A FINITE ELEMENT MODEL FOR EJECTION OF GREEN PARTS AFTER PM COMPACTION

A Study on the State of the Art of Powder Metallurgy

and

Development of a Finite Element Model

by

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A thesis submitted to the Department of Mechanical Engineering

in conformity with the requirements for

the degree of Master of Science in Engineering

Queen’s University

Kingston, Ontario, Canada

September, 2008

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ABSTRACT

A Finite Element Model for Ejection of Green Parts after PM Compaction

The present study describes the development of an FE model of tooling during production of a transmission gear. Results of the simulation at the puck/die interface during ejection examine the behavior of friction. Machine component deflections under pressure and areas of wear/binding are also predicted. The tooling was developed and modeled in Abaqus, an FE pre- and post-processor. A metal PM (Powder Metallurgy) puck is simulated from the point at the end of compaction, and then at several positions during ejection. A test setup was designed and built. The apparatus will be used to create iron powder compacts, and experimental results will be used to evaluate future models. Experiments with the new design will enable future studies of friction at the puck/die interface. The current design is for a simple puck and an increase in part geometry complexity is proposed with preliminary design requirements.
ACKNOWLEDGMENTS

Firstly I would like to thank Dr. Jacob Jeswiet for his help and support throughout my work. Indeed, without his help and guidance, I would have been lost. I extend special thanks and recognition to Mr. Alex Szekeres, who in his patience and wisdom has been a mentor and friend to me from the beginning. I must also extend sincere thanks to Mr. Hossein Kashani-Zadeh, whose expertise with Abaqus and FEA was invaluable. Finally, Mr. George Matsoukas and his guidance on how to write this paper made the process much smoother.
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NOMENCLATURE

Variables and Constants:

\( \Delta E \)  change in energy
\( u \)  displacement vector
\( t \)  time
\( \Omega \)  domain of deformable body
\( \rho F \)  volume force vector
\( P \)  surface load
\( Sc \)  contact surface area
\( \sigma \)  true stress field
\( v \)  normal vector to \( Sc \)
\( \varepsilon \)  strain
\( f \)  friction coefficient during ejection
\( f_c \)  friction coefficient during compaction
\( s \)  compacting punch speed
\( \tau \)  quasistatic time step
\( V \)  volume of puck
\( w \)  the kinematically possible state of a system satisfying the non-penetration condition
\( F^s \)  force of tear
\( F^c \)  force of wear
\( Y(F) \)  Criterion for perfect friction
$F_N$ normal component of contact force

$|F_T|$ Euclidian norm of tangential component of contact force

$F_T^s$ tangential tear force

$v$ Poisson’s Ratio

$E$ Young’s Modulus
Chapter 1

Introduction

The objective of this thesis is to develop a model of the Powder Metallurgy (PM) ejection process of a green part (not sintered). This model will be a first step in developing a comprehensive set of models of the PM process that can be used by industry. The essential features of powder metallurgy are the production of a metal powder, chemical or mechanical, and its consolidation at a temperature that is below the melting point of the major constituent into a fairly strong solid. The coalescence of the powder particles requires the application of mechanical pressure followed by heat.

Powder metallurgy, in its earliest form, was first practiced by the predecessors of the Incas in Ecuador long before Columbus made his voyage to the New World. The Incas cemented grains of platinum together by a metal with a lower melting point, and then sintered the lump to produce usable objects. Many writers on powder metallurgy have referred to Wollaston’s work in producing malleable platinum, published in 1829, and the process he developed for it, as the beginning of the modern renaissance in the field. The process involved igniting ammonium chloroplatinate to produce fine powdered platinum, inserting it into a mechanical hand press, and manually compacting it to produce a cake. Subsequent to two sintering stages and further mechanical hammering, the cake would be ready for work as any other metal would.¹

This was only the beginning. As knowledge of materials increased and processes refined, it became possible to manufacture a vast range of products more cheaply than

¹ Smith, Cyril Stanley.
conventional methods. Electric lamp filaments, contacts, and bearings were a few of the first to make the transition. Indeed, this ability of powder metallurgy to produce objects of equivalent quality less expensively is still the primary reason why the transition is continuing to be made even today.

1.1 Motivation

The Powder Metallurgy industry is changing rapidly. Major reasons for this are increasing globalization, changing markets and changing manufacturing sites, especially in the automotive sector. A snapshot of the number of automobiles sold, globally, was published by the International Road Federation in 2002\(^2\). The low number of vehicles in China, at that time, can be viewed an indicator of the pent-up demand that existed in that large market. The apparent pent-up demand leads to increased consumer purchases and the need for PM products in the automotive industry.

\(^2\) “International Road Federation.”
It can already be seen, in Table 1, that the low number of automobiles in China in 2000 has been followed by large increases in China in 2005 and 2006, with large increases predicted for 2007. This is occurring as prosperity increases. This is the pent-up demand discussed earlier and indicated by the numbers in Figure 1. For reference, it may be noted that as of 2002, there were 590 million passenger cars worldwide (roughly one car for every eleven people).4

Not only have sales increased in China, an alliance has been formed between a US automotive company, Chrysler, and a Chinese automotive company, Chery, to start producing a compact 1.3 litre engine vehicle for the US market.5 The obvious implication is the manufacturers assume the market will change in North America.

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3 Ibid.
5 “Chrysler, China’s biggest automaker ink deal.”
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Table 1: The Increase in Automobile Sales in China for 2005 to 2007

The GDP for China and India is already large and growing rapidly. Although GDP per capita is low, the pent up demand is still there. The largest changes in GDP per capita, above 10%, can be seen to occur in the markets where GDP/capita is relatively low, but all the indicators show this is changing rapidly.

Globe and Mail.
Economists also generally believe these markets will expand dramatically in the future. This can be observed on a discussion about the recent paper by Sir Nicolas Stern\(^9\), in which it is stated that in 50 years time even countries with low GDP’s will be much more prosperous. Implicit in the discussion is that with increased prosperity there will be increases in markets.

In Canada, the automotive industry is the largest manufacturing sector, accounting for 12% of manufacturing GDP and 26% of manufacturing trade. From 1995 to 2005 industry shipments have risen from $69.2 billion to $97.6 billion annually.\(^{11}\)

\(^9\) “A special report on Brazil.”

\(^{10}\) “Economics focus.”

\(^{11}\) “Canada’s Automotive Industry 2006.”
Powder metallurgy plays an important role in the automotive sector. From 1988 to 2003, automotive applications of powdered metal increased from 15 to 40 pounds per North American-made auto/light truck, and as such now represent a $900 million a year industry unto itself only in the United States.\textsuperscript{12}

The information given above shows that powder metallurgy represents an industry on the rise globally. The bulk of current research is based on 1) achieving uniform density throughout the part during compaction, 2) the prevention of crack formation and part failure during ejection, and 3) increasing the accuracy of final part dimensions. This thesis is concerned with item 2).

1.2 Research Objectives

A large portion of automotive applications includes powdered metal transmission gears. Manufacturers experience lengthy product development periods due to the abovementioned issues, in that each time a new part is developed, the part must physically be produced on the plant floor to see how it behaves in the forming process. A lot of trial and error is also required with the inputs for the production machines to ensure the production of quality parts with a high level of repeatability. This requires the shutdown of assembly lines, which translates to lost productivity and hence lost revenue. A major reason for the trial and error procedure is the lack of understanding of what occurs during part production. Hence, the objectives of the current research are as follows:

\textsuperscript{12}Goto, Ryuichiro.
1 Develop a contact model for ejection of iron powder to produce a simplified gear or puck using linear Finite Element Analysis (FEA) to predict the frictional forces/coefficients between the die and the part.

2 Design and build a test setup to carry out compaction and ejection of iron powder to produce a puck.

3 Develop a contact model for compaction and ejection of iron powder to produce a complex gear using linear FEA to predict the following: punch face deflections, stresses in the punches, core rod and die, and frictional forces and nature of contact between components. The gear in question would be a synchro hub used in the Pontiac Solstice, with pertinent data on tooling and production provided by the manufacturer, Stackpole Limited Automotive Gear Division.\(^\text{13}\)

4 Design a test setup to carry out compaction and ejection of iron powder to produce a puck with a hole through the center; perform experiments and compare results with both certain predictions of the synchro hub FEA and data from Stackpole.

This document is divided into eight additional chapters. In the next chapter, relevant background in the field of Powder Metallurgy is explored. In Chapter 3, previous literatures in FEA and Tool Design as pertaining to Powder Metallurgy are studied. Chapter 4 describes the test setup development and experimental methods pertaining to verifying the predictions of the simple puck FEA, and Chapter 5 is a discussion of the finite element model created to simulate the effects of production of the synchro hub on the tooling. In Chapter 6, test setups are discussed that would be used to validate certain predictions made by the simple puck as well as synchro hub FEA and data provided by Stackpole Limited.\(^\text{13}\)
Stackpole. The remaining Chapters 7, 8 and 9 address conclusions of the research, recommendations for future work, and references used in the project respectively. Four appendices follow the text of this thesis.
Chapter 2

Background

2.1 Introduction

The following gives a background on the state-of-the-art of PM. Industry analysis, descriptions of PM equipment, and a survey of products can be found in Appendix A.

2.2 Overview of Raw Materials

There are two major kinds of raw materials used in PM—metal powder and the lubricant.

I. Metal Powders

1. Kinds of powders

Most commonly used are alloys of iron, steel, tin, nickel, copper, aluminum, and titanium, as well as refractory materials such as tungsten, molybdenum, and tantalum.

2. Production methods

There are four ways of producing metal powders: Solid State Reduction, Atomization, Electrolysis, and Chemical.

14 “Pick PM.”
i. Solid State Reduction

In solid-state reduction, the metal ore is crushed, mixed with a reducing species, and passed through a furnace. A reaction takes place there that leaves a cake of spongy metal which is crushed, then separated from all non-metallic material, and finally sieved to produce powder. No refining operation is involved, so the purity of the powder depends on the purity of the raw materials. The particles of powder produced in such a way are irregular and sponge-like, soft, readily compressible, and give compacts of good pre-sinter (green) strength.

ii. Atomization

Molten metal is separated into small droplets and frozen before the drops come into contact with each other or with a solid surface. Typically, the impact of high-energy jets of gas or liquid disintegrates a thin stream of molten metal to achieve this. This technique is applicable to metals that can be melted and is used for the production of iron, copper, alloy steels, brass, bronze, low-melting-point metals such as aluminum, tin, lead, zinc, and cadmium, and high-melting-point materials such as tungsten, titanium, and rhenium.
iii. Electrolysis

By choosing conditions such as electrolyte composition and concentration, temperature, and current density, many metals can be deposited in a spongy or powdery state. Further processing in the form of washing, drying, reducing, annealing, and crushing is often required, and ultimately yields high-purity and high-density powder. Electrolysis is most commonly used for producing copper powder, along with iron, chromium, and magnesium. Electrolysis has high energy costs and therefore is generally limited to high-value powders such as high-conductivity copper powders.

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15 Ibid.
iv. Chemical

The most common chemical powder treatments involve oxide reduction, precipitation from solutions, and thermal decomposition, and produce powders that have a great variation in properties yet closely controlled particle size and shape. Due to pores present within individual particles, oxide-reduced powders are characterized as spongy. Solution-precipitated powders provide small ranges of particle size and high purity. Thermal decomposition is mostly used to process carbonyls. These powders, once milled and annealed, exceed 99.5% purity.

II. Lubricants\textsuperscript{16}

Non metallic powders are mixed with metal powders to improve the compressing characteristics of the blend, and are known as binders or lubricants. They reduce interparticle friction and friction between particles and die walls. Graphite and stearic acid are the most commonly used lubricants. Other substances used for these purposes are inorganic materials such as mica, talc, and magnesium carbonate, inorganic as well as organic colloids, salicylic acid, camphor, paraffin, mineral oil, rosin, and synthetic thermoplastic resins. These are particularly effective when used in the form of solutions, often in ether.

The organic additions evaporate or are decomposed during the sintering process, or they are boiled out in a low temperature baking process before sintering. Additions which leave traces of carbon as residues in the sintered product cannot be used in

\textsuperscript{16} Schwarzkopf, Paul.
applications where carbon is harmful. Also, this evaporation or decomposition of organic additives increases to some extent the porosity of the finished parts, and in some cases are added specifically for this purpose. Zinc stearate and other metal soaps are suitable additions for the production of parts with interconnected pores.

Putty-chase-type mixers are particularly suited for the incorporation of lubricants and binders to a metal powder. Coarse agglomerates formed during the mixing process are eliminated by sieving, and stabilized gyrating screens are often used for that purpose.

Figure 4: Putty-chase-type Mixer\textsuperscript{17}

\textsuperscript{17} Schwarzkopf, Paul.
2.3 Description of the Powder Metallurgy Production Process

I. Overview

The following is an outline of the major steps in producing a powdered metal part, and various options and alternative methods within each.

Figure 5: The PM Process

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18 “Pick PM.”
Forming occurs after the powder has been mixed. There are three ways this is done: hot, warm, and cold compaction, as shown in Figure 5.

○ Hot compaction

Hot (sometimes referred to as warm) compaction is useful over cold compaction with powders that exhibit improvement of plastic deformability with increasing temperature. It permits production of very dense parts without long sintering at excessively high temperatures, thus eliminating the shrinkage effects of sintering. Parts thus produced exhibit smaller grain size and better hardness and strength. However, the harsh environment within the die leads to high levels of die wear; this leads to lower production rates per machine than the more standard cold compaction, and hence the process is more expensive.¹⁹ There are several kinds of hot compaction.

- Isostatic –The powder is confined within a flexible membrane, made of materials such as vinyl plastisols, that is immersed in a pressurizing medium. This achieves uniform compaction pressure and thus density throughout part. The membrane is typically a metal or glass, and the pressurizing medium used is gas. Heat is also applied to plastically deform the membrane in order to compact the powder. No sintering is therefore required.²⁰

- Extrusion –The powder is extruded at high pressure through a die. This method produces parts that are very long in one dimension. Typical reduction ratios in cross-sectional area are 18:1.²¹

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¹⁹ Schwarzkopf, Paul.
²⁰ “Isostatic Pressing.”
²¹ Cho, H.S.
Die Compacting – Forces are applied to the powder from the die and compacting punches, resulting in parts with very good dimensional and weight control. Wear and binding of the tool, in addition to part failure at ejection, are issues.

Centrifuging – Powder is compacted by the utilization of centrifugal forces. This eliminates pressure transmission issues found in the other methods, because the forces are applied equivalently on each individual powder particle. This process is limited to small parts that must fit inside the centrifuge.

Spraying – This method is used to produce semi-finished products. It involves liquid metal atomization and droplet consolidation to produce a near-net-shape

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22 Vila, Christian.
23 Schwarzkopf, Paul.
product. The as-sprayed material is close to full density, and requires very little subsequent machining.\textsuperscript{24} However it is a time consuming process also limited to smaller parts.

- Cold compaction\textsuperscript{25}:

This is the other major forming technique. No external heat is applied, and several of the techniques outlined above are used but simply without the heat. There are several specific methods used in cold compaction.

- Die Compacting – Cold compaction die compacting is the most common method used in powdered metal part forming

- Isostatic: Cold isostatic forming is similar to its hot counterpart except that the membrane is usually a rubber/elastomeric material, and the pressurizing medium used is liquid.

- Injection Molding

- Rolling – Compressive forces exerted by rotating rollers compress the powder into weak strips that require sintering. The powder moves through the rollers at speeds as slow as 100 mm/s, in order to facilitate expulsion of air from the compressed powder during manufacture. This method is mostly used for producing strip-like parts.

\textsuperscript{24} “Spray Forming.”

\textsuperscript{25} Schwarzkopf, Paul.
Warm compaction\textsuperscript{27} This is a variation of hot compaction, where lower heat during sintering is required subsequent to the compaction process. Die compacting and injection molding are the primary methods of warm compaction. It is the least used form of compaction because most powders do not exhibit much improvement in deformability at these temperatures, and appreciable post-compaction sintering is still usually required.

\textbullet{} Sintering\textsuperscript{28}. The sintering stage of the production process has two major varieties.

\textbullet{} Atmosphere Sintering – Sintering is performed within a controlled atmosphere that prevents undesired reactions and facilitates desired reactions.

\textbullet{} Vacuum Sintering – This method promotes the removal of adsorbed gases. It is of most interest with materials such as Ta, Cb, Ti, and Cr, which have a high affinity to the gases usually employed in controlled atmospheres.

\textsuperscript{26} Groover, Mikell P.
\textsuperscript{27} Schwarzkopf, Paul.
\textsuperscript{28} Ibid.
• Optional Operations also exist within the production process in manufacturing and finishing.

