect to each edge.
4. Results and Analysis

This chapter presents the results obtained, first the results achieved from the gage R&R analysis are presented, then the results of the measurements on the green compacts, successively the results of the optimization of the pressing process, and finally the results from the tests on the sintering process.

4.1 Gage R&R analysis

The gage R&R analysis was performed in order to quantify the variation of the measurement system. The heights of the three edges of four inserts (12 parts) were measured with a digital gage by three operators. The result of the gage R&R analysis performed with the commercial software is shown in Table 6.

<table>
<thead>
<tr>
<th>Source</th>
<th>% Study variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total gage R&amp;R</td>
<td>&lt; 30%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>21.98%</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>11.31%</td>
</tr>
<tr>
<td>Part-to-Part</td>
<td>96.90%</td>
</tr>
<tr>
<td>Total variation</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

The process variation (the total gage R&R percentage) is less than 30%, which means the measurement system variation is low enough to discriminate between parts, hence the measurement system is acceptable. The precise value is not reported because is a confidential data. The part-to-part percentage contributes to the total variation with the highest percentage, which is a good indicator showing that the highest variation is due to the difference between parts and is not due to the measurement error of the three operators. Note that the sum of the Study variation percentages of the sources do not have to add up to 100% because these percentages are based on standard deviations and not on variances. Figure 22 illustrates the Contribution and Study variation for each of the sources of variation of the measurement system given in Table 6. Figure 23 illustrates the “R-chart” of the twelve parts measured by the three operators involved in the gage R&R analysis, with two repetitions. The “R-chart” is a control chart of ranges which graphically displays operators’ consistency. The plotted point represents, for each operator, the difference between the two measurements carried out for each part.
If the measurements are the same the range is equal to zero. The points are plotted for each operator so that is possible to compare the consistency of each operator. The center line is the grand average of the ranges. It is an acceptable value if compared to the size of the measurement. The “UCL” and “LCL” are respectively the upper control limit and lower control limit; if the points on the R-chart fall above the upper control limit, the operator is not consistently measuring the parts. If operators measure consistently, the ranges are small relative to the data and the points fall within the control limits. By looking at the position of the points in Figure 23, only two points fall above the upper control limit, which correspond to the part 8 for operator 2 and operator 3, and this can attributed to a defect, such as residual debris, on that specific part. Thus, it is possible to conclude that the operators measured the parts with a similar consistency, and with an acceptable precision.

Figure 24 illustrates the Xbar-chart of the twelve parts measured by the three operators with two repetitions. The Xbar-chart compares the part-to-part variation to the repeatability component; the plotted points represent, for each operator, the average measurement of each part, and the center line is the overall average for all part measurements by all operators. The control limits (UCL and LCL) are based on the number of measurements in each average and the repeatability estimate.

The values of the measurements are fictive due to confidentiality.
It is desirable to observe more variation between part averages than what is expected from repeatability variation alone for a proper execution of the analysis. In Figure 24 many points are above or below the control limits which indicate that part-to-part variation in much greater than the measurement device variation. Figure 25 shows the Operator by Part interaction plot which displays the average measurements by each operator for each part. Each line connects the averages for a single operator.

Ideally, the lines should be identical and the part averages vary enough so that differences between parts are clear. In the case of Figure 25 the lines are parallel, they follow one another closely, and the differences between parts are clear, hence the operators are measuring the parts similarly. Figure 26 illustrates the “By-operator” plot which shows all of the analysis measurements arranged by operator. This plot is useful to determine whether measurements and variability are consistent across operators. Black circles represent the means and a line connect them, when the line is parallel to the x-axis the operators are measuring parts similarly, on average. In Figure 26 the line is parallel to the x-axis between operator 2 and operator 3, while is slightly leaning between operator 1 and operator 2, but still acceptable; it is a confirmation that the operators are measuring the parts similarly.
Furthermore, the By-operator plot can be used to assess whether the overall variability in part measurements for each operator is the same by observing the size of the blue rectangles. In this case the size of the rectangles is similar for all three operators which confirms that the operators are measuring consistently. Figure 27 illustrates the “By-part” plot which shows all the measurement in the analysis arranged by part.

The measurements are represented by sold circles while the means by empty circles. The lines connect the average measurements for each part. Multiple measurements for each part show little variation since the solid circles are close together. The averages vary enough so that differences between parts are clear.

4.2 Measurements of the green compacts

The measurements on the green compacts were carried out first of all in order to quantify the variation of the height of the three edges of the insert before the sintering process. Three runs of inserts were pressed, the results are shown in Table 7.
The values of the measurements are fictive due to confidentiality.

