MSc Theses

Lund University

Production and Materials Engineering | Department of Mechanical Engineering Science

Summaries of student’s work in the academic year 2021/20222

Photo: Louise Larsson

Preface

Another year has passed and we are happy to congratulate our students for a well-conducted work. The year has been full of challenges and triumphs for our students at Production and Materials engineering that now have finished their degree works. In this book we have gathered the summaries of the work handed in by our students. This has been a voluntary opportunity and 10 students have decided to contribute.

You will here have the opportunity to read about project including experiments on material characteristics, producibility tests and monitoring design within our three branches of subject, production technology, material engineering and manufacturing systems.

Enjoy!

The full length reports can be found on the university home page at: https://lup.lub.lu.se/student-papers/search.

Master Program Directors

Jinming Zhou and Christina Windmark

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Material and Resource Efficiency within Manufacturing Industry:

A study of strategic differences in material efficiency strategies based on size of enterprises and their location

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ABSTRACT

Global material consumption has been on the rise ever since commencement of industrialization and constant population rise. This statement holds good even for industries using solid metals as raw materials and the efficient use of materials is the need of the hour. The issues such as depleting metal sources due to continuous extraction and cost intensive counter measures to deal with problems related to increased raw material consumption has opened the scope for this research. Before providing solutions to these issues, one needs to understand the current state of industrial "readiness" to address material efficiency. Parameters such as KPIs, in-process data collection techniques, waste reduction tools, drivers, and barriers to implement material efficiency strategies have been gathered through literatures to assess the current state of the industry's readiness to implement material efficiency strategies. The assessment was done through a survey followed by complementary interviews for unique responses, where responses with highest frequency were considered favorable. Based on the responses, low-cost suggestions were made using existing literatures to increase efficiency of the raw material (metal) during its life cycle. Results of the survey were interpreted based on the size of the industry i.e., Large (L), Medium (M), Small (S) and Micro (XS) manufacturing enterprises, primary raw material (Core machining industries and Chemical industries with machining workshops) used. An attempt to find the relation between the industry's readiness and its geographical location (country based) was also performed.

1. INTRODUCTION

Global production has been on the rise due to rapid industrialisation and growing population throughout the world. This leads to the rise in consumption of natural material resources to meet the demand of the materialistic world. Metal is one such naturally occurring resource whose accessibility has increased over time and industries today do not greatly consider the rate at which known, naturally occurring metal reservoirs are depleting. To tackle and spread awareness of the issues regarding the unsustainable natural resource consumption the UN released a set of sustainable development goals (SDGs) amongst which SDG 12 sets targets for industries to ensure sustainable resource consumption. Large (L), Medium (M), Small (S) and Micro (XS) sized manufacturing enterprises are equally accountable due to the impact each of the have on the material consumed and waste generated. Similarly, industries in developed countries need to comply with several strict environmental policies sworn in to making the production system more sustainable unlike the developed countries where monetary profits and economic development leads to more lenient policies and approach to monitoring the compliance of the industry. Hence, looking into the possibility of the location of the country having an impact on the degree of sustainable practices used within the industry is one of the intentions of this thesis. Similarly, assessing the current state of material efficiency strategies in each of these enterprise types is key to provide future solutions based on the current level of application of material efficiency strategies.

Based on this, the following research questions were formulated which looked into (i) the current industrial practices to reduce raw material consumption and increase raw material value retention (ii) raw material consumption and in-process material behaviour tracking methods used in industries (iii) impact of the size of the industry on the material efficiency practices (iv) driving factors to implement material efficiency strategies (v) barriers to implementing material efficiency strategies (vi) role of the status of developing or developed country in an industries push towards efficient use of material resource.

2. METHODOLOGY

In this thesis, the material efficiency strategy used within the industry and the research questions are assessed using parameters such as Key Performance Indicators (KPIs) for raw material consumption used in the industry, in-process data collection techniques used in industries, waste reduction tools used and recycling practices within the industry, drivers, barriers faced by industries to implement material efficiency strategies found through the literature search. Due to these parameters being indicators of quality, the best way to analyse these parameters was through a qualitative and a descriptive analysis. The data on the current industrial practices was collected through the online survey based on the research parameters mentioned above. The responses were then analysed by grouping them based on the type of industry and the raw material used to provide a microscopic understanding of the practices. Based on the type of primary raw material used the responses were divided into "core metal fabricating industries" (industries which used metal as a primary raw material) and "chemical industries with machining workshops" (industries which primarily used chemicals as raw materials but had machining workshops which mimicked small or micro manufacturing industries). Through the literature search, key strategies such as zero waste, circular economy, and net-positive philosophies to reduce overall material consumption throughout the different stages of material product life cycle were discussed.