○ Manufacturing (subsequent to sintering)
  ▪ Repressing\(^{29}\) - The compacted powder part is placed in a closed die and subjected to small strains at high strain rates. This technique is useful for closing surface pores, finish, hardness, size precision, and adding detail to the part. Sizing adjusts the final compact dimensions, while coining adds surface configurations, such as a surface impression, to the compact.
  ▪ Resintering
  ▪ Forging

○ Finishing
  ▪ Machining
  ▪ Heat treating
  ▪ Steam treating
  ▪ Plastic impregnation – This is done for parts intended for retention of fluids or gases under pressure, and in preparation of other finishing operations such as plating or painting.
  ▪ Plating
  ▪ Tumbling – In this process, the parts to be finished are placed in a container and rolled or vibrated so that they rub against each other and/or some sort of abrasive or polishing media.

\(^{29}\) German, R. M.
- Oil impregnation - Improvement of frictional properties and abrasive wear resistance is achieved via oil impregnation.

- Shot peening – To create a harder and denser, and therefore a stronger, surface layer. This increases the fatigue strength.

![Figure 8: Shot Peening Configuration](image)

II. Details on the Powder Metallurgy Production Process

The production process for powdered metal parts requires several stages. The following is a description of these stages used at Stackpole Ltd. Automotive Division in Mississauga, Ontario to produce powdered metal parts, as observed by the author on

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30 “Shot Peening.”
22nd September, 2006. Values quoted in the following section were also provided by Stackpole technicians that operate the equipment. The forming process they use is cold die compaction, and it being the most common forming process, merits the additional detail that follows. Refer to Figures 9 and 10 below for an overview of the setup and process.

![Figure 9: Overview of Components Involved, Depicting Locations of Die Walls, Top and Bottom Punches, and Part](image)

Figure 9: Overview of Components Involved, Depicting Locations of Die Walls, Top and Bottom Punches, and Part
1. Mixing

To produce a part with a desired final metallic composition, various amounts of powders are mixed together with the selected lubricants in large rotating drums. These amounts used are generally proprietary.

2. Powder insertion / Filling (Figure 10 step 1)

A hopper is filled with the powder mixture, and upon proper positioning over the die deposits the powder within it. This is usually done via the gravity feed technique, whereby the powder simply falls or is blown into the die. However another less common technique, known as suction filling, is also sometimes used;
in this method, a vacuum is created within the die and as the powder is dropped in, the bottom punches are retracted and powder is drawn in.

Once the powder is in the die, the top punches are lowered and both sets of punches are shifted such that the powder between them is in the shape of the final product (as per Figure 9).

3. Forming process
   a) Cold die compaction (*Figure 10 step 3*) is carried out, at pressures of 600 – 700 MPa, where the punches compress the powder to give a compacted shape called a puck.
   b) Ejection
      i. The force the top punch exerts on the part is decreased to the “hold-down force” by reducing it to 10% of the original value (*Figure 10 step 4*).
      ii. Either the die is held stationary and the top/bottom punches are moved away in tandem, or the punches are held stationary and the die is moved away (*Figure 10 step 5*). At this stage, the solid part is known as the “Green Product” at around 90% density, but with much lower tensile strength. This step is critical to the process, because the friction of the die and punch walls against the puck can create cracks.

4. Next, sintering is carried out to produce the final part. The green part is heated in furnaces, at temperatures of 2/3 to 4/5 of the melting point of the metal, to achieve recrystallization and grain growth.
Chapter 3

Previous Literature

3.1 Finite Element Analysis in Powder Metallurgy

The basic elements of PM are shown in Figure 9. The theory involved in the process of powder metallurgy can be broadly grouped into three categories: compaction models, ejection modeling, and machine modeling. Compaction models consider issues such as die filling, density prediction, density dependent modeling, friction, and crack prediction. Ejection modeling discusses springback, density dependent elasticity, hyperelasticity, plastic friction models, and friction with velocity dependence. Finally, the machine modeling involves consideration of testing requirements, industrial production parameters, solid modeling software, and force data. To gain further knowledge on the above, please refer to Appendix C for the report entitled “Final report on ejection, machine and compaction modeling” by Alex Szekeres, Project Engineer on the Queen’s University-Stackpole Ltd. Collaborative Project.  

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31 Szekeres, Alex.
3.2 Tooling Design

3.2.1 Introduction

Traditionally, PM tooling was designed on the basis of production experience. At present modeling and simulation are used to predict not only final dimensions, but also most aspects of the PM processing steps. Rapid prototype manufacturing also brought PM tooling to another level. Two major factors in the compacting operation control part design, those being the flow behavior of powders and the pressing action. Metal powders do not flow hydraulically because of the friction between the particles and the dies. The design should ensure adequate powder distribution within each cavity to allow satisfactory compaction. Metal powders have limited lateral flow and therefore limitations exist on the contours that can be produced.  

Shape of Rigid Tooling

Rigid tooling is the most common form of tooling, and differs from other kinds (such as rolling or injection molding) in that the powder is confined in a rigid die cavity. The die cavity is entered by punches which compact the powder. This powder densifies and forms the exact shape of the die and punches, and is then ejected from the die cavity.

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32 van Rooyen, Isabel J.
33 “ASM Handbooks Online”.
Major Tooling Systems

Single-action systems generally produce thin single-level parts pressed from one direction (hence having a density gradient in the direction of pressing). During compaction, the die, core rod and one of the punches (usually the lower) remain stationary while the other punch compacts. In ejection, the upper punch moves away from the part and the lower punch ejects the part out of the die. The core rod is stationary, and the part is ejected from both the die and core rod simultaneously.

Double-action systems primarily produce any thickness single-level parts pressed from both directions (hence having the lowest density at the center with highest densities at its top and bottom surfaces). The pressing from top and bottom is done simultaneously because the punches have the same travel rate. The die and core rod remain stationary.

Floating die systems involve a die mounted on a yielding mechanism (spring-loaded, hydraulic or pneumatic). As the upper punch enters the die and starts to compact the powder, friction between the powder and die wall causes the die to move down. If it is a double-action system, this has the same effect as an upward-moving lower punch. After pressing, the die moves back to the fill position. At this point, the die is pushed down (usually by removing the top punch first and then adding spacers between the press piston and the die) and the part is ejected. In a double-action system, the lower punch can eject the part as well.

Ibid.
3.2.2 Tooling Design

Tooling Layout

A layout is required to design a suitable set of tools and determine the physical dimensions of tooling members. It helps to determine fill, pressing and ejection positions and to eliminate interference at these positions. The die space drawing provided with every press, which usually starts in the ejection position, is the basis of the tooling assembly layout. Generally, tooling members are never closer than in the ejection position, which constitutes the minimum space available to contain all components.

Die Design

Dies are commonly constructed by using inserts that are held in the larger die by shrink fitting. The amount of interference between the two depends on their sizes and the compacting pressure used, and should be such that the stress on the insert is always compressive (for round dies). The powder can be considered a fluid in a closed container that transmits part of the axial pressure to the die walls, and so the die must be designed as a pressure vessel. Practically, this pressure on the die walls is no more than half of the axial load. Other considerations include initial tool cost, shear strength of the die material, and die shape.

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Punch Component Stress

The compaction process causes compressive stresses to develop in the punches. These must be below the yield stress of the material within an acceptable safety factor. Additionally, buckling calculations must be done for long or thin-walled punches. The circumferential tensile stress created from the axial load must also be calculated, and if it and the accompanying deflection is great, tooling clearances should be designed so that when the outer wall expands, it is supported by the die wall and is prevented from reaching its yield stress.

During ejection, the bottom punch adapter experiences significant stress. It must be able to resist the ejection of the punch without permanent deformation, which may occur as a result of bending loads it is subjected to that create a tensile stress around the centre hole. This stress should not exceed the fatigue strength of the material.

Deflection Analysis

Producing parts at compacting pressures higher than 690 MPa presents a variety of issues that must be addressed. Most importantly, deflection and springback can occur. Deflection occurs due to the column loading effect on the punches. When the loading is released, the punches should return to their original dimensions if the material has remained in the elastic region; this return is known as springback and can be harmful to the part. The deflection must be minimized and characterized especially when there are two or more bottom punches. This is because if the total deflection of each punch is
different, then during ejection the part will move with the punch that has the greater
deflection, leaving a portion of it unsupported and susceptible to cracking.

A punch under load is usually in pure compression, so Hooke’s Law applies. If the
punch has varying cross-sections, the deflection for each section with constant cross-
section can be calculated using Hooke’s Law and then summed for the total deflection.

3.2.3 Tool Materials

Die inserts are usually made of wear resistant materials, and for the compaction of
carbide, ceramic or ferrite powder, are usually made of medium to course grain cemented
carbide. Because the elastic moduli of carbides are around three times higher than those
of steels, the outer die must be designed with enough stiffness to support three times the
expected loading (because of the high stiffness of the carbide). Otherwise, the carbide is
liable to break. The outer die can be made of medium carbon alloy steel such as AISI
4340 of between 42 to 46 HRC (Rockwell Hardness).

Due to the stresses on punches during the production process, toughness is a much
more important property than wear for the punch material. For the most stressful
applications where even wear becomes a consideration, steel grades such as M2 or CPM
10V should be considered.

36 “ASM Handbooks Online”.
Core rods require both high toughness and wear resistance, but generally the primary concern is wear. Tungsten carbide is the most common material found, although for particularly abrasive conditions grades such as CPM 10V and M2 have been used.

Operational factors include polishing or lapping die working surfaces and core rods to a mirror-like surface finish; final polishing should be done in a direction parallel to the axis of the tool. Punch faces should also have a fine finish. This has the effect of reducing friction, thereby reducing load on the tool members. Ejection is also made easier, and premature failure due to scratches and other stress risers is minimized.

3.2.4 Tooling Clearances

Standard tooling clearance is 0.016 mm/25 mm, or 0.0006 in/1 in, on the total diameter. It is prudent to use minimal clearances to begin with, because material can then be removed if an increase in clearance is required. The clearances must also be less than the size of the powder grains to prevent their entrapment. However care must be taken when compacting to higher densities, because higher compacting pressures are required, leading to higher tooling temperatures and hence greater dimensional changes. The clearances must be large enough to prevent binding and seizure of the tool members. As a guide, standard clearances between die walls and punches range from 0.005 mm to 0.008 mm for precision parts. Other parts can have clearances up to 0.013 mm.

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37 Saheb, S.D.K.
Specific shapes and features in the part require certain guidelines of their own. Minimum wall thickness, for example, is the most common feature that has its own specific requirements. It is governed by the overall part size and shape. At a minimum, the thickness should not be less than 1.5 mm or 0.06 in thick, with a maximum length-to-wall thickness ratio of 8 to 1. The other most common feature is a step. Simple steps or level changes not exceeding 15% of the overall part height can simply be formed by face contours in the punches.
Chapter 4

Modeling of Production of Simple Puck

4.1 Introduction

The objective of this section is to address whether friction between powder and tooling can be predicted computationally. Figure 11 (a) shows the PM system designed specifically for this project. The figure shows the main elements to be modeled, including the wall where friction occurs between the puck and carbide liner.

A linear elastic, static, implicitly solved finite element simulation was solved for the production of a simple puck using the powder metallurgy process. Linear contact analysis between all components was considered, with an experimentally determined linear elastic material model for the powder and a theoretical, quasistatic quantum friction model obtained from literature. Convergence studies were conducted to determine optimum mesh density. The results of these studies are presented in this chapter. It should be noted that the model was developed in order to recreate the conditions of the experimental test setup being built simultaneously, to facilitate an accurate comparison of results upon completion of the test apparatus.
4.2 Modeling Methods

4.2.1 Approach

Solid models of the top and bottom punches, iron powder compact (known as the puck), carbide die insert, outer metal die, radial load pin, compression ring, load cell, and clamping ring were created in a 2D/3D CAD system known as Solid Edge\textsuperscript{38} and exported to Abaqus\textsuperscript{39}, an FEA software suite. Figure 11 (a) shows the parts modeled.

A finite element model of these components was constructed in Abaqus using tetrahedral elements because these define geometry better than cubic elements. Figure 11(b) shows the actual FE model.

Quadratic elements were used for the puck, carbide insert, radial load pin, compression ring, and load cell, in lieu of the demand for better accuracy in results in those components if maximum agreement with the experimentally determined friction coefficient was to be found.

The remainder of the components were meshed with linear elements. A quarter model approach was used due to symmetry of the system. Refer to the model as depicted below in figure 11(b).

Care must be taken to avoid compatibility issues at interfaces between linear and quadratic elements. This was circumvented by making each part homogeneous in either linear ($1^{st}$ order) or quadratic ($2^{nd}$ order) elements. At the interface between parts comprised of different orders of elements contact was established with fixed ties. This means the whole surface moves together.

\textsuperscript{38} “Solid Edge.”

\textsuperscript{39} “Abaqus FEA.”
Figure 11b: Experimental Simulation FE Model Constructed with Abaqus
4.2.2 Contact Analysis Approach

In reality, the outer metal die and the carbide die insert were shrink-fitted together. Therefore, subsequent to the shrink-fitting, they behaved as one component. In Abaqus, such a situation is modeled using the ‘tie’ constraint, which fuses two components together. However, the limitation of a tie is that it applies throughout all steps of the simulation, and cannot be turned off at any point. During the steps of the simulation in which the shrink-fit process was modeled, it would not be possible to apply a tie because a contact interface with stresses was required to accurately simulate the real condition. Furthermore, with a tie in place between the carbide die insert and the outer metal die, the carbide die insert would be prevented from making contact with the radial load pin during compaction and ejection. However, a tie was required during compaction and ejection because it was necessary that as the friction between the puck and the carbide die insert caused it to translate, it would cause the outer metal die to translate as well. Without this, no forces would be applied to the compression ring or the load cell, and so a friction prediction could not be made. Therefore it was necessary to create two models, one with a tie constraint and one with a regular frictional contact interface between the carbide die insert and the outer metal die.

Another issue was that in reality, after the shrink fit, the carbide die insert-outer metal die unit sat on top of the compression ring and was simply held in place by the clamping ring; as such, it was not fixed in any degree of freedom. However, in static FEA, every component must have some degree of freedom constrained; otherwise, the partial
differential equations defining it do not converge on a finite solution. A boundary condition could not be applied anywhere on the die unit because it was required that it be allowed to translate vertically and deform radially (in order to create the stresses necessary for a friction prediction). It could not be tied to the clamping ring for the whole simulation, because it also needed to be tied to the load cell and their combined stiffness would not allow the die unit to translate freely and compress the compression ring the right amount during compaction. It could not be tied to the compression ring during ejection for similar reasons.

Therefore four models were created. One modeled compaction with a tie between the die unit, one modeled compaction with a frictional contact interface, another modeled ejection with a tie, and the last one modeled ejection with the frictional interface. In the compaction models, the die unit was tied to the compression ring, and in the ejection models, was tied to the clamping ring. The puck was tied to the bottom punch. Friction between the punches and the carbide die insert was taken to be an arbitrarily low value of 0.01. This was an engineering decision based upon experience of practitioners at Stackpole. Furthermore, tests were conducted at other values of friction; 0.015 and 0.005. No differences were observed in stress distributions.

For the friction coefficient between the puck and the carbide die insert during compaction, reality was not simulated in this research. That was because the iron powder behaves in a plastic non-linear fashion in compaction, which although would have a significant affect on the friction coefficient (causing it to change through compaction)
was out of the domain of this work. Instead the paper by Wikman and N. Solimannezhad et al\textsuperscript{40} was used as a source for the value of 0.14 for the friction coefficient used in this work. This was reasonable, for one, because the authors of that paper used Distaloy AE in their work, a powder under investigation in the current work. Secondly, they arrived at that value by fitting the upper punch load after compaction computed by their FEA to the measured load from their experiment by optimizing this friction coefficient through a 17 iteration routine. This method ensured that the variation of the magnitude of the friction coefficient through compaction was accounted for.

4.2.3 Ejection Friction Model

Modeling friction at the die/part interface during ejection is central to this work. A single value estimation of the coefficient of friction throughout ejection is difficult to make, because it varies from the beginning to the end of ejection. Nonetheless a friction with wear criterion model has been developed for this purpose, based on the works of Curnier\textsuperscript{41} and Kravchuk\textsuperscript{42}.