<table>
<thead>
<tr>
<th>Run</th>
<th>Average ( \Delta H ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0030</td>
</tr>
<tr>
<td>2</td>
<td>0.0055</td>
</tr>
<tr>
<td>3</td>
<td>0.0060</td>
</tr>
</tbody>
</table>

The highest value of \( \Delta H \) was observed on run 3, the value is 6 \( \mu \)m. It means that before the sintering process the variation of the height of the three edges of the insert can reach this value.

The second reason why the measurement on the green compacts were carried out was to quantify the misalignment of the punches mounted in the pressing machine. The average height of each edge of the three runs of green compacts was considered for the analysis. Between each run the top and bottom punches were rotated together of 120° degrees, while the die was kept fixed on his position. By comparing the values of the height of the same edge for the three runs, the variation is about 5 \( \mu \)m. It means that rotating the top and bottom punches generate a misalignment which causes a variation of the height of the green compact. This misalignment is due to the imperfect geometry of the surfaces of the punches and the pressing machine in contact.

### 4.3 Optimization of the pressing process

The optimization of the pressing process was carried out according to the Design of experiments theory, hence seventeen runs of inserts were measured after the pressing and sintering process (blanks). The results and the parameters used in the pressing of each run are presented in Table 8. The average \( \Delta H \) was calculated for each run after the measurements; the highest value observed was 19.6 \( \mu \)m in run 3. The pressing parameters in run 3 consist of the lowest speed of the filling shoe, the highest number of shakes of the filling shoe and the die oriented in position (a). The best result observed, the lowest value of the average \( \Delta H \), was 7.9 \( \mu \)m in run 15, where the speed and the number of shakes of the filling shoe were the same as in run 3 but the die was oriented in position (c). The data of the average \( \Delta H \) reported in Table 8 were used as response for the optimization process performed by mean of the software “MODDE Pro”. The plot of the regression model terms obtained is illustrated in Figure 28. The first three terms from the left are the basic terms, speed of the filling shoe (Speed), number of shakes (Shk), and orientation of the die (deg), the other terms are the interactions terms.
Table 8. Average $\Delta H$ measured on the seventeen runs of blanks.

<table>
<thead>
<tr>
<th>Run</th>
<th>Die orientation</th>
<th>Average $\Delta H$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(a)</td>
<td>0.0145</td>
</tr>
<tr>
<td>2</td>
<td>(a)</td>
<td>0.0182</td>
</tr>
<tr>
<td>3</td>
<td>(a)</td>
<td>0.0196</td>
</tr>
<tr>
<td>4</td>
<td>(a)</td>
<td>0.0168</td>
</tr>
<tr>
<td>5</td>
<td>(a)</td>
<td>0.0144</td>
</tr>
<tr>
<td>6</td>
<td>(b)</td>
<td>0.0151</td>
</tr>
<tr>
<td>7</td>
<td>(b)</td>
<td>0.0141</td>
</tr>
<tr>
<td>8</td>
<td>(b)</td>
<td>0.0156</td>
</tr>
<tr>
<td>9</td>
<td>(b)</td>
<td>0.0092</td>
</tr>
<tr>
<td>10</td>
<td>(b)</td>
<td>0.0108</td>
</tr>
<tr>
<td>11</td>
<td>(b)</td>
<td>0.0098</td>
</tr>
<tr>
<td>12</td>
<td>(b)</td>
<td>0.0093</td>
</tr>
<tr>
<td>13</td>
<td>(c)</td>
<td>0.0083</td>
</tr>
<tr>
<td>14</td>
<td>(c)</td>
<td>0.0086</td>
</tr>
<tr>
<td>15</td>
<td>(c)</td>
<td>0.0079</td>
</tr>
<tr>
<td>16</td>
<td>(c)</td>
<td>0.0090</td>
</tr>
<tr>
<td>17</td>
<td>(c)</td>
<td>0.0086</td>
</tr>
</tbody>
</table>

If the green bar is smaller than the interval represented by the segment delimited by the two horizontal lines, the model term is not statistically significant. As it is observable in Figure 28 all the interaction terms are not statistically significant, hence they can be deleted from the regression model in order to increase the quality of the approximation of the response function, leading to the refined regression model presented in Figure 29.
To be precise, also the basic terms speed and number of shakes are not statistically significant so they could be deleted from the model as well, but since they are basic terms it is favorable to keep them in order to obtain a more complete optimal combination of the factors. The only model term statistically significant is the orientation of the die (deg). By running the optimization with the refined regression model, the optimal combination obtained which minimize the response average $\Delta H$ is presented in Table 9. The optimal combination of the pressing parameters consists of the lowest speed of the filling shoe, the highest number of shakes of the filling shoe and the die oriented in position (c). This combination of parameters decreases the average $\Delta H$ from about 17.5 $\mu$m to 7.5 $\mu$m, which is a notable result.
Table 9. Optimal combination of the three pressing parameters which minimize the average $\Delta H$.