Kravchuk established that the solution to the system of differential equations and boundary conditions describing the quasistatic problem of contact between a linearly elastic body and a rigid body, can be found using a method of successive approximations and existence theorems applied to the following quasivariational energy inequality:

\begin{footnotesize}
\textsuperscript{40}Wikman and N. Solimannezhad et al. \\
\textsuperscript{41}Curnier, A. \\
\textsuperscript{42}Kravchuk, A. S.
\end{footnotesize}
\[
\Delta E = \int_{\Omega} \sigma(u) \varepsilon(v) \, d\Omega - \int_{\Omega} \rho F^t \, d\Omega - \int_{Sc} P' \, dSc - \int_{Sc} \sigma v \, dSc.
\]

In terms of the iterative procedure, it is
\[
\Delta E = a(u^{t+dt}, w - u^{t+dt}) - \int_{\Omega} \rho F^t (w - u^{d+dt}) \, d\Omega - \int_{Sc} P' (w - u^{d+dt}) \, dSc - \int_{Sc} (\sigma^{t+dt} v) (dw - du') \, dSc,
\]

where \( a = \int_{\Omega} \sigma(u) \varepsilon(v) \, d\Omega \). See page xi for nomenclature.

For successive approximations to converge, the inequality of positive definiteness \( a \geq \alpha \) \(|v|^2\) must hold, and the friction coefficient \( f \) must satisfy the inequality \( f < \alpha / C \) where \( C \) is a constant defined by the elastic moduli, the body shape, and the fixing conditions.

In the definition of \( a \), \( \sigma(u) \) and \( \varepsilon(v) \) do not vary throughout the puck, and expressing \( v \) as the product of compacting punch speed \( s \) and quasistatic time step \( \tau \) the above inequalities can be combined and written as
\[
C < [\sigma(u) \varepsilon(v) V] / [(s \tau)^2 f]
\]

From Curnier, a force of tear \( F^S \) is defined as that which occurs when the sliding motion of the two bodies is monotone and oriented along some preferential direction, resulting into an anisotropic tear of the contact surfaces. Additionally a force of wear \( F^c \) is defined as that which occurs when the two bodies rub against one another in alternate arbitrary directions, resulting in an isotropic wear of the surfaces.

As defined by Curnier, the law of friction states that the force of friction is proportional to the load and independent of area of contact and other state variables. Combining this definition with the non-penetration condition the criterion of perfect friction is
\[ Y(F) = F_N \leq 0 \quad \text{for contact, and} \]
\[ |F_T| + fF_N - C \leq 0 \quad \text{for slip} \]

where \( C \) is as defined earlier.

Curnier states that the Euclidian norm of \( F_T \) being intended to allow for anisotropic surface roughness, can be disregarded in the current case. Also, the wear and tear forces are incorporated into the friction criterion by including a tangential tear force \( F_T^S \), and considering \( F^c \) to be starting with the virgin value \( F^c = C \), such that the criterion becomes

\[ Y(F) = F_N \leq 0 \quad \text{for contact, and} \]
\[ (F_T - F_T^S)^2 + fF_N - C \leq 0 \quad \text{for slip} \]

In the problem at hand, \( F_T^S \) may be considered absent and the slip region dominates. By including the definition of \( C \) this criterion can be rewritten as

\[ F_N f^2 + F_T^2 f - \{ \sigma(u) \varepsilon(v) \ V \} / (s \tau)^2 = 0. \]

\( F_N \) is taken as half of \( F_T \) according to a paper by PM Modnet\(^{43}\) and an estimate of \( F_T = 4000 \) N, the ejection force halfway through ejection, is also obtained from literature\(^{44}\) for a 9.87 mm tall compacted SC100 iron powder puck. With all quantities in the above equation therefore known, an arbitrary value of \( \tau = 0.0015 \) seconds is chosen to yield a reasonable \( f \) value of 0.14. This value gives input/output values of friction that match

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\(^{43}\) PM Modnet Methods and Measurements Group.

\(^{44}\) Gethin, D. T. et al.
closely. It is this value of $f$ that is used in the computational model as the friction coefficient for the die/part interface during ejection.

### 4.2.4 Loading and Kinematics

Loading and kinematics were applied to the simulation model in such fashion as would best mimic reality. To this end, the shrink-fit needed to be modeled accurately. This was accomplished by positioning the carbide die insert away from the outer metal die, applying pressure to the OD, moving the part into place, and releasing the pressure.

The linear springback had also to be accommodated for. This was done by first referring to data collected at the Stackpole Ltd. Automotive Gear Division plant in Mississauga, ON. The data was collected by performing metal powder compaction and ejection for a simple rectangular bar using E1177, a corporate iron powder mixture similar to Distaloy AE. Die cavity area was measured, and the corresponding areas of the ejected samples were also recorded. From this, an equivalent average strain of 0.004 in the long dimension was calculated. Using this as the strain in all three dimensions of the puck, the required post-compaction puck size was calculated from a desired (and expected) final, post-ejection puck size of 6.35 mm tall with 25.4 mm OD.

The top and bottom punches were positioned in the model such that the vertical distance between them equaled that for the required post-compaction puck size. A post-ejection sized puck was compressed in all directions, placed between the punches, and released. The face of the bottom punch that would be held in place by the piston was
fixed in all directions. With the face of the top punch in contact with the puck fixed in all directions, the requisite pressure was applied to the face that would be attached to the piston.

Finally, the pressure applied to the top punch would be reduced by 90% during the hold-down step, and then the bottom punch, puck, and top punch would all be translated upwards to eject the part out of the die unit. The top punch would be removed and the entire production process would hence be complete. Note that a step was created halfway through ejection to capture the stress state of the system during ejection.

4.2.5 Material Properties

In this analysis, all materials were taken to behave in a linear, elastic fashion with no temperature dependence. These were reasonable given that the strain region in which the components lay was far from the elastic-plastic boundary (well within the elastic region), and temperatures developed during part production were low enough to neglect any effects. The top and bottom punches were made out of AISI M2 steel, having $E = 228$ GPa and $v = 0.29^{45}$. The outer metal die was made of AISI 4340 steel, with $E$ and $v$ values of 205 GPa and 0.29 respectively.$^{46}$ For the carbide die insert, a C-12 grade carbide was used, with properties of 567 GPa and 0.28.$^{47}$ Also indicated by all drawings was a hardness of 58-60 HRC for each component.

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$^{45}$ Lindsay.
$^{46}$ Ibid.
$^{47}$ Wolfe.
For the puck, it was necessary to determine appropriate $E$ and $v$ values to use in the simulation, which would be able to represent the behavior of the powder as an elastic solid, through compaction and ejection, with a fair degree of accuracy. From Jonsen and Haggblad\textsuperscript{48} it was found that $v = 0.28$ was acceptable for iron powder compacts. For $E$, the following plot was obtained that shows the trend of $E$ with increasing density for green iron powder compacts.

![Graph showing Young's and Shear moduli as functions of density for green iron powder compacts.](image)

Figure 12: Young’s and Shear Moduli as Functions of Density for Green Iron Powder Compacts

For the purposes of the simulation prior to tuning with the experimental results, the Young’s Modulus at the highest density expected to be reached with the three powders,

\textsuperscript{48} Jonsen, Par and Hans-Ake Haggblad.
that being 7.31 g/cm³ with Distaloy AE, was used for the puck. That value was 24.4 GPa.⁴⁹

4.2.6 Puck Ejection Simulation

A summary is presented of the concepts given above as they pertain to the puck modeling. At the end of compaction, the forces on the puck are as shown in Figure 13(a). Figure 13(b) shows the forces on the puck during ejection (where $F_2 > F_1$).

![Figure 13: Forces on Puck at (a) End of Compaction and (b) Beginning of Ejection.](image)

An elastic, solid puck with linear elastic springback is assumed, and Poisson's Ratio and Young's Modulus values taken from literature. Tetrahedral elements are used due to their ability to better represent the curved geometry, and the 2nd order quadratic displacement model is chosen to calculate displacement on the nodes for better accuracy of results. Figure 14 below shows the meshed solid model of the puck (note that a quarter model was utilized due to symmetry).

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⁴⁹ “ASM Handbooks Online.”
Stress distributions, and hence forces leading to friction coefficients, can be shown at the end of compaction and at four stages during ejection. Similar results were expected at these four stages. Figure 15 shows the relative positions of these stages, with stages a) and b) as defined in Figure 13. Stages c) and d) are simply when the puck is further up the die cavity, and stage e) is upon complete ejection of the puck from the die.

Figure 15: Relative Positions of Stages of FEA
With the springback data from Stackpole Ltd., and friction values from literature and the author’s model, friction values at the puck/die interface could be obtained as a result of the analysis. The following figure shows the von Mises stress distribution within the puck, as predicted by the analysis, at the end of compaction (top) and during ejection (bottom). Identical scales are used to present the stresses in MPa. Note that an unnaturally high maximum stress, very similar in both steps, was found despite the application of different forces. This was due to the presence of a singularity that appeared within the mesh (inset). It was identified as such because of the continual increase in stress observed within its region (visible in grey) with corresponding refinement of the mesh. It can therefore be disregarded.
Figure 16: Stress Distributions within Puck at the End of Compaction (Top) and During Ejection (Bottom) with View of Singularity (Inset)
4.3 Results

4.3.1 Convergence Studies

The shape of the contact surfaces can be adjusted automatically within Abaqus – this is a function that can be chosen. It is only necessary to refine the mesh at:

- The face of the load pin in contact with the carbide die insert
- The compression ring
- The load cell

These are shown in Figure 17 (refer to Figures 11a and 11b for initial meshed representation of these parts). Figure 25 also shows elements that were modeled.
Figure 17: Radial and Axial Stresses in MPa at End of Compaction and Halfway Through Ejection for Compression Ring (Top), Load Cell (Middle), and Load Pin Face (Bottom)
The results of the convergence study are shown below in Figure 18, for the radial forces on the load pin and axial forces at the strain gage locations identified in Figure 24. As noted in Chapter 4.3.2 the forces are based upon experimental data collected at the facilities of the industrial partner. The convergence study was conducted by decreasing the length of the sides of the tetrahedral elements used (in which all sides are equal length by definition). This has the effect of refining the mesh. As mentioned earlier this refining of the mesh was done only on the face of the load pin in contact with the carbide insert, the compression ring, and the load cell.

![Figure 18: Mesh Convergence Study Results for Radial Force on Load Pin Face and Axial Forces on Strain Gauges](image-url)
4.3.2 Contact Analysis Results

The radial force results on the load pin in the frictional interface model, and the vertical force results on the load cell and compression ring in the tie models, are determined to draw comparison with past studies. These are shown in Table 2 for the ideal meshes as determined in the convergence studies. The contact force results are shown at the end of compaction and halfway through ejection, so as to allow proper prediction of $f$. The foregoing is developed with experimental data from an industrial partner – see acknowledgements.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maximum Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compaction</td>
</tr>
<tr>
<td>Load Pin</td>
<td>18.57</td>
</tr>
<tr>
<td>Compression Ring</td>
<td>3.04</td>
</tr>
<tr>
<td>Load Cell</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 2: Maximum Force Predictions at End of Compaction and Halfway Through Ejection at Load Sensors

The preceding table summarizes the maximum forces predicted by the FE model at the load pin and strain gages in the load cell / compression ring during compaction and halfway through ejection.
4.3.3 Friction Coefficient

The nature of $f$ during the ejection phase in PM is not well understood. No computational model to date has been developed that explicitly includes a value of friction coefficient that is different during ejection than the one used during compaction. In the present study, friction between the puck and carbide die insert is implemented using an optimized coefficient during compaction from past literature, and one derived by a friction with wear criterion model during ejection. Changes in this coefficient have an effect on the axial loads experienced by the die unit in being pushed down or pulled up along with the powder compact during compaction and ejection.

Values of $f_c = 0.14$ and $f = 0.14$ are used in the FE model. Maximum axial and radial forces observed during compaction and ejection respectively, as noted in Table 2, are then used to calculate friction coefficients as per $f$ and $f_c = \text{Radial Force} / \text{Axial Force}$ to see how the effects of the friction inputs spread throughout the system. These resulted in $f_c = 0.16$ and $f = 0.13$.

4.3.4 Discussion

A computational contact FE model was created to simulate friction during the PM production of a simple puck. Values of friction coefficient from literature and from a friction with wear criterion were used during compaction and ejection respectively. Convergence tests were performed to determine optimum mesh density. Predicted values
for axial forces in strain gage locations and radial forces in the load pin passed the convergence tests indicating the model was computationally robust.

Contact analysis results gave maximum axial forces of 3.04 kN and 1.07 kN, and radial forces of 18.57 kN and 8.02 kN, during compaction and ejection respectively. This is in agreement with the paper by Gethin et al\textsuperscript{50}, despite the different material model, loading, kinematics, and contact analysis approach used here. Values found for axial forces during compaction and ejection were 13.26 kN and 4 kN, respectively (Gethin et al). There is agreement between results of radial and axial forces developed due to friction on the die unit with past literature. However to the best of the author’s knowledge, no previous work has experimentally determined radial force values during compaction and ejection Therefore, it was not possible to verify these.

The use of different friction coefficients for compaction and ejection in PM was investigated. A friction with wear criterion for ejection was derived from the quasistatic solution of a general contact problem, and was used to obtain \( f = 0.14 \). Because the value of \( f \) varies through ejection, this value was chosen as it was expected to represent the friction condition halfway through ejection. A value of \( f_c \) for compaction was obtained from past literature in which \( f_c = 0.14 \) was found through optimization to account for the variation in \( f_c \) during compaction accurately. Friction coefficients were then calculated from force results from the computational model to see how the effects of the \( f \) and \( f_c \) inputs spread throughout the system. These were found to be \( f_c = 0.16 \) during compaction

\textsuperscript{50} Gethin et al.
and $f = 0.13$ during ejection. They showed agreement with the inputs and hence validated the successful FE representation of the effects of friction in the entire model.

One of the problems with the current model is the material model used for the puck. Although a non-linear and plastic particulate model is required, a linear elastic solid model is used. As a result of this the single friction coefficient value used attempts to represent a quantity that varies through the compaction step. Similarly the single value used for $f$ during ejection attempts to represent a quantity that changes through the ejection step. However in this case, the changing ejection $f$ is due to dynamic effects, and this is the other major problem with the model in that the static model used in it cannot be used for effective representation either.
Chapter 5

Modeling of Production of Synchro Hub

5.1 Introduction

It was now desirable to determine whether the behavior of tooling involved in producing a complex part could be accurately modeled using FEA. To this end, a linear elastic, static, implicitly solved FE model was attempted of compaction of E1177 iron powder in the production of a synchro hub in the Pontiac Solstice, manufactured by the Automotive Division of Stackpole Ltd. at their Mississauga, ON plant. The intent was eventual validation of it with both data from Stackpole Ltd. and an experimental setup discussed in Chapter 6.

In order to ensure that the model was a precise representation of reality, models of the tooling were created in Solid Edge, and imported into Altair Hypermesh\textsuperscript{51}, an FE pre-processing software. Loading was applied and linear contact analysis was set up. This static model was submitted to the Abaqus implicit solver, but the memory resources available at Queen's University were not sufficient to solve the problem with contact analysis. It was not possible to successfully solve the model with HPCVL more than two contact interactions. Meaningful results were obtained in the non-contact regions of the

\textsuperscript{51} “Altair Hypermesh.”
model, where penetrations between components were observed. These were indications of wear and potential binding.

It should also be noted that due to the nature of the geometry, many vertexes with acute angles were present. In such regions, known as singularities, FE software have difficulty converging to a finite stress value, and keep increasing in a convergence test. Therefore these regions always show stresses far greater than surrounding regions and must be ignored in the interpretation of the results, as was done in this work.

5.2 Methods

5.2.1 Modeling Approach

An FE model of the tooling involved in producing synchro hub was created. Drawings provided by Stackpole for each component were used to create the 3-D models in Solid Edge. These were imported into Hypermesh, where they were assembled. The following components were modeled: the core rod, carbide die insert, outer die, top inner punch, top middle punch, top outer punch, bottom inner punch, bottom middle punch, and the bottom outer punch. The outer die and carbide insert were tied together. Note that half-symmetry was applicable and so was used. Refer to Figure 19 below.
Figure 19: Hypermesh Assembly of Synchro Hub Tooling
Meshing was conducted using quadratic tetrahedral elements, due to the highly complex geometry. Very fine meshes were required at the numerous, large contact interfaces between components to accurately represent the complex faces that were interacting there; however, it is important to note that the mesh densities used were the absolute minimum possible that did not allow excessive element distortion during contact interaction setup (Abaqus will adjust the slave nodes to remove overclosure, and in doing so distort elements). Highly distorted elements, such as those resulting from initial attempts at using extremely coarse meshes, would have resulted in highly inaccurate data.

5.2.2 Loading and Kinematics

Only the compaction phase of the production process was considered. To this end, the bottom faces of the outer die, carbide insert, and core rod, along with the faces of the punches at the ends opposite to those that would be in contact with the powder, were fixed in all degrees of freedom. The symmetry condition was applied to the faces that lay in the symmetry plane. Finally, the punch faces that would be in contact with the powder had a pressure of 800 MPa applied to them. This was the value used at Stackpole Ltd. to press the powder.

5.2.3 Material Properties

In this analysis, all materials were taken to behave in a linear, elastic fashion with no temperature dependence. These were reasonable given that the strain region in which the
components lay was far from the elastic-plastic boundary (well within the elastic region), and temperatures developed during part production were low enough to neglect any effects. From the drawings provided by Stackpole Ltd., the material of each component was ascertained. The top and bottom inner punches were made out of AISI M2 steel; the remainder of the punches were made of Vanadis 4 steel, with $E = 205$ GPa and $v = 0.29^{52}$. The outer metal die was made of AISI 4340 steel. For the carbide die insert, Stackpole Ltd. used a modified C-11 grade carbide, with properties of 567 GPa and 0.28. Finally, the core rod was of C-13 grade carbide. Also indicated by all drawings was a hardness of 58-60 HRC for each component.

5.3 Results

5.3.1 Contact Analysis Results

Upon first attempt, the model was submitted to the Abaqus implicit solver with computing resources available at Queen’s University. Encountering an error stating a lack of sufficient memory, the contact interactions were removed one by one and the simulation was rerun each time. It was found that using these resources, the simulation would only run without any contact. However due to the deformation of tools, some wear and binding predictions could be made (as covered in the next section).

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A subscription to HPCVL, the High Performance Computing Virtual Laboratory in Kingston, ON, was obtained due to the ample memory that would be had there. In essence, the network consists of a network of 216 dual-core 1.5 and 1.8 GHz processors with 8 GB of RAM available to each. By availing a larger number of processors during a simulation, more memory can be accessed.

The procedure used for submitting a job was to first create the assembly, apply loads and boundary conditions, define contact, and conduct meshing in Hypermesh. The input file generated was imported into the local Abaqus server and a Data Check, an operation in Abaqus where the software conducts a check to ensure the success of the simulation beforehand, was carried out. Upon its success, the file was sent to HPCVL. Via a UNIX based interface, the file was converted from DOS to UNIX format, and necessary supporting files were created that would describe for the system how many processors and what kind of memory distribution system to use. The simulation was then run.

It was found that, even despite a successful Data Check, the full contact model submitted to HPCVL would generate a fatal error. Intensive troubleshooting, conducted in conjunction with Dr. Hartmut Schmider at HPCVL, uncovered a bug in the HPCVL system that was causing the simulation to shut down following pre-processing (the first phase of a simulation in which Abaqus sets up the assembly, contact surfaces, boundary conditions, etc.). They could not resolve the issue. Again, as done with the local resources, contact interfaces were eliminated one by one. Also, the number of processors used was reduced systematically. It was found that the simulation ran successfully if the
contact was run with no more than two processors, and limited to a tie between the outer die and the carbide die insert and one friction interaction. The interface between the bottom outer punch and the carbide die insert was chosen because the non-contact analysis showed most severe contact there. An arbitrarily low value of 0.01 for the friction coefficient was used.

Below is a view of the output file generated by the Abaqus solver at HPCVL. Shown are the von Mises stresses developed in the tooling as a result of compaction, with the view cut to view a quarter model instead of the half model, and so allow a better view of stresses. It can be seen in Figure 20 (with components as defined in Figure 19) that significant stresses are developed in all components other than the die. These stresses, disregarding singularities at vertexes in the model where artificial regions of high stress are created, are at a maximum of around 1.5 GPa. This is well below the compressive strength value for Vanadis 4 and M2, which is 2 GPa (at 58 HRC)

\footnote{Ibid.}
Figure 20: View of Contact Run Stress Plot Results in MPa from HPCVL

Also, additional stresses can be seen in Figure 21, an extreme close-up view, in the top outer punch and carbide die insert resulting from contact between them. The view is shown with the maximum legend von Mises value of 2.4 GPa in order to put the stresses into perspective with regards to the compressive strength of the punch material (AISI
M2). The grey areas are indicative of elements that are experiencing stresses higher than the compressive yield strength of the material.

![Image of von Mises Stress Distribution](image)

**Figure 21:** Plot of von Mises Stress Distribution in MPa from Contact Run at HPCVL

### 5.3.2 Wear and Binding

Significant conclusions were drawn in regards to wear and binding by analyzing the results of the model of compaction. Regions of penetration between components were observed in the non-contact regions, brought about by the Poisson’s Ratio effect resulting from a vertical load on the components; a vertical compression leads to a proportional...
lateral expansion. Table 3 below provides a summary of these vertical punch deflections via analytical and FEA methods.

<table>
<thead>
<tr>
<th>Punch</th>
<th>FEA Deflection</th>
<th>FEA Deflection</th>
<th>Analytical Prediction of Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%)</td>
<td>(mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>Top Inner</td>
<td>0.15</td>
<td>0.22</td>
<td>0.29</td>
</tr>
<tr>
<td>Top Middle</td>
<td>0.35</td>
<td>0.72</td>
<td>0.80</td>
</tr>
<tr>
<td>Top Outer</td>
<td>0.31</td>
<td>0.29</td>
<td>0.37</td>
</tr>
<tr>
<td>Bottom Inner</td>
<td>0.28</td>
<td>1.55</td>
<td>1.44</td>
</tr>
<tr>
<td>Bottom Middle</td>
<td>0.31</td>
<td>0.88</td>
<td>1.08</td>
</tr>
<tr>
<td>Bottom Outer</td>
<td>0.34</td>
<td>0.45</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 3: Summary of Vertical Punch Deflection Predictions

It can be seen that agreement between the predictions of the FEA and those obtained via analytical methods was found. The discrepancies that were seen were a result of the approximations that had to be made in calculating the areas used in the method, described in Chapter 6.3.3, to be used in the analytical deflection predictions.

These vertical deflections led to horizontal deflections that caused the OD and ID of each component to get larger. For the purpose of characterizing the extent of penetration at all tooling interfaces, a simulation was run with no contact. Penetrations resulting from this were observed between the bottom inner and middle punches, bottom outer punch with the carbide die insert, top inner and middle punches, top middle and outer punches,
and top outer punch with the carbide die insert. The most severe case was between the bottom outer punch and the carbide die insert, which was a penetration of 0.25 mm over distance of 19.05 mm. Refer to the figure below.

![Region of Most Severe Penetration](image_url)

Figure 22: Region of Most Severe Penetration Observed in Non-Contact Analysis

As described earlier, the contact analysis predicted very high stresses between the bottom outer punch and the carbide die insert. Coupled with the prediction of serious
penetration at that interface from the non-contact analysis, it can be safely said that wear will occur there, with the possibility of binding.

5.4 Discussion

In this chapter, an FE model of compaction of a synchro hub was set up with the intent of validation via comparison to data from Stackpole Ltd. and an experimental test setup designed to mimic the situation. Subsequently, once confidence in results was achieved, it was desired to make predictions on any wear and binding that may occur between tooling components, in addition to estimating a friction coefficient during ejection. A lack of memory issue arose with resources available at Queen’s University, related to the large number of elements required to sufficiently define the highly complex geometry at the contact interfaces. A subscription was obtained for HPCVL, the High Performance Computing Virtual Laboratory in Kingston, ON, but problems inherent to HPVL again prevented successful contact analysis of the whole problem. Meaningful results on wear were still obtained from a non-contact and a limited-contact analysis.

It was not possible to verify these results with the data from Stackpole Ltd., because that consisted of springback and punch force-time curves which would be meaningless without a full contact model. Mesh convergence was not carried out either, because increasing the mesh density would require using more processors, in which case the simulation would not work at all. To the best of the author’s knowledge, no past studies have performed a direct validation of a contact model for a highly complex automotive
part such as the synchro hub at hand, in which meaningful data was compared to experimentally derived results. Therefore, the issues that arose during the author’s attempt could not be compared to any prior attempt.

Many singularities were observed in the model. Disregarding stresses predicted in those regions, it was found that all tooling components experienced stresses up to a maximum of 1.5 GPa, well below the compressive yield strength value of their materials of 2 GPa. This agreed well with expectation. In the contact region between the carbide die insert and the bottom outer punch, very high stresses were observed. This was consistent with the presence of an exceptionally high concentration of acute-angle vertices in the area, hence singularity regions. As mentioned earlier it was not possible to refine the mesh any further due to the fatal error encountered at HPCVL; however, given the stress distribution in the surrounding region is likely to be around 1.79 GPa. It is reasonable that this is higher than that in the bulk of the tooling, but still lower than the compressive yield strength.

Calculations were done to compute the vertical deflections in the punches expected as a result of compaction. Results from the FEA compared well with these, in light of the difficulty in splitting the components up into a sufficient number of sections such that each section has a homogenous cross-sectional area. With the most serious penetration in the non-contact analysis being found at the interface set up for contact in the contact analysis, the fact that the stresses predicted there are so high seems reasonable. This is encouraging because although the combined evidence from the non-contact and contact
analyses indicate wear at many interfaces, the stresses developed at all other interfaces would be lower than that at the bottom outer punch and carbide die insert interface, and even the stresses there are reasonable.

The main problem with the current model was the lack of inclusion of any effects from the powder during compaction. This would result in lower radial stresses on the carbide die insert, because in reality the powder would push out against it as it was compacted. It would also result in a lack of vertical stresses on the carbide die insert, which would come from friction between the powder and it during compaction.
Chapter 6

Test Setups

6.1 Introduction

Based upon experience with the models developed in this thesis, and noting that the models used data from Stackpole in designing the machine elements, experimental tests are proposed for two scenarios: 1) a simple test puck setup, and 2) a complex test puck setup. They are described in the sections below.

6.2 Simple Puck Test Setup

6.2.1 Overview

To validate the computational model being developed, an experimental test setup is being built at the Mechanical Engineering Department at Queen’s University. Compaction and ejection of metals powders will be performed in order to produce simple pucks and draw comparisons to a computational wear simulation of the exact same
experimental setup using linear contact analysis in Abaqus. This will be done in order to allow changes to be made to the model and its implementation to match experimental results; specifically, it will allow the inclusion of an estimation of the actual friction coefficients to be found between the part and the die during compaction and then during ejection.

To ensure the validity of the experimental results and to allow comparison with previous powder metallurgical process studies, the machine is designed to produce pucks with a standard outer diameter and thickness. In addition to this, powders obtained for the experimentation were chosen in accordance with those used most commonly in previous work.

6.2.2 Materials and Methods

6.2.2.1 Experimental Apparatus and Materials

The experimental machinery is a hydraulic press with two cylinders acting opposite to one another in a vertical configuration (see Figure 23). In this configuration the top and bottom punches can be moved independently. At the centre is a powder metal die manufactured specifically for this application while closely replicating production conditions. The die is made of two components. An outer casing made of AISI 4340 high alloy steel and a die insert of grade 12 carbide. Both of which are typical in industrial applications. Surface finishes, press fit characteristics, tolerances, and geometric detailing are all similar to those found in the automotive industry today.
The press will be used to carry out measurements on three kinds of metal powders – SC100.26, NC100.24, and Distaloy AE. These powders have been chosen to allow comparison of results to the largest selection of relevant papers, as they were found to be most commonly used in previous works. They are also reflective of the kinds of powders with the kinds of characteristics usually used in industry. Refer to the table below for a summation of their compressibility properties.

<table>
<thead>
<tr>
<th>Applied Pressure (MPa)</th>
<th>Density (g/cc)</th>
<th>SC100.26</th>
<th>NC100.24</th>
<th>Distaloy AE</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>6.35</td>
<td>6.25</td>
<td>6.74</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>6.91</td>
<td>6.83</td>
<td>7.14</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>7.16</td>
<td>7.07</td>
<td>7.35</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Compressibility of Experimental Powders

6.2.2.2 Loading and Kinematics

Measurements carried out include, firstly, the positions of the top and bottom punches. This allows for careful control of their positions as they must work in tandem during the ejection process, holding the component between them with a force approximately equal one tenth the force needed for compaction while moving upwards until the component is fully removed from the die. Second, the forces applied to the test specimen by each of the punches are recorded at all stages of the process. See Figure 24 for a closeup of the vertical force sensors on the press.
Third, the vertical forces acting on the die, a direct result of friction between the specimen and the inner die wall, are measured using a compression ring (Figure 25).
during compaction and a tension load cell during ejection. Last, the radial force resulting from the exertion of pressure from the test component on the wall of the inner die is measured using the radial sensor pins shown in Figure 29. With the measurement of both the radial force on the die wall and vertical force on the same wall a ratio equal to the coulomb friction coefficient is revealed - one of the primary goals of this research initiative.

Figure 25: Section Detail Schematic of Experimental Test Setup
6.2.2.3 Experimental Procedure

The procedure developed to carry out the experimental work was formulated to recreate industrial techniques as closely as possible. As such, the steps to be followed would be as described here:

1. Draw bottom punch up to a certain distance below the top of the die, equal to the depth of powder required to yield a part of the desired final thickness after compaction. This is calculated by accounting for the compressibility and expected springback of the powder.

2. Insert powder manually by filling the cavity created by the die and bottom punch (described above), smoothing the top surface of the powder-filled cavity by hand such that it is flush with the top of the die.

3. Draw the bottom punch down to a depth within the die that would result in the compacted part being aligned with the radial sensors at the end of compaction. Note depth at the compaction face of the punch, as shown by bottom punch depth monitoring control.

4. Lower the top punch, stopping movement once the difference between the depth of its compaction face and that of the bottom punch is equal to the desired final part thickness. Note the vertical force via the force sensors in the top punch.

5. Raise the top punch such that the vertical force equals one-tenth of the force noted in the previous step. This is the holddown force.

6. Raise both punches simultaneously and eject the part completely from the die.

7. Raise top punch such that it loses contact with the part. Remove the puck.
6.2.3 Discussion

A hydraulic test setup is being built. It is important to emphasize that although industrial techniques and materials were matched as closely as possible in this, for the sake of simplicity it was not intended as a recreation of a part with any real-life application. Experimentation will be used in this case to draw comparisons to a finite element simulation model with the same loading and boundary conditions, and to past powder metallurgy friction coefficient studies.

6.3 Proposed Complex Puck Test Setup

6.3.1 Overview

To further validate the results obtained from the synchro hub FEA in Chapter 5, and hence improve confidence in its predictions of wear and binding, a complex puck test setup was proposed. By modifying the test setup described in Chapter 6.2 through the inclusion of a core rod, it was intended that further data on friction between powder and the tooling would be produced and any variation in it from the core rod to the die would be exposed. Also, the greater number of components would increase the amount of component interactivity data available and create more significant wear. The examination of contributions of powder-tooling interactions and tooling-tooling interactions to wear
could be carried out, and hence lead to a better understanding of wear and binding of tooling at Stackpole Ltd.

6.3.2 Materials and Methods

The experiment and component designs presented in this section were a result of a trial-and-error process in which design verification techniques, details of which are presented in Chapter 6.3.3, were used continually to arrive at the optimal designs.

6.3.2.1 Experimental Apparatus

This being a modification to an already existing simpler test setup, the major constraint in the design was to ensure maximum backwards-compatibility. The ability to use as many of the existing components as possible and minimize changes to the assembly would allow for a more efficient and cost-effective solution. Hence, the only changes were the replacement of the existing top and bottoms punches with new designs. Further components would be introduced as well, as described below.

The premise of the new design was the inclusion of a 12.7 mm OD core rod, thus producing an annulus with 25.4 mm OD, 12.7 mm ID, and 6.35 mm thickness. This core rod was required to be fixed in place, with no motion throughout the production process, without interfering with the activity of the punches. It was imperative that this be so because during compaction and ejection, friction between the powder and the core rod
would pull the core rod downwards and then upwards respectively. To allow the core rod to move with the powder would then not model the synchro hub production at Stackpole Ltd. accurately, because their core rod was immovable as well.

At Stackpole Ltd., their method of fixing the core rod in place was to drive a hole through the length of the core rod and put a bolt through it, which would thread on to an immovable platen. This was impossible in this setup because of the much smaller diameter of the core rod. The larger diameter carbide core rod at Stackpole Ltd. would be able to sustain the weakening due to the presence of a hole, and increased susceptibility of failure due to any small lateral forces while under axial load, despite the brittleness of the material. However, a 12.7 mm OD rod would not be able to do so.

This made it necessary to fix the core rod to the press table surface. The system to accomplish this would, due to the geometry of the assembly, be required to be in two separate parts: one above the press table, and one below, to fix the two ends of the core rod. Further, it would need to pass through and out the sides of the punches, because the ends of the core rod would be inside hollowed out spaces in the punches (to accommodate the core rod as compaction proceeded). Finally, provision had to be made for a method to measure the vertical forces on the core rod due to friction during compaction and ejection. The assembly of the proposed design is shown below, with descriptions and figures of each component. Unless otherwise noted, as per industry norm, units are inches and tolerances to be used are +/- 0.005”.