<table>
<thead>
<tr>
<th>Speed of the filling shoe [mm/s]</th>
<th>No. of shakes of the filling shoe</th>
<th>Orientation of the die</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest</td>
<td>Highest</td>
<td>(c)</td>
</tr>
</tbody>
</table>

Decreasing the speed and increasing the number of shakes of the filling shoe have slightly positive influences in decreasing the average $\Delta H$, although they are not statistically significant. In order to visualize their effects, the response surface plots are presented. Figure 30 is the response surface plot with the orientation of the die fixed in position (a), Figure 31 is the response surface plot with the orientation of the die fixed in position (b) and Figure 32 is the response surface plot with the orientation of the die fixed in position (c).

![Response surface plot](image)

Figure 30. Response surface plot for the optimization of the pressing process. Orientation of the die in position (a).
These response surface plots consist of a plane which means that the relationship between the two parameters speed and number of shakes of the filling shoe and the response is linear. This is confirmed by the fact that the interaction terms of the regression model which gives a quadratic behavior...
were deleted in order to refine the regression model because they were not statistically significant. The colors of the response surface plots represent the variation of the response average $\Delta H$; the red color indicates high value of the response while blue color indicates low value. The aim of the optimization performed was to minimize the response, hence the blue color outline indicates the direction to follow to achieve suitable values of the response. The same behavior was observed for all the three orientations of the die. The hypothesis was that the lowest speed, the highest number of shakes and the die oriented in position (c) would have led to a better distribution of the powder into the die cavity. Nevertheless, as seen in Figure 29, the speed and number of shakes of the filling shoe are not statistically significant, which means that decreasing the speed and increasing the number of shakes have slightly positive influence but not determinant. The only significant change in the response average $\Delta H$ is obtainable by changing the orientation of the die, in particular, rotating the die in position (c) leads to decrease significantly the average $\Delta H$ (7.9 µm).

Furthermore, the lengths of the blanks with respect to the three edges was measured in order to ensure that the new set of parameters was not affecting significantly other dimensions of the insert. The variation of the lengths of the blanks ($\Delta m$) before the optimization process was 3.4 µm; after the optimization process it was measured for run 15 and it was 5.9 µm. This result shows a slight increase of $\Delta m$ which can be considered acceptable since it has not a high magnitude.

4.4 Tests on the sintering process

The orientation of the tray where the inserts lay in the sintering furnace can play an important role in compensating the variation of the height of the inserts. The relationship between the density of the powder into the insert and variation of temperature due to the cooling flow generated when the sintering furnace is cooling down, can contribute to compensate the variation of the height of the insert. The test was performed by pressing four runs of inserts with the same pressing parameters, but the orientation of the tray of the last two runs (b) was rotated with respect to the first two runs (a). The pressing parameters used for pressing the inserts as well as the results of the measurements are presented in Table 10. The trays oriented according to the orientation (b) showed a lower value of average $\Delta H$ respect to the orientation (a). The lowest value of average $\Delta H$ obtained is 5.8 µm which is even lower value compared to the 7.9 µm previously presented. This is a remarkable result, especially if compared to the initial average $\Delta H$ of about 17.5 µm. However, the number of runs pressed is limited since only four runs were pressed, hence further tests can be useful to confirm the results achieved. Furthermore, the lengths of the blanks with respect to the three edges was measured for run 4 and the variation $\Delta m$ was 4.6 µm, which is an acceptable value.
The values of the measurements are fictive due to confidentiality.

Table 10. Pressing parameters and measurements results of the test concerning the sintering process.

<table>
<thead>
<tr>
<th>Run</th>
<th>Tray orientation</th>
<th>Average $\Delta H$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(a)</td>
<td>0.0087</td>
</tr>
<tr>
<td>2</td>
<td>(a)</td>
<td>0.0065</td>
</tr>
<tr>
<td>3</td>
<td>(b)</td>
<td>0.0064</td>
</tr>
<tr>
<td>4</td>
<td>(b)</td>
<td>0.0058</td>
</tr>
</tbody>
</table>
5. Discussion

This study was focused on decreasing the difference of the heights of the three edges of triangular shaped cutting tool inserts used in turning. The origin of the problem was known to be related to the distribution of powder into the die during the pressing process. Different density distribution of powder into the die cavity leads to, after pressing, a green compact with inhomogeneous density distribution of the powder. When the green compact is subjected to the sintering process, different shrinkage occurs according to the difference in density distribution of the powder, lower density leads to greater shrinkage and vice versa; different shrinkage causes the variation of the heights of the blank under study which was measured and quantified as about 17.5 µm. This variation is not negligible considering the precision which the standard machining operation requires in industry. The pressing process was investigated in order to confirm that the density distribution of the powder into the die was the origin of the variation of the height of the blank. The measurements on the green compacts revealed that the variation of the height before the sintering process is about 6 µm as shown in Table 7. Hence, 6 µm out of 17.5 µm are attributable to the geometry of the top and bottom punches. Furthermore, the punches can be mounted in the pressing machine with three different orientations. The tests showed that mounting the punches in different orientations can cause a variation of the height of the green compact of about 5 µm.