Support: This component would be secured to the press table via four Grade 9 hex head bolts, 1 ¼” long with 3/8”-16 thread. Its angled nature was to allow it to both be secured
to the press table and reach over the top edge of the die as far as possible (to reduce the length of the crossbar horizontal piece and minimize the ‘moment arm’ effect on it, hence reducing stress due to the load from the core rod).

Figure 26: Support
Plug: The plug would be manufactured out of a block of steel, and hammered into the support. They would then be welded together. The lip would be required to avoid contact with the top edge of the die, desirable for reasons outlined in the support description.

Figure 27: Plug
Crossbar: This component would be created out of one piece of AISI M2 steel. The top crossbar would sit in the groove in the plug and held in place by the slab, pressed against the top surface of the core rod. The bottom crossbar would be identical to the top, except for a ¼” hole centered ¼” from the end, at both ends of the horizontal section. These would be used to hold it to the underside of the press table by two Grade 9 hex head bolts, 1 ½” long with ¼”-20 thread. The hole in the shaft (shown in Detail D in the figure below) would accommodate a similar-sized protrusion on the ends of the core rod. The draft angle on its wall would, in conjunction with a similar draft angle on the protrusions on the core rod ends, serve to center the core rod to eliminate lateral movement and hence minimize the likelihood of failure under axial load. Lastly, strain gauges would be attached to the horizontal sections on the faces closest to the powder, close to the secured ends. The electronics are identical to that of the strain gauges in the simple test apparatus.
Figure 28: Top Crossbar

Shaft

Horizontal Section
Slab: The slab would be made out of one piece of steel, and would be held in place on top of the plug with a 3/8”, 1 ½” long Grade 9 hex head bolt with 3/8”-16 thread. Its purpose would be to hold the crossbar down as the carbide pushes up on it during ejection.
Core Rod: The core rod would be made out of one solid piece of C-11 carbide, and would be held in place by the top and bottom crossbars. The drafts on the protrusions at either end of it would, when coupled with the corresponding drafts on the insides of the holes on the ends of the crossbars, serve to center the core rod.

Figure 30: Core Rod
Top Punch: This component, made out of one piece of AISI M2 steel, would be mounted on to the top piston via a clamping ring. As explained earlier, the hollowed inside would be to accommodate the core rod as the punch approaches its end-of-compaction position. The slot through the side is to allow the horizontal portion of the crossbar to pass through, to sit on the plug located outside.

Figure 31: Top Punch
Bottom Punch: It would be similar to the top punch except it would be mounted on the bottom piston. The bottom crossbar would pass through it and be bolted into the bottom of the press table.

Figure 32: Bottom Punch
6.3.2.2 Tolerancing and Clearances

Many dimensions do not require extraordinarily close tolerances, so as mentioned before the majority would be specified to +/- 0.005”. This was chosen as the tightest tolerance achievable with relative ease by the lab technicians at the Queen’s University Mechanical Department Machine Shop, without resorting to more expensive manufacturing methods. However, given the close fits of several components, it would be necessary to give attention to the clearances and tolerances at the following interfaces. Note that considerations for the high importance attached to these interfaces included eliminating particle penetration into the interface (with grain sizes on the order of 1.77 x 10^{-3} inches without allowing contact between components that would lead to significant binding.

Crossbar-Punch: Both components would have an idealized OD and ID respectively of ½”. However a gap and tolerances on both are required that accommodate the abovementioned considerations. To this end, the ANSI Standard for Running and Sliding Fits (RC) was used. The RC 3 fit is described as a precision running fit, and is the closest fit which can be expected to run freely. It is intended for precision work at slow speeds. This fit was used in determining the clearance and tolerances because it described the use of these components well. Accordingly, the crossbar shaft OD was reduced to 0.4992 +/- 0.0002” and the punch ID was increased to 0.50035 +/- 0.00035”.

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Crossbar-Core Rod: The idealized diameter would be ¼”. RC 2 was used in this case, because it describes the interaction of these components well, in that it is intended for accurate location, and parts made to this fit turn easily but are not intended to run freely. In keeping with this the hole diameter in the crossbar shaft would be specified at 0.25 + 0.0004”, and the protrusion diameter on the ends of the core rod would be 0.2498 +/- 0.0002”. The depth of the hole was set at an arbitrarily small tolerance of 0.125 +/- 0.0002”, with the heights of the protrusions on the core rod set at 0.125 + 0.0002”, so as to allow for slight touching. The draft angle on both was also set to an arbitrarily small tolerance value of 92.5 +/- 0.5°.

Core Rod-Punch: With the core rod required to be the same OD as that of the shaft on the crossbars, its OD would be set as 0.4992 +/- 0.0002”.

Punch-Carbide Die Insert: The ID of the carbide die insert was preset at 0.998 +/- 0.0002”. Choosing to be in accordance with the sizing and tolerances set for the simple setup punches by Alex Szekeres, the OD of the new punches would be 0.9967 +/- 0.0002”.

6.3.2.3 Loading and Kinematics

Axial loads would be applied to the ends of the top and bottom punches furthest from the powder, via the corresponding pistons, oriented towards the powder. In doing so, the punches would move downwards and upwards respectively (relative to the ground). The
crossbars, passing through the slots in the sides of the punches and fixed to the press table, would not obstruct punch movement because the slot length would be slightly greater than punch travel distance.

6.3.2.4 Experimental Procedure

Setup

The top and bottom punches would first be removed from the setup and replaced by the newly designed ones, which would be retracted to their pre-compaction positions. Next, the crossbars would be slid into position, bolting the bottom crossbar to the press table, and the core rod would be placed inside the bottom punch resting on the crossbar and with the top crossbar resting on it. Following this, the support-plug assembly would be slid into position under the top crossbar and bolted on to the press table. Finally, the slab would be positioned on the plug and bolted into place. This would all be done loosely, and once all parts were in place the bolts would be tightened in such manner as to ensure correct alignment of all components.

Experimentation

The same three powders (Distaloy AE, SC100.26, and NC100.24), would be compacted. Using compressibility data\textsuperscript{55}, and with the intent of producing the puck at the

\textsuperscript{55} Hoganas Iron and Steel Powders for Sintered Components.”

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center-line of the topmost normal load pin, the procedure outlined in 4.2.3 for the simple puck test setup would be replicated.

6.3.3 Design Validation

In order to keep results as similar as possible to the simple test setup, the same materials was chosen for the new components as with those in the simple setup. Stress-strain calculations were first done using the Young’s Modulus relation to ensure the amount of was acceptable. Knowing that the maximum pressure used at Stackpole Ltd. to produce their parts was 800 MPa, that pressure was considered to be applied to the face of the punches in contact with the powder. This resulted in an equivalent force of 300 kN, which was then applied independently to the various cross-sections of the punch. The individual deflections were found and added up. For the bottom punch, this total was 0.66 mm over a total punch length of 190.5 mm, which is insignificant.

Similar methods were used to ensure that the final designs for the core rod and crossbars were sound. This was followed by creating solid models of all the new component designs, and running finite element simulations on them with appropriate loading, boundary and material conditions in order to double check the soundness of the designs. It should be noted that this was an iterative process. The analytical method outlined above was carried out, rejected based on unacceptable stresses developed, and modified until the analytical results were satisfactory. Upon running the computational simulation, areas of concentrated stress became evident that then required design changes
and beginning the cycle again. Another consideration that had to be kept in mind throughout the design process was the requirement that the new components fit in the existing simple test setup apparatus with minimal effort and modifications.

6.3.4 Discussion

A test setup was designed as an upgrade to the existing simple puck test setup, to allow for more extensive analysis of the frictional behavior of the hydraulic press and the part produced. It is important to emphasize that although industrial techniques and materials were again matched as closely as possible in this, for the sake of simplicity it was not intended as a recreation of a part with any real-life application – simply one with more characteristics of a real gear, namely the inclusion of a hole in the middle of it. Experimentation would be used in this case to draw comparisons to the finite element simulation model (described in Chapter 5) with the same loading and boundary conditions. In addition, it could be used as an investigation on the behavior of various core rod materials.
Chapter 7

Conclusions

The following goals of the present study were achieved in accordance with the outlined research objectives:

1. A contact model was created, for compaction and ejection of iron powder to produce a simplified gear or puck, using linear finite element analysis to predict frictional forces/coefficients between the die and the part. It was found that results agreed with previous studies. Data from Stackpole was used to develop elastic models of the equipment.

2. A test setup to carry out compaction and ejection of iron powder to produce a puck was designed and built.

3. An attempt was made to develop a contact model for compaction and ejection of iron powder to produce a complex gear using linear FEA to predict the following: punch face deflections, stresses in the punches, core rod and die, and frictional forces and nature of contact between components. This was not completed because it was found that the memory resources available were not sufficient to carry out the simulation.

4. In collaboration with Mr. A Szekeres, a test setup was designed to carry out compaction and ejection of iron powder to produce a puck with a hole through the center; the setup was not actually built. Upon completion it will be able to
perform experiments and compare results with both certain predictions of the synchro hub FEA and data from Stackpole.

Chapter 8

Recommendations for Future Work

As outlined in the work presented above, there is much future work that can be done in this project. To begin, once the simple puck test setup is completed, experimentation can be carried out and used to validate the corresponding finite element simulation. With this tool, the simulation can be tuned to represent reality and then be used as a reliable source of information in regards to behavior of the friction coefficient during compaction and separately during ejection.

Also, the complex test setup remains to be built. Upon its completion, friction effects due to presence of the core rod can be examined, something that is likely to introduce complexities not seen in the simple puck setup. If this were to be combined with a completed finite element model mimicking its loading and boundary conditions, a validated computational simulation would be had that could be used as a basis for far more complicated analyses involving more realistic parts.
Chapter 9

References


“ASM Handbooks Online”. Volume 7, p 344 to 354.


“Economics focus.” The Economist, p 80. 16 December 2006.


“GKN Sinter Metals”. February 1 2007 <http://www.gknsintermetals.com/>


“International Road Federation.” The Economist. 11 April 2002.

“Isostatic Pressing”. 30 October 2006


<http://pickpm.com/>


“Precision P/M”. February 1 2007 <http://www.precisionpm.com>


<http://www.wpi.edu/Academics/Research/PMRC/Research/>


“Sintermetali Ltd.” 13 April 2007 <http://www.sintermetal-bg.com/about.htm>


“SMS Meer SMS Group”. 30 October 2006 <http://www.sms-meer.com/index2_e.html>


“Spray Forming”. 15 October 2006
<http://www.mpif.org/DesignCenter/spray_form.asp?linkid=45>

Szekeres, Alex. “Final report on ejection, machine and compaction modeling”. Kingston, ON: Mechanical and Materials Engineering, Queen's University.


Appendix A

Further Background on Powder Metallurgy

Industry Analysis

I. Latest Information\textsuperscript{57}

In 2005, in North America, the following observations were made:

- A decline in SUV sales led to a decline in metal powder shipments.
- Iron powder parts market was experiencing the most growth in Asia at the expense of North America and Western Europe.
- Wild fluctuations in commodity prices were seen.
- New transmissions were projected to come into production in 2007-08 which will use large amounts of PM parts.

II. Growth Rate\textsuperscript{58}

In a study conducted in 2002, the average growth rate for the PM industry had been 11\% per year for the preceding decade. It was also found that the growth of the entire

\textsuperscript{57} EPMA Annual Report 2005."

\textsuperscript{58} Goto, Ryuichiro.
industry was heavily dependent on automobile production. From 2001 to 2003 it was expected that the PM parts content in a typical North American family vehicle would increase by 8%, which would be a continuing trend that would impact the industry favorably.

It was also mentioned that four-wheel drive vehicles contain more PM parts than two-wheel drive vehicles; although at the time of the study this was a positive note because the increasing sales of such vehicles, at the present time is this not encouraging because of the recent decrease in sales of large four-wheeled SUV’s.

III. Buyers and their Behavior\textsuperscript{59}

In any industry, it is important to understand the needs of the target demographic, and develop a relationship and open dialogue with them to maximize satisfaction and hence profits. The relationship between the suppliers and buyers of PM products is similar to that of many other products. For long term partnership commitment, investments must be made in solving interdependent problems which manifest themselves through joint motivation and coordination of activities. Common standards for problem resolution that recognize the goals of both parties drive healthy communication, and yield improved supplier performance and efficiencies for the customer and better profits for the supplier. In conclusion, while engineering and product excellence will always be critical in the relationship between buyers and sellers, complementary customer management skills such as those outlined above are also essential in the PM industry.

\textsuperscript{59} Bantham, John.
IV. Political and Legal Environment

The EPMA, that is the European Powder Metallurgy Association, and similar organizations in North America work closely with governments as a key part of their roles. In particular, the potential negative impact of EU environmental legislation in the form of the New Chemicals Policy means that there has been much activity in this direction with lobbying on the important issue it raises.

In essence, the New Chemicals Policy is based on the suggestions of ‘green’ lobby groups in the EU – which have very active counterparts in North America – that the chemical industries have for too long been making excessive profits at the expense of human health and the environment, and that the majority of chemicals on the market have never been tested by industry. Hence, the integrity of those that produce and use metal powders is called into question, and given the increasing trend in society towards ‘green’ initiatives this is something to watch for.

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60 “EPMA Annual Report 2005.”
Description of PM Equipment

Equipment used in the production of powdered metal parts includes furnaces, presses, and mills. Tooling refers to the powder dies and compaction ram punches that come into direct contact with the powder. Examples of manufacturers and their products are as follows:

- **Aadvanced Machinery Inc.** based out of Clinton Township, MI. New, used and rebuilt powder compacting presses, isostatic presses, extruders, and mixers. See below for a listing of several of their powder metallurgy machines.  

**PRESSES**

**Cold/Hot Isostatic**

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<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
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<tr>
<td>AA-5319</td>
<td>Autoclave Engineers Isostatic Press 3” dia. x 18”d, wet bag iso press, 30,000 psi, threaded closure</td>
</tr>
<tr>
<td>AA-5509</td>
<td>Autoclave Engineers Isostatic Press, wet bag, Model IP3-22-60, 3” dia. x 22” deep, 60,000 psi, pin closure</td>
</tr>
<tr>
<td>AA-4895</td>
<td>Loomis, Mdl. 200-11-3-6.5-40, DRY BAG isostatic press, 3” dia. x 6.5”deep, 40,000 psi, excellent condition</td>
</tr>
<tr>
<td>AA-5449</td>
<td>Olin (Pentronix), Model ILA/6/60, DRY BAG isostatic press, 6 stations, in line automatic, excellent for spark plugs, balls, nozzles</td>
</tr>
<tr>
<td>AA-1784</td>
<td>Haskel Pumps, 20,000 to 70,000 psi, various models, (25)</td>
</tr>
</tbody>
</table>

**Mechanical and Hydraulic**

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61 "Aadvanced Machinery Inc."

Page 104 of 169
AA-5349  Pentronix PTX Powder Compacting Press mechanical, Mdl. 3101, 35 ton, anvil, high speed

AA-5068  Colton Powder Compacting Tablet Press, mechanical, Mdl. 350, 40 ton

AA-5385  Stokes Powder Compacting Tablet Press, mechanical, Mdl. S-5, 40 ton, dual motion, 6 1/4" fill

AA-5522  Alpha Powder Compacting Press, hydraulic, 40 ton, opposed ram, die set

AA-5529  Alpha Powder Compacting Press, hydraulic, 60 ton, opposed ram, die set

Figure 33: AA-5300 by Aadvanced Machinery Inc.\(^{62}\)

\(^{62}\) Ibid.
• **Fluitron, Inc.** based out of Ivyland, PA. Cold and warm isostatic presses capable of pressures to 60,000 psi (custom designs to 150,000 psi). Standard chamber diameters from 1" I.D. to 6" I.D., and lengths from 6" to 24"; Larger chambers available to 16" ID.\(^6^3\)

• **Savage Engineering and Sales, Inc.** based out of Garfield Heights, OH. Manufacturer of powder metallurgy presses. Presses with single and opposed compaction rams, ejectors, compaction tools and feeders available.\(^6^4\)

\(^{63}\) “Fluitron Inc”.

\(^{64}\) “Savage Hydraulic Presses.”
Figure 34: Powder Compaction Presses by Savage Inc.\textsuperscript{65}

\textsuperscript{65} Ibid.
• Dorst based out of Kochel am See, Germany. A supplier of machines and equipment for producing ceramic and powder metal components. Raw material preparation and forming technology are its special fields.\textsuperscript{66}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure35.png}
\caption{Dorst TPA 1600/3 Hp\textsuperscript{67}}
\end{figure}

\textsuperscript{66} "Dorst".
\textsuperscript{67} Ibid.
• SMS Meer (AKA Mannesman) based out of Mönchengladbach, Germany. Provides both services for planning and erecting complete plants in the metals industry, and the machinery to equip them with. This includes hydraulic powder and forging presses, mills, and seamless and welded tube production machines.  

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68 Ibid.
69 “SMS Meer SMS Group”.
Figure 37: CPA-Controlled Punch Adapter by SMS Meer

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Ibid.
Given below is a more complete list of companies manufacturing various powder metallurgy machinery and tooling.\textsuperscript{72}

\textsuperscript{71} Ibid.
\textsuperscript{72} "ThomasNet".
1. **Elnik Systems, Div. of PVA MIMtech, LLC - Cedar Grove, NJ**
   Manufacturer
   Company Profile: Manufacturer Of Vacuum, Vacuum/Hydrogen, Inert Atmosphere, Furnaces For Heat Treating, Sintering, MIM/PIM Processing, Tool Hardening, Brazing, Annealing, Degassing, Stress Relieving, Tempering...

2. **Centorr/Vacuum Industries, Inc. - Nashua, NH**
   Manufacturer

3. **ALD Vacuum Technologies, Inc. - East Windsor, CT**
   Distributor, Manufacturer, Service Company
   Company Profile: Inert gas powder atomizers from 25 to 5000 lbs. For superalloys & other nonferrous metals employing VIM, ESR/CIG & cold-wall induction melting technology.
4. **AVS, Inc./Advanced Vacuum Systems - Ayer, MA**  
Manufacturer  
Company Profile: Design & manufacture of vacuum & atmospheric debind & sintering **furnaces**. Vacuum 10-6 to 2500 PSIG. Temperature TO 2300 degrees Celsius, specialized gas flow & binder burnoff or trapping systems....  
http://www.avsinc.com/mini2.html

5. **CM Furnaces, Inc. - Bloomfield, NJ**  
Manufacturer, Service Company  
Company Profile: High Temperature Laboratory **Furnaces**, Production **Furnaces** & Continuous Pusher **Furnaces** To 2000 Celsius In Air, Inert & Reducing Atmospheres. Standard & Custom Design **Furnaces** For Ceramics, **Powder**...  
http://www.cmfurnaces.com/PowderMetal.cfm

6. **Abbott Furnace Co. - St. Marys, PA**  
Manufacturer, Service Company  
Company Profile: Manufacturers Of Industrial **Furnaces** & Equipment Including Annealing, Brazing, Sintering, Heat Treating, Tempered, Draw & Austempering **Furnaces**. Spare Parts. Instrumentation & Miscellaneous...  
http://www.abbottfurnace.com/products/products.html
1. **Aadvanced Machinery Inc. - Clinton Township, MI**

   Distributor, Manufacturer, Service Company

   Company Profile: New, used & rebuilt powder compacting presses, powder metallurgy presses, powder metal presses, compacting presses, powder presses, ceramic presses, preform presses, tablet presses, mechanical...

   http://www.aadvancedmach.com/mech.html

2. **Fluitron, Inc. - Ivyland, PA**

   Manufacturer, Custom Manufacturer, Service Company

   Company Profile: Cold & Warm Isostatic Presses To 150,000 PSI For Ceramics & Powder Metallurgy; Lamination Presses For Electronic Circuit Lamination To 10,000 PSI; Standard & Custom Systems; ASME U, U2, R Certified

   http://www.fluitron.com/press.html

3. **Savage Engineering & Sales, Inc. - Garfield Heights, OH**

   Manufacturer, Service Company

   Company Profile: Manufacturer of powder metallurgy presses. Presses with single & opposed compaction rams, ejectors, compaction tools & feeders available. Powder compaction press features opposed rams with fixed...
4. McGrath, E., Inc. - Salem, MA

Distributor

Company Profile: Distributor of reconditioned & surplus high-tech equipment specializing in high vacuum, precision optical & semiconductor processing equipment.

http://www.emcgrath.com

5. Macrodyne Technologies, Inc. - Buffalo, NY

Manufacturer, Service Company

Company Profile: Hydraulic **Presses** (50-5,000 Tons) For Metalforming, Plastic, Rubber, Wood, Compaction, & Laminate Industries. Ancillary Equipment Includes Transport/Handling, Quick Die Change/Die Handling Equipment...

http://www.macrodynepress.com/

6. Warwick Manufacturing & Equipment, LLC - North Brunswick, NJ

Distributor

Company Profile: Buy & Sell Used Chemical, Food & Cosmetic Process, Packaging, Pharmaceutical Equipment

http://www.warwickequipment.com/inventory.asp
7. **American Tool Co. - Lincoln, RI**

Manufacturer, Custom Manufacturer, Service Company

Company Profile: Manufacturer of hydraulic coining **presses** up to 1,200 ton capacities, custom designed hydraulic equipment, specialty coining tools.

http://www.americantoolcompany.com/services.htm

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Metals: Powder

1. **Acupowder International, LLC - Union, NJ**

Distributor, Manufacturer

Company Profile: Non-ferrous elemental & alloy metal **powders**. Particle sizes from coarse to ultra-fine. Particle shapes from spherical to irregular. Also copper, tin, bronze, brass.

http://www.acupowder.com/

2. **Chemalloy Co., Inc. - Bryn Mawr, PA**

Manufacturer

Company Profile: Produces The Widest Variety Of **Metals**, Alloys, Minerals &
Chemicals Made To Exact Sizes & Chemical Composition. Crushing, Grinding, Screening; Lump; Coarse & Fine Sizes Powders. Briquetting

http://www.chemalloy.com/powders.htm

3. Atlantic Equipment Engineers, A Division of Micron Metals, Inc. - Bergenfield, NJ

Distributor, Manufacturer, Custom Manufacturer

Company Profile: High Purity Metals, Metal Powders & Compounds, Oxides, Borides & Silicides, Nitrides & Carbides. Wide Range Of Purities & Particle Sizes

http://www.micronmetals.com/

Product Catalog: Metals: Powder products

Product Catalog Quick Links:

High Purity Metal Powders and Compounds

4. F. W. Winter & Co., Inc. - Camden, NJ

Distributor, Manufacturer

Company Profile: Variety Of Metal & Alloy Powder. Range Of Grades & Sizes Available In Stock

http://www.fwwinter.com
5. **Indium Corp. of America - Utica, NY**

Manufacturer


6. **Hoeganaes Corp. - Cinnaminson, NJ**

Manufacturer

Company Profile: Complete Line Of Iron, Steel, Stainless Steel, Low/High Alloy & Binder Treated Powders For Structural, Welding, Cutting, Hardfacing, Chemical, Friction, Electromagnetic & Photocopy Applications

http://www.hoeganaes.com/navpages/structuralparts.htm

Table 5 below is provided as well, with the intention of providing a listing of the major powder metallurgy forming equipment manufacturers around the world.
<table>
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<tr>
<th>Manufacturer</th>
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<th>Compaction Subtype</th>
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<td>Fluitron, Inc.</td>
<td>Ivyland, PA</td>
<td>Cold</td>
<td>Isostatic</td>
<td>150000</td>
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<td>Thermal Technology, Inc.</td>
<td>Santa Rosa, CA</td>
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<td>150000</td>
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<td>11</td>
<td>270</td>
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<td>Up to 100000 kg/hr</td>
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<td>12</td>
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<td>35 300</td>
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Table 5: List of Major Powder Metallurgy Forming Equipment Manufacturers
Survey of Products

I. Overview

Powdered metal is used to create a wide variety of parts, including bearings, gears, rings, die tools, complex planetary carriers for four-wheel drive torque transfer system, locks, nuts, blades of stainless steel used in laparoscopic surgical scissors, manifolds weighing over 6.5 tons used on offshore oil platforms, steel connecting rods for engines, mounts, holders, brackets, and speaker magnetics.

II. Market Segmentation

Figure 39: PM Products Market Distribution

73 “Pick PM”.
The end-product manufacturers are segmented into several divisions. These are in line with the final consumer markets where these products are sold, and include those making:

- **Automotive Parts** – These are for use in engines, transmissions, braking and suspension systems, and bodies and interiors (locks, rearview mirror mounts, speakers). This is the largest segment.

- **Industrial Products** – Fluid power applications such as valve plates and piston barrels, and solenoid components are some applications to name a few.

- **Consumer Products** – Examples are power tools (ratchets, blade holders, rotor cores) and household items (window brackets, pepper grinder mechanisms, loudspeaker magnetics, automatic garage door opener components).

- **Bioengineering** – Although this field is known to use powdered metal parts, its small size has made it very difficult to obtain information on it in regards to powdered metal use. This industry is very secretive about their processes. However, the PM metal structure and its relative porosity can be an advantage to the implant process.
1. Complementary Products

The largest group of end-products in the market that are complementary to PM parts – that is, such products that are rarely produced without them – are all automobiles, trucks, and vehicles in general. PM parts are such an intrinsic part of engines, transmissions and vehicle interiors that the auto industry is in fact the largest client base for PM part manufacturers.

2. Major Producers

Stackpole Ltd: A company based out of Mississauga, Ontario, they are a major producer of automotive PM parts in Canada. They are also global competitors in the

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74 “Sintermetali Ltd.”
PM industry, with an award-winning record of innovation and long-term contracts with GM for the production of a variety of parts. Involved in several major research collaborations with universities across Canada, including Queen’s, it won the Ontario Chamber of Commerce “Company of the Year” award in 1996.\textsuperscript{75}

GKN Sinter Metals: This is another large global leader in the PM industry, specializing in the production of automotive PM parts. Based out of the United States it employs over 7000 employees and has 30 locations across the globe. GKN also produces many other parts for such applications as outdoor power equipment and power tools.\textsuperscript{76}

Precision Powdered Metal Parts, Inc: A major force in the PM industry, it a North American leader in providing parts for use in power tools, lock hardware, lawn and garden applications, sporting goods, and even parts for the electronics and computers industry. With over 75000 square feet of production area and more than 15 acres of land, they produce large numbers of parts a year.\textsuperscript{77}

3. Substitute Products

Products that may be used in place of PM parts differ from them in the process through which they were manufactured. In the past these parts were primarily produced either by casting or machining (using a power-driven machine tool, such as a lathe, milling machine or drill, to shape metal).

\textsuperscript{75} “Stackpole Ltd.”
\textsuperscript{76} “GKN Sinter Metals”.
\textsuperscript{77} “Precision P/M”.

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Appendix B

A Finite Element Model for Ejection of Green Parts in PM Compaction
A FINITE ELEMENT MODEL FOR EJECTION OF GREEN PARTS IN PM COMPACTION

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KEYWORDS

Finite Element Analysis, powder, ejection, manufacturing.

ABSTRACT

Using industrial partner experimental data for powder metal compaction, a Finite Element Analysis (FEA) model has been developed for the ejection phase of green parts in the powder metallurgy process. This paper describes development of that model which will be used by industry. The model will provide engineers with the opportunity to study the friction in the ejection process, the nature of which is largely unexplored to date.
Included in the paper is a description of the model and relevant details. Also a description of the design of a testing apparatus, and the method of friction sensing that will be used to validate future results, is given. A friction model is developed for PM ejection and an FE model is created, using industrial data, as a first step to better represent friction in ejection as compared to past work. Validation is carried out via comparison to past work.

INTRODUCTION

The essential features of powder metallurgy are the production of a metal powder, chemical or mechanical, and its consolidation at a temperature that is below the melting point of the main constituent, into a fairly strong solid. Coalescence of the powder particles requires the application of mechanical pressure followed by heat. The advantage of the process is a near net shape is made in one step.

Research Objectives

Transmission components form a large portion of automotive applications of powdered metal compaction. Manufacturers experience lengthy product development periods because each time a new part is developed, the part must be produced physically on the plant floor to see how it behaves in the forming process. A lot of trial and error is
required in setting up dies for production machines for a new production run. Setting up the PM equipment properly ensures the production of quality parts with a high level of repeatability. However, this requires the shutdown of production lines, which translates to lost productivity and lost revenue.

A major reason for long down times in setting up for a new production run is the lack of understanding of what occurs during part production. The first objective of the current research is to develop an advanced contact model for compaction and ejection of iron powder to produce a simplified gear or puck using linear FEA to predict the following: punch face deflections, stresses in the punches, die and part, frictional forces between the die and the part, and changes in dimensions of the part during ejection. The second objective is to design and build a test setup to carry out compaction and ejection of iron powder specimens; perform experiments and compare results with predictions of FEA. This paper deals with the first objective: development of an FE model using experimental data provided by an industrial partner.

PREVIOUS LITERATURE

Theory Relevant to FE Analysis in Powder Metallurgy
Models of the powder metallurgy process can be broadly grouped into three categories: compaction models, ejection modeling, and machine modeling. Compaction models consider issues such as die filling, density prediction, density dependent modeling, friction, and crack prediction. Ejection modeling is concerned with springback, density dependent elasticity, hyperelasticity, plastic friction models, and friction with velocity dependence. Finally, machine modeling involves consideration of testing requirements, industrial production parameters, solid modeling software, and force data (“Materials Data Requirements” 2002).

![Experimental Test Press](image)

**FIGURE 1. EXPERIMENTAL TEST PRESS.**

**Tooling Design**
Traditionally, PM tooling was designed on the basis of production experience. At present modeling and simulation are used to predict not only final dimensions, but also many aspects of the PM processing steps. Rapid prototype manufacturing also brought PM tooling to another level. Two major factors, in the compacting operation, control part design, they are: the flow behavior of powders and the pressing action (“Materials Data Requirements” 2002).

**SIMPLE PUCK EXPERIMENTAL SETUP**

The experimental machinery is a hydraulic press with two cylinders acting opposite to one another in a vertical configuration (see Figure 1). In this configuration the top and bottom punches can be moved independently. At the centre is a powder metal die manufactured specifically for this application while closely replicating production conditions. The die is made of two components. An outer casing made of AISI 4340 high alloy steel and a die insert of grade 12 carbide. Both of which are typical in industrial applications. Surface finishes, press fit characteristics, tolerances, and geometric detailing are all similar to those found in the automotive industry today.
Measurements carried out include, firstly, the positions of the top and bottom punches. This allows for careful control of their positions as they must work in tandem during the ejection process, holding the component between them with a force approximately equal one tenth the force needed for compaction while moving upwards until the component is fully removed from the die. Second, the forces applied to the test specimen by each of the punches are recorded at all stages of the process. Third, the vertical forces acting on the die, a direct result of friction between the specimen and the inner die wall, are measured using a compression ring (figure 2) during compaction and a tension load cell during ejection. Last, the radial force resulting from the exertion of pressure from the test
component on the wall of the inner die is measured using the radial sensor pins shown in figure 2. With the measurement of both the radial force on the die wall and vertical force on the same wall a ratio equal to the coulomb friction coefficient is revealed - one of the primary goals of this research initiative.

MODELING OF PRODUCTION OF SIMPLE PUCK

To address whether friction between the compacted powder and the tooling can be predicted computationally, a direct comparison between experimental results and a linear elastic, static, implicitly solved finite element simulation is needed. To make the comparison as consistent as possible, an exact model of the experimental apparatus and setup is constructed in Abaqus (“Abaqus FEA” 2007) finite element software. Loading and kinematics applied to the model are consistent with how they will be applied in the test setup. Linear contact analysis between all components is considered, with an experimentally determined linear elastic material model for the powder and a theoretical, quasistatic quantum friction model obtained from literature. Convergence studies are conducted to determine optimum mesh density. The results of these studies are presented in this chapter.

Method
**Modeling Approach.** Solid models of the top and bottom punches, iron powder compact (puck), carbide die insert, outer metal die, radial load pin, compression ring, load cell, and clamping ring are created in Solid Edge (“Solid Edge” 2007) and exported to Abaqus. A finite element model of these components is constructed in Abaqus using tetrahedral elements, which are chosen because the cylindrical geometry of the parts cannot be represented satisfactorily with hexahedral elements. Quadratic tetra elements are used for the radial load pin, compression ring, and load cell, to fill the demand for better accuracy in results in those components. The remainder of components are meshed with linear tetrahedral elements. The size of elements was reduced around regions with high curvature and small features.

A quarter model approach is used due to symmetry of the system; see Figure 3.