Furthermore, the pressing process was optimized in order to achieve a more uniform distribution of the powder into the die in order to reduce the variation of the heights of the blanks. The results presented in Table 8 showed that rotating the die in position (c) decreased significantly the variation of the heights of the blanks, reaching the value of about 7 µm, which is a consistent reduction of about 55% with respect to the initial variation of 17.5 µm. Decreasing the speed and the number of shakes of the filling shoe over the die showed positive influences in reducing the variation but not determinant. The plots illustrated in Figure 28 and Figure 29 show that the influences are not statistically significant. Additionally, the lengths of the blanks with respect to the three edges was measured in order to quantify the effect of the variation of the pressing parameters on the other dimensions of the blanks. The variation of the lengths of the blanks (Δm) before the optimization process was about 3.5 µm. After the optimization process it was measured only for one order and it was about 6 µm. This result shows a slight increase of Δm which can be considered acceptable since it has not a high magnitude.

The optimization of the pressing process was performed according to the Design of experiments theory in order to reduce the number of runs needed, and the CCF design was utilized to produce the experimental plan. However, other designs could have been used such as the “D-optimal” design which utilizes a different algorithm for the optimization of the process.
Moreover, the effects of the sintering process were investigated in order to further decrease the variation of the height of the blanks. The orientation of the tray, where the green compacts laid with respect to the source of the cooling flow, was rotated in position (c) and the results, presented in Table 10, showed further improvements as the variation of the height was decreased until about 6 µm. If compared to the initial variation of 17.5 µm, it is a total reduction of about 65% of the variation of the heights of the blanks. This test consisted of only four runs of inserts pressed, two for each orientation of the tray. Hence, it indicates the positive trend to follow but further tests are needed to confirm this result. Furthermore, the lengths of the blanks with respect to the three edges was measured also in this case for one order and the variation $\Delta m$ was 4.5 µm, which is an acceptable value.

The sintering process is at the moment under investigation in other projects at Sandvik Coromant because the effects of that process are manifold and have high impact on the dimensions of the blank. Hence, it will be important to combine the results obtained in this study with the knowledge achieved in further research regarding the sintering process.
6. Conclusions

The variation of the height of the triangular shaped insert was investigated in order to reduce it, the variation was about 17.5 µm after the sintering process. In order to identify the origin of this variation, the variation of the height of the green compacts, before the sintering process, was measured and it was observed to reach a maximum of about 6 µm. This variation can be attributed to the misalignment of the punches mounted in the pressing machine.

Successively, the optimization of the pressing process was carried out according to the Design of experiments theory and the results showed that rotating the die in position (c) leads to a significant decrease of the variation of the height of the insert, reaching the value of about 7.5 µm after sintering. Increasing the speed and decreasing the number of shakes of the filling shoe revealed to have a slightly positive influence but they are not statistically significant.

Furthermore, tests on the sintering process were carried out in order to further decrease the variation of the height of the insert. The results indicated that orienting the tray opportune in the sintering furnace, can lead to further decrease the variation down to about 5.5 µm. Moreover, the variation of the lengths of the blanks with respect to the three edges was measured for two orders and the results showed a slight increase but acceptable. Hence, the set of parameters which decreases significantly the variation of the heights of the three edges of the inserts do not affect significantly the length of the inserts.

These are important results which are directly applicable to the manufacturing process in the Sandvik Coromant production site in order to increase the quality of the inserts.
7. Future work

In order to confirm the results obtained on this study further tests are needed. Particularly smaller sizes of the insert studied need to be investigated, after that the tests can be performed on different powders since in this project only one type of powder was utilized. Finally, other methods of die filling can be tested, such as suction filling, in order to verify whether further developments are obtainable.
References


Appendix A

The technical drawing of the insert studied was removed due to his classification as confidential information of Sandvik Coromant.
Appendix B

All the measurements of the inserts carried out were removed due to their classification as confidential information of Sandvik Coromant.
Faculty of Technology
351 95 Växjö, Sweden
Telephone: +46 772-28 80 00, fax +46 470-832 17 (Växjö)