**Contact Analysis Approach.** In reality, the outer metal die and the carbide die insert are shrink-fitted together. Therefore, subsequent to the shrink-fitting, they behave as one component. In Abaqus, such a situation is usually modeled using the ‘tie’ constraint, which fuses two components together. However, the limitation of a tie is that it applies throughout all steps of the simulation, and cannot be turned off at any point. Therefore due to requirements of the analysis it is necessary to create two models, one with a tie constraint and one with a regular frictional contact interface between the carbide die insert and the outer metal die.
Another issue is that, in reality, after the shrink fit, the carbide die insert-outer metal die unit sits on top of the compression ring and is simply held in place by the clamping ring; as such, it is not fixed in any degree of freedom. However, in static FEA, every component must have some degree of freedom constrained; otherwise, the partial differential equations defining it do not converge on a finite solution. Therefore three models are created. One models compaction with a tie between die and unit. Another models ejection with a tie, and the final models compaction and ejection with the frictional interface.

In the compaction phase, the die unit is tied to the compression ring, and in the ejection phase, is tied to the clamping ring. Friction between the punches and the carbide die insert is taken to be an estimated value of $f_{pc} = 0.01$.

The friction coefficient between the puck and the carbide die insert during compaction, is approximated in this research. That is because the iron powder behaves in a plastic non-linear fashion under compaction. Although it would have a significant effect on the friction coefficient (causing it to change through compaction) is not within the domain of this work. Instead, a friction coefficient value of $f_c 0.14$ from the 1999 paper by B. Wikman and N. Solimannezhad et al (Wikman 1999) is used. The authors of that paper used Distaloy AE in their work, a powder under investigation in the current work. Secondly, they arrived at that value by fitting the upper punch load after compaction computed by their FEA to the measured load from their experiment by optimizing this
friction coefficient through a 17 iteration routine. In doing so they ensured that the variation of the magnitude of the friction coefficient through compaction was accounted for.

FIGURE 3. FE MODEL OF SIMPLE PUCK EXPERIMENTAL SETUP (COMPLETE ASSEMBLY).

**Ejection Friction Model.** A single value estimation of the coefficient of friction throughout ejection is difficult to make, because it varies from the beginning to the end of
ejection. Nonetheless a friction with wear criterion model has been developed based on the works of Curnier (Curnier 1983) and Kravchuk (Kravchuk 1981).

Kravchuk established that the solution to the system of differential equations and boundary conditions describing the quasistatic problem of contact between a linearly elastic body and a rigid body, can be found using a method of successive approximations and existence theorems applied to the following quasivariational energy inequality:

\[ \Delta E = a \left( u^{+dt}, w - u^{+dt} \right) - \int_{\Omega} \rho F^t \left( \omega - u^{+dt} \right) \, d\Omega - \int_{Sc} P^t \left( w - u^{+dt} \right) \, dSc - \int_{Sc} \left( \sigma^{+dt} \right) \left( d\omega - du^t \right) \, dSc, \]

where \( \Delta E \) = change in energy,

\( u \) = displacement vector,

\( t \) = time,

\( w \) = the kinematically possible state satisfying the non-penetration condition,

\( \Omega \) = domain of deformable body,

\( \rho F \) = volume force vector,

\( P \) = surface load

\( Sc \) = contact surface area,

\( \sigma \) = true stress field,

\( v \) = normal vector to \( Sc \),

and \( a = \int_{\Omega} \sigma(u) \varepsilon(v) \, d\Omega. \)
For successive approximations to converge, the inequality of positive definiteness $a \geq a\|v\|^2$ must hold, and the friction coefficient $f$ must satisfy the inequality $f < \alpha / C$ where $C$ is a constant defined by the elastic moduli, the body shape, and the fixing conditions.

In the definition of $a$, $\sigma(u)$ and $\varepsilon(v)$ do not vary throughout the puck, and expressing $v$ as the product of compacting punch speed $s$ and quasistatic time step $\tau$ the above inequalities can be combined and written as

$$C < [\sigma(u) \varepsilon(v) V] / [(s \tau)^2 f]$$

where $V = \text{volume of puck}$.

From Curnier, a force of tear $F^S$ is defined as that which occurs when the sliding motion of the two bodies is monotone and oriented along some preferential direction, resulting into an anisotropic tear of the contact surfaces. Additionally a force of wear $F^C$ is defined as that which occurs when the two bodies rub against one another in alternate arbitrary directions, resulting in an isotropic wear of the surfaces.

As defined by Curnier, the law of perfect friction states that the force of friction is proportional to the load and independent of area of contact and other state variables. Combining this definition with the non-penetration condition the criterion of perfect friction is
\[ Y(F) = F_N \leq 0 \quad \text{for contact, and} \]
\[ |F_T| + fF_N - C \leq 0 \quad \text{for slip} \]

where \( F_N \) = normal component of contact force
\( |F_T| \) = Euclidian norm of tangential component of contact force
and \( f \) and \( C \) are as defined above.

Curnier states that the Euclidian norm of \( F_T \) being intended to allow for anisotropic surface roughness, can be disregarded in the current case. Also, the wear and tear forces are incorporated into the friction criterion by including a tangential tear force \( F_T^S \), and considering the force of wear \( F^c \) to be starting with the virgin value \( F^c = C \), such that the criterion becomes

\[ Y(F) = F_N \leq 0 \quad \text{for contact, and} \]
\[ (F_T - F_T^S)^2 + fF_N - C \leq 0 \quad \text{for slip} \]

In the problem at hand, \( F_T^S \) may be considered absent and the slip region dominates. By including the definition of \( C \) this criterion can be rewritten as

\[ F_N f^2 + F_T^2 f - [\sigma(u) \varepsilon(v) V] / (s \tau)^2 = 0. \]
\( F_N \) is taken as half of \( F_T \) according to a paper by PM Modnet (PM Modnet Methods and Measurements Group 2000), and an estimate of \( F_T = 4000 \) N, the ejection force halfway through ejection, is also obtained from literature for a 9.87 mm (0.389”) tall compacted SC100 iron powder puck (Gethin 1993). With all quantities in the above equation therefore known, an arbitrary value of \( \tau = 0.0015 \) seconds is chosen to yield a reasonable \( f \) value of 0.137.

**Loading and Kinematics.** Loading and kinematics are applied to the simulation model in such fashion as would best mimic reality. To this end, the shrink-fit needs to be modeled accurately. This is accomplished by positioning the carbide die insert away from the outer metal die, applying pressure to the OD, moving the part into place, and releasing the pressure.

The linear springback also has to be accounted for. This is done by first referring to data collected by our industrial partner; see acknowledgements. The data was collected by performing metal powder compaction and ejection for a simple rectangular bar. Die cavity area was measured, and the corresponding areas of the ejected samples were also recorded. From this, an equivalent average strain (0.0038344) was calculated. Using this as the radial strain of the puck and making appropriate conversions for axial strain, the required post-compaction puck size is calculated from a desired (and expected) final, post-ejection puck size of 6.35 mm (¼”) tall with 25.4 (1”) OD.
The top and bottom punches are positioned in the model such that the vertical distance between them equals that for the required post-ejection puck size. A post-ejection sized puck is compressed radially, placed between the punches, and released. With the faces of the top and bottom punches in contact with the puck fixed in all directions, the top punch is then translated down in order to bring the puck to its required post-compaction size. This step effectively brings the puck to the state it would be in at the end of compaction.

Finally, the pressure applied to the top punch is reduced by 90% during the hold-down step, and then the bottom punch, puck, and top punch are all translated upwards to eject the part out of the die unit. The top punch is removed and the entire production process is complete. Note that four steps are created through ejection to capture the stress state of the system throughout.

![Mesh Convergence Study Results](image-url)

**FIGURE 4. MESH CONVERGENCE STUDY RESULTS FOR RADIAL FORCE ON LOAD PIN AND AXIAL FORCES ON STRAIN GAUGES**
**Material Properties.** In this analysis, all materials are taken to behave in a linear, elastic fashion with no temperature dependence. These are reasonable given that the strain region in which the components lie are far from the elastic-plastic boundary (well within the elastic region), and temperatures developed during part production are low enough to neglect any effects. In the test setup, the top and bottom punches were made out of AISI M2 steel, having a Young’s Modulus of 227.5 GPa and a Poisson’s Ratio of 0.29 (Lindsay 2007). The outer metal die was made of AISI 4340 steel, with Young’s Modulus and Poisson’s Ratio values of 204.8 GPa and 0.29, respectively (Lindsay 2007). For the carbide die insert, a C-12 grade carbide was used, with properties of 567 GPa and 0.28 (Wolfe 2007). Also indicated by all drawings was a hardness of 58-60 HRC for each component. Therefore these values are used in the FE model.
For the puck, it is necessary to determine appropriate Young’s Modulus and Poisson’s Ratio values to use in the simulation, which would be able to represent the behavior of the powder as an elastic solid, through compaction and ejection, with a fair degree of accuracy. From literature it was found that a Poisson’s Ratio of 0.28 was acceptable for iron powder compacts (Jonsen 2005).

For the purposes of the simulation, the Young’s Modulus at a density of 0.264lb/in$^3$ with Distaloy AE, i.e. the highest density expected to reach with the three powders with Distaloy AE, is used for the puck. That value is 24 GPa (“Materials Data Requirements” 2002).

**Results**
**Convergence Studies.** The shape of the contact surfaces can be adjusted automatically within Abaqus – this is a function that can be chosen. It is only necessary to refine the mesh at the face of the load pin in contact with the carbide die insert and the compression ring and load cell (shown in Figure 5). The results of the convergence study are shown for the radial forces on the load pin and axial forces at the strain gage locations in Figure 4. As noted below the forces are based upon experimental data collected at the facilities of the industrial partner.

**Contact Analysis Results.** The radial force results on the load pin in the frictional interface model, and the vertical force results on the load cell and compression ring in the tie models, are determined to draw comparison with past studies. These are shown in figure 5 for the ideal meshes as determined in the convergence studies. The contact force results are shown at the end of compaction and halfway through ejection, so as to allow proper prediction of $f$. The foregoing is developed with experimental data from an industrial partner – see acknowledgements.

**TABLE 1. MAXIMUM FORCE PREDICTIONS AT END OF COMPACTION AND HALFWAY THROUGH EJECTION AT LOAD SENSORS**
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<th>Ejection</th>
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<td>8.02</td>
</tr>
<tr>
<td>Compression Ring</td>
<td>3.04</td>
<td>N/A</td>
</tr>
<tr>
<td>Load Cell</td>
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<td>1.07</td>
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The following table summarizes the maximum forces predicted by the FE model at the load pin and strain gages in the load cell / compression ring during compaction and halfway through ejection.

**Friction Coefficient.** The nature of $f$ during the ejection phase in PM is not well understood. No computational model to date has been developed that explicitly includes a value of $f$ that is different during ejection than the one used during compaction. In the present study, friction between the puck and carbide die insert is implemented using an optimized coefficient during compaction from past literature, and one derived by a friction with wear criterion model during ejection. Changes in this coefficient have an effect on the axial loads experienced by the die unit in being pushed down or pulled up along with the powder compact during compaction and ejection.

Values of $f_c = 0.14$ and $f = 0.137$ are used in the FE model. Maximum axial and radial forces observed during compaction and ejection respectively, as noted in Table 1, are then used to calculate friction coefficients as per $f$ and $f_c = \text{Radial Force} / \text{Axial Force}$ to
see how the effects of the friction inputs spread throughout the system. These resulted in $f_c = 0.164$ and $f = 0.133$.

**Discussion and Comparison to Past Work.** A computational contact FE model was created to simulate friction during the PM production of a simple puck. Values of $f$ from literature and from a friction with wear criterion were used during compaction and ejection respectively. Convergence tests were performed to determine optimum mesh density. Predicted values for axial forces in strain gage locations and radial forces in the load pin passed the convergence tests indicating the model was computationally robust.

Contact analysis results gave maximum axial forces of 3.04 kN and 1.07 kN, and radial forces of 18.57 and 8.02, during compaction and ejection respectively. This is in good agreement with the 1993 paper by Gethin et al, despite the different material model, loading, kinematics, and contact analysis approach used here. Values found for axial forces during compaction and ejection were 13.26 kN and 4 kN, respectively (Gethin 1993). There is agreement between results of radial and axial forces developed due to friction on the die unit with past literature. However to the best of the author’s knowledge, no previous work has experimentally determined radial force values during compaction and ejection. Therefore, it was not possible to verify these.

The use of different friction coefficients for compaction and ejection in PM was investigated. A friction with wear criterion for ejection was derived from the quasistatic
solution of a general contact problem, and was used to obtain \( f = 0.137 \). Because the value of \( f \) varies through ejection, this value was chosen as it was expected to represent the friction condition halfway through ejection. A value of \( f \) for compaction was obtained from past literature in which \( f = 0.14 \) was found through optimization to account for the variation in \( f \) during compaction accurately. Friction coefficients were then calculated from force results from the computational model to see how the effects of the \( f \) inputs spread throughout the system. These were found to be \( f = 0.164 \) during compaction and \( f = 0.133 \) during ejection. These showed excellent agreement with the \( f \) inputs and hence validated the successful FE representation of the effects of friction in the entire model.

One of the problems with the current model is the material model used for the puck. Although a non-linear and plastic particulate model is required, a linear elastic solid model is used. As a result of this the single friction coefficient value used attempts to represent a quantity that varies through the compaction step. Similarly the single value used for \( f \) during ejection attempts to represent a quantity that changes through the ejection step. However in this case, the changing ejection \( f \) is due to dynamic effects, and this is the other major problem with the model in that the static model used in it cannot be used for effective representation either.

**CURRENT WORK**
**Friction Experimentation**

The foregoing uses experimental data from an industrial partner to develop an FE model for studying friction at the compacted part-die wall interface. A value of friction during ejection has been determined using a friction with wear criterion model. However, although actual data is used to develop the model, it must now be tested with friction sensors.

**Modeling of Production of Synchro Hub.** An automotive transmission synchro hub (gear) is a realistic, complex PM part. It is now desirable to determine whether the behavior of tooling involved in producing a synchro hub part can be accurately modeled using FEA. To this end, a linear elastic, static, implicitly solved FE model of compaction of a proprietary iron powder mixture in the production of an automotive synchro hub, manufactured by the industrial partner is being developed. Drawings from the industrial partner have been used. Initial problems encountered have been with computing memory resources.

**CONCLUSIONS**

An advanced contact model was developed for compaction and ejection of iron powder to produce a simplified gear or puck using linear finite element analysis (FEA) to predict
the following: punch face deflections, stresses in the punches, die and part, frictional forces between the die and the part, and changes in dimensions of the part upon ejection.

The present study has demonstrated that the use of a linear, elastic, static FE model can be used to accurately simulate the production process for a simple puck. This work can be used as a first step towards developing a more complex model that would contribute to predicting and preventing crack propagation in automotive transmission gears.

ACKNOWLEDGEMENTS

The authors thank their industrial partner, Stackpole Ltd., for the use of their production facilities for running experiments giving useful data, and for providing their own experimental data and product drawings.

The authors also thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ontario Centres of Excellence (OCE) for generous support (NSERC CRD CRD340571-06, OCE DE40824). Finally we thank Höganäs for the generous contributions of PM material.

REFERENCES


Lindsay, Keith (2007, June 6). *Bohler-Uddeholm*. Personal communication.


Appendix C

Report on Ejection and Machine Modelling
Executive Summary

With the objective of reducing the time required for product development, it was found that a model of the relaxation and ejection of the powder compact would yield the most improvements for the least effort. Ejection has been studied in literature, although not as extensively as compaction modelling. It can be done with implicit finite element code, that is less computationally intensive when applied over larger time steps and is always less prone to error. Commonly used software applications are LS-Dyna and ABAQUS.
because they are both very powerful and allow the user to implement their own specialised material models and algorithms.

In the case of powder metallurgy it is always necessary to implement customised material models, and specifically for ejection modelling models of elasticity and friction are most important. Several have been used in the past, but none have been adopted by the whole academic community. Therefore, a test platform must be used to verify the accuracy of the models of elasticity and friction to be used. Once verified the appropriate models will be implemented in the finite element code to achieve the goals of the project.

**Report on Ejection and Machine Modelling**

**Introduction**

This report is a synopsis of the tools used for modelling ejection as found in the literature. These will cover modelling of ejection and the modelling of equipment. The integration of these two tasks with one another will also be treated.

**Ejection**

A model of the ejection process will require that many parameters be established before modelling can even begin. First it is necessary to know what the shape of the green powder compact will be prior to relaxation and ejection. It must also be known how this green compact behaves immediately after compaction. That is, what amount of springback can be expected and how does this vary between the axial and radial components of stress generated as a consequence. Once the part is allowed to relax, as the
punches are backed off along the axis of compaction, a model of the elastic response of the material must be used to determine the remaining state of stress immediately prior to ejection. Without this knowledge the very next requirement cannot be met.

The forces of friction acting between the die wall and the powder compact are the loads that will cause failures during ejection and without the aforementioned knowledge of the state of stress in the compact, one cannot model friction, which is a combination of the normal stress at the interface and the coefficient of friction dictated by surface characteristics. The following section will discuss methods that have been used to answer some of these questions.

**Determination of Initial Shape**

Initial shape is to be determined from the required shape as specified by the customer, while taking into account the effect of sintering. This is a reasonable assumption since this is how the tooling is designed and the pressing schedules are decided. If this requirement is not met, then the compaction or filling portions of the process have failed. This initial shape is generally a little larger than that of the volume constrained by the die and punches, and so there is springback.

**Springback**

Springback always occurs in powder metallurgy and powder manufacturers like Höganäs provide estimations of springback depending on the pressure and density to which a powder is compacted. Die type is also a factor in the amount of springback.
measured. For instance, steel dies will allow 0.03%-0.07% more springback than carbide dies.\textsuperscript{i}

Experimental results from the compaction, relaxation, and ejection of iron powder show that although the force relaxation was not linearly elastic it was, in the opinion of the researchers, close enough to be represented by a linearly elastic model.\textsuperscript{ii} Since this assertion by Gethin et al. in 1994, it seems that the consensus has moved towards non-linear elastic models for powder metal compacts being required to accurately model friction, and therefore ejection. Part of this task includes determination of the ratio between radial and axial stresses. Although this is normally treated by poisson’s ratio, more complicated relationships have been found, as follows.

Determination of friction has led to empirical equations establishing the relationship between axial and radial stress in an iron compact.\textsuperscript{x}

\[
\sigma_r = 0.087\sigma_a^{1.38}
\]  \hspace{1cm} (1)

This equation was developed around 1980 for the purpose of measuring friction during powder compaction but has not figured prominently in the literature since 1994.

One of the greatest difficulties with determination of springback is that it will vary depending on the geometry of the part formed.\textsuperscript{xiv} Logically, characterizing the powder used through experiment will allow the finite element model to predict this variation. Data collected by Stackpole engineers may advance understanding and verification of both springback and modelling efforts respectively.

To date several mathematical representations of elastic response of the powder have been used. Most often they are applied through compaction and ejection. For this
reason the accuracy of these mathematical representations with respect to elasticity at ejection densities may be compromised by the need to fit the curve to data covering a large range of densities. This problem may be compounded by the fact that some of the researchers were not particularly interested in elastic response during relaxation and ejection, but rather they were interested mostly in the change in elastic response during compaction. Below are some of these mathematical models of elastic or bulk moduli.

**Density Dependent Elasticity**

The model of elasticity presented by Bejarano et al. and proposed by Pavier determines the elasticity of the powder as a function of its density or plastic volumetric strain. That is, the current density, $\rho$, divided by the initial density, $\rho_0$.

To relate the density to the elastic modulus, $E$, two experimentally determined parameters are required. These are, $K$ and $\alpha$, as shown in equation (2).

$$E = K \exp \left( \frac{\rho}{\rho_0} \right)^\alpha$$  \hspace{1cm} (2)

These parameters are obtained by conducting cyclic tests at a number of densities. These tests may only be necessary at the green density for an ejection model.

**Hyperelasticity Based Formulation**

Coube and Riedel used an equation representing the non-linear elastic response of Distalloy AE during relaxation; see equation (3). Poisson’s ratio, $\nu$, is held constant at 0.28. The dependence of the modulus of elasticity on density is determined by
material parameter $A$, which is the elastic modulus of the ejected component, is found by measuring the sound velocity through the component. $A$ is found through experiments, and the other material parameter, $n$, is set at 0.33 according to a micromechanical model developed by Coube in his PhD thesis. $v$ and $q$ are the hydrostatic and effective stress, respectively.

$$E = A \left[ \frac{(1 + v)}{3} q^2 + 3 \left( \frac{1}{2} - v \right) p^2 \right]^{\frac{n}{2}} + E_0$$  \hspace{1cm} (3)

**Empirical Formulations**

Technically all the models used to predict elastic response are generated by fitting curves to the experimentally obtained data. Equation (4), like equations (2) and (3), has experimentally determined coefficients. $I_1$ is the first invariant of the stress tensor, which is really hydrostatic pressure and in the upper line the equation is shown for all cases where the hydrostatic stress is negative, or compressive. Evidently that is the condition most often found in powder metal compaction. $C_1$, $C_2$, $C_3$, were found to be 9.790 GPa, 19.35 Pa, and 24.36, respectively. Distaloy AE was the powder used in these experiments. The units attributed to the coefficients ensure that the bulk modulus, $K$, is a pressure. The plastic volumetric strain, $\varepsilon_v^p$, is simply the natural logarithm of the ratio of current density ($\rho$) to initial density ($\rho_0$). The bulk modulus is related to elastic modulus as shown in equation (5).

Poisson’s ratio, $v$, is 0.28 in this case.
\[ K = \begin{cases} C_1 + C_2 \exp\left( C_3 \sqrt{|\varepsilon|^p}\right), & \text{if } I_1 < 0 \\ C_1 + C_2, & \text{if } I_1 \geq 0 \end{cases} \] (4)

\[ K = \frac{E}{3(1-2v)} \] (5)

In some cases even the above mentioned formulae have been modified at the ejection density because the model did not fit closely to the experimental data at high density. Jonsén et al. found it necessary to adjust the fit of equation (4) at ejection densities because it did not follow the experimental data closely. Figure (1) shows how the experimentally found bulk moduli do not fall close to the curve fit offered by equation (4) at plastic volumetric strains above 0.8.\(^\text{vii}\)

![Figure 1: Bulk modulus, K, vs. plastic volumetric strain\(^\text{v}\)](image)

**Friction**
Friction is modelled primarily as coulomb friction, which is a function of normal stress, and the friction coefficient, $\mu$. This is usually defined as a ratio of the transverse stress (or force of friction) to the normal stress (or force). In the case of powder metallurgy, friction varies greatly with density. This is likely due to the changes in surface characteristics that occur during the densification process, and the interaction of this changing surface with that of the die is exactly what the friction coefficient is meant to capture.

Measurements of friction can be grouped into two categories. Those are shear type and instrumented die type equipment. The shear type involves pressing the powder in a die and against a plate (see Figure 2). The plate is then removed at a prescribed speed and punch pressure. The friction is measured, but is always perpendicular to the pressing direction. For this reason measurements of friction that would occur parallel to the pressing direction are simulated by varying the punch pressure to a level that induces the expected normal stress that would have been exerted against the die wall under normal pressing conditions. This is where the instrumented die system excels since it does not vary greatly from the configuration of an industrial pressing system. It only incorporates instrumentation to measure at least the punch and die forces in the pressing direction, and often also features measurement of radial stresses, which occur perpendicular to the pressing direction and are most relevant to calculating the coefficient of friction.
Plastic Friction Model

This model is presented by researchers from the University of Wales Swansea in order to capture the sticking behaviour at the initial stages of ejection. The part is naturally resistant to movement because it is held against the die which is assumed in this work to be perfectly rigid. A friction criterion, $F_r$, is used to determine whether there is sticking or slipping between the powder/tooling interface. If $F_r$ is less than zero there is no motion and therefore sticking. When $F_r$ becomes equal to zero there is slipping between these surfaces.

$$F_r = \left| \tau \right| - \mu \sigma_N + b$$

(6)

$\tau$ is the surface shear stress and $\sigma_N$ is the normal stress at the surface. $\mu$ is the wall friction coefficient, which was set to 0.08 according to experimental results. The
exponents a and constant b are indicative of wear and tear phenomena. (I don’t know what these are.)

**Friction From Instrumented Punches**

What follows is the determination of friction from experimental force data, using an empirically developed relationship for axial and radial stress within an iron/copper compact. \( D_o \) is the outer radius of the cylindrical compact, and \( D_i \) is the inner radius. \( \sigma_{za} \) and \( \sigma_{zb} \) are the axial stresses at the top and bottom of the compact, respectively. The length of the compact is represented by \( L \), and the friction coefficient by \( \mu \). In this formula all variable are known except for \( \mu \), which is the object of the calculation. This method is inexact because there is no direction measurement of radial stress, which is the normal stress for the purpose of friction calculations.

\[
\sigma_{zb} = \left[ \sigma_{za}^{-0.53} + \frac{0.1322 \mu L}{D_o - D_i} \right]^{2.63}
\]  

(7)

**Empirical Friction Model from Shear Plate Measurements**

PM Modnet compiled results from a number of research efforts in friction measurement in 2000. Of those results the shear plate measurement method was found to be the most consistent predictor of friction coefficient. As a result a linear best fit relating normal pressure, \( \sigma_N \), and density to friction coefficient was developed. It was presented with a \( \pm 0.02 \) error band with respect to the mean friction coefficient. \( \text{xi} \)
\[ \mu = 0.194 - 0.015 \rho - 3.45 \times 10^{-3} \sigma_N \]  

(8)

Testing with instrumented dies was also performed but did not yield results that were as consistent. This may be for many reasons, but one major cause could be that not all the dies were capable of measuring radial pressure and so an estimation of radial pressure being 0.5 times the axial pressure was used to calculate the friction coefficients. This is perhaps too simplistic an approach although it is claimed that there is good agreement with experimental measurement of radial/axial pressure.

**Friction with Velocity Dependence**

Doremus et al. completed shear plate tests with a tungsten carbide/Distaloy AE die wall/powder combination. A range of densities from 4.75 g/cc to 7.3 g/cc were tested. The tests were conducted at normal stresses from 50 to 800 MPa, and at velocities from 0.35 mm/s to 100 mm/s. So, the experiments were under conditions similar to industrial pressing, except that the test apparatus was a shear plate testing machine, similar to that shown in Figure (2).\(^\text{xii}\)

It is most significantly found that an increase of velocity had an effect on the measured friction coefficient, which is represented in equation (9). \(\mu_0\) is the lowest coefficient of friction achieved in a test, which involved sliding the plate over a distance of 80 mm while in contact with the powder metal compact. Over the first 15 mm of travel the coefficient of friction would drop from its static value to the value of \(\mu_0\) in equation (9). The density of the powder is denoted by \(\rho\), the normal stress by \(\sigma_N\), and the velocity by \(V\).\(^\text{xii}\)
\[ \mu_0 = \exp\left(\frac{-\sigma_n}{1169}\right) \times \left(- \frac{0.14 \rho}{7.33} + 0.224\right) \times \left(1.437 \tanh\left(\frac{V}{12.6} + 0.886\right)\right) \]  \tag{9}

Cante et al. also used an equation to calculate friction that is dependent on relative velocity between the die wall and powder compact. They stated that the “dynamic friction model exhibits a more robust behaviour for numerical simulations”. Unfortunately, they did no more to elaborate this model than to describe it as density and velocity dependent.

**Software Used**

In most cases the software packages used to simulate compaction are LS-Dyna or ABAQUS. These packages could be used with either explicit or implicit integration. Usually, an explicit integration is used for compaction modelling because it less computationally intensive, which is a necessity for such complex simulations. As a disadvantage explicit time integration can result in unmanageable error if not properly implemented over relatively small time steps between calculations.

Implicit time integration has been used by Bejarano et al. when simulating ejection, presumably because of the reduced complexity due to the very tiny volume changes involved, and only rarely occurring plastic deformations. The software package used was ABAQUS implicit.

In both LS-Dyna and ABAQUS user defined material properties and algorithms can be used to govern the simulations. This is probably the most significant factor in selecting a software package to perform this type of simulation. It is unlikely that any
software exists today that has intrinsic algorithms capable of representing powder metal properties, especially since there is not yet consensus about what these might be.

**Testing Requirements**

The first requirement of a test platform is to allow elastic and friction models to be verified or created for the purpose of finite element modelling. While achieving this goal the characteristics of the industrial pressing situation must be captured. If a variable like pressing speed is not attained in the experimental test platform it must be certain that there is no significant effect on the outcome of the experiments. It is apparent from previous work that certain variables must be held to the same values as are found in industry.

**Industrial Production Parameters**

During compaction the punches move at about 25 mm/s. Die withdrawal occurs at about 70-90 mm/s, and punch ejection at 20-30 mm/s. Few laboratory press systems can achieve these speeds with any of their components. Most have maximum speeds of 10 mm/s or less, while a few can reach speeds in the 80-100 mm/s range. It is always preferable to run experiments with the same process parameters as those found in industry, and with some researchers finding velocity to affect friction coefficients it would be prudent to test those findings. Apparently, a large variation in hold down force may be expected between different parts. For this reason an appropriate hold down force, high enough to prevent cracking and low enough to prevent distortion of the part, must be found through
trial and error.¹⁵ This represents a significant opportunity for ejection modelling to reduce the time required to find the ideal hold down force. Distortion of the part can be predicted by the finite element model and the likelihood of cracking should also be possible to predict. Armed with these limits at least a safe operating range for the hold down force could be determined, if not a single ideal force value.

Because springback and friction coefficients are significantly affected by material choices, the types of die materials should closely match those used in the industrial setups. At Stackpole some of the commonly used metals are Vanadis 4, 6, 10, 23, and CPM 1V, 3V, 6V, 10V, and 15V.¹⁵ Choosing between these and other materials used for both dies and punches will involve selecting based on frequency of use and similarity of properties. The surface quality of the die inserts must also be matched, in order to accurately measure friction.

**Summary of Requirements**

A number of models of elasticity and friction exist and have been summarised. The mathematical models of elasticity are especially similar in their form and dependence on density and material testing. It is through these tests with appropriately designed equipment that is capable of mimicking the industrial pressing situation, that both the friction and ejection models can be tested for their accuracy. It will be likely that the tests will spawn new relationships that are better tailored to the problem of predicting elastic response solely for the ejection process, which is not the case for any of the previously discussed models of elasticity.
The experimental test setup may be required to function at speeds similar to industrial presses, will require that similar die materials are used, and will require that the same pressures are evolved, even if this means using a very small test specimen of 10-25 mm in diameter.

**Machine Modelling**

It is suspected that the tooling itself does not always perform consistently and may have interactions between components and the powder compact that cause unwanted results. Friction between components and changes in temperature may affect the forces required and the forces delivered to the powder during compaction and ejection. Even the elastic recovery of the tooling is not adequately described by the theoretical values provided by the press software, and must be modified by personnel to ensure proper operation. These problems may be alleviated or minimised by including models of the specialised tooling that is loaded into the press to produce a given part.

**Solid Modelling Software**

The solid modelling software used at Stackpole includes Pro/Engineer, which is a very popular software package. Components first designed in this or another software package could then be transferred to the FEM software chosen for ejection modelling, where they will become part of the simulations. Their interactions can then be monitored, and problems identified.
Sources of Force Data

As an example, ejection forces for tests with admixed lubricant required ejection forces of 31kN in tests conducted by Degoix et al. The powder blend of Fe, Cu, Ni, Mo, and C was compacted at 690MPa ± 10MPa and resulted in green density of 7.21 g/cm³. But, this sort of data is not prevalent in the literature.

The first and simplest method of estimating the forces of compaction is taking the powder manufacturer’s provided data for compaction pressure necessary to achieve the required density. This multiplied by the area of the powder being pressed by the punch reveals the estimated force required. This is the starting point for tool design. But solving the problem of section 0 with respect to hold down force will probably yield more precise ejection force estimates, as will the process of modelling the ejection. The prescribed positions and motions of the powder metal component will be known. From experiments the friction and elastic properties should also be known. These together should allow for accurate estimates of forces and stresses in not only the powder compact but also in the machine tooling.

Summary of Requirements

For modelling of the machine components it will be necessary to obtain solid models of the machine tools an preferably their assemblies in either their native format, but a format in any case readable by the finite element analysis software used for the ejection models. Once imported the tooling can become part of the simulations that will still centre around the ejection model.
Conclusions and Recommendations

Appropriate mathematical models must be selected for both the elastic response at ejection densities and also the friction characteristics between dies and powder compacts. Unfortunately, the bulk of the work performed to date is with Distaloy AE and very few other metal powders. This has allowed researchers to compare different approaches and tackle different aspects of compaction and ejection while avoiding the necessity of retesting the material itself (triaxial tests, cyclic elastic response tests, etc…).

The reality is that in industry Distaloy AE is not the only powder used. The specific metal powders used at Stackpole will have to be tested at the densities that will be achieved in industrial parts. The relevance of any one model of elasticity will be decided by whether it can be made to agree with the experimental results. If a new mathematical fit is necessary, it will be made.

In the case of a friction model it matters even more that the correct die material is used. It is not only the powder used, but even more so than with elastic models the die material used that has a significant effect on the outcome. So, the test equipment must have the same or sufficiently similar materials.

The mathematical models must be validated experimentally. If necessary they developed anew. They can be implemented into the finite element simulations where they will allow the prediction of tooling forces, loading of the powder compact, and the determination of an appropriate ejection schedule to minimise the time taken to achieve consistent production of new products.

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