3. Results

The survey had 19 participants with a response rate of 29.231%. Out of the 19 participants, 16 of them were L, 2 were XS and 1 was M. After analysing their responses to 27 questions which were divided between 3 sections, i.e., section 1 enquired upon the information on the participating industry (No. of employees, No. of production locations, raw materials, and raw material shape form), section 2 based on the research parameters, section 3 enquired the drivers, barriers and advantages experienced by the industries upon implementing material efficiency strategies. Upon analysing the responses, the research questions were answered as below:

Application of both waste prevention and waste management activities in manufacturing industries is an encouraging sign to reduce raw material consumption and retain its value. KPIs have been historically used to track the system performance and similar trend is seen even to this date. The use of KPIs to track environmental performance of the material is neglected and could be improved upon, however, input and scrap quantity generated were regularly tracked. The KPI of actual to planned scrap ratio was minimal and increasing its use can assist industries in fine-tuning their processes to minimize waste. Manual data collection and PLC is still heavily relied upon in industries despite the errors associated with it, however, the use of modern sensor-based data collection techniques coupled with Industrial Internet of things (IIOT) is still at its early stages. A highly effective waste minimization tool i.e., Value Stream Mapping was rarely used whereas 5S and Root Cause Analysis were often used.

4. Discussion

Large Manufacturing Industries have a greater responsibility to mindfully consume raw materials, and according to the survey they do take greater accountability in consuming raw materials when compared to Medium and Micro enterprises. However, there are large variations amongst the large manufacturing industries based on the use of KPIs, in-process data collection techniques and waste reduction tools used opens a scope of uniformity to increase their potential in mindful raw material consumption. The Micro enterprises need to use higher number of KPIs and in-process data collection techniques.

Implementing material efficiency actions and strategies was mainly driven by the rising raw material costs, therefore one can say that industries use material efficiency as a cost reduction tool and not as an environmental enhancement tool. Similarly, the common industrial perception of high investment costs and slow return on investments hindered its application.

The possibility of developed countries implementing material efficiency strategies effectively is better when compared to developing nations as the Swedish industries that took part in this study on an average used higher number of KPIs, data collection techniques, waste reduction tools when compared to Indian industries. However, this part of the survey requires further research as the difference in the sample sizes between Indian responding industries and Swedish responding industries is very large.

References

[1] Ganesh Achar, Amruth Material and Resource Efficiency within Manufacturing Industry: A study of strategic differences in material efficiency strategies based on size of enterprises and their location, Lund University (2022).

Effect of cutting parameters on hole defects while drilling twill reinforced bio-composites

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ABSTRACT

Composites like CFRP and GFRP have been a popular alternative in several industries such as aerospace, automotive, energy, marine and consumer goods. However, these materials being non-recyclable, bio-composite materials are being investigated to explore areas where it can replace the conventional composites. One such alternative is Flax-PLA based bio-composite which is 100%recyclable.

This study aims to investigate the effect of cutting parameters such as feed, cutting speed and type of drill on the defects produced while drilling 2mm Flax-PLA based bio-composite materials. The study involves benchmarking 4 different drills and 72 combinations of cutting data for each of the drill. Further, the type of defects is classified and the defect areas are analyzed against the used cutting data.

Results indicate there are 7 different types of defects that can be observed while drilling bio-composites which are (1) Spiraled Crown Burrs, (2) Transient Burrs, (3) Uniform Cylindrical Burrs, (4) Fracture Burrs, (5) Exit Burrs with Drill Cap, (6) Inter-hole Longitudinal Burrs and (7) Uncut chips.

Feed rate plays the most significant role in determining the hole quality in this study. With increase in feed per tooth from 0.005mm/rev to 0.1mm/rev, there is first a drastic reduction in defect area (mm^2) owing to the relation between the cutting-edge radius of the tool and feed per tooth used which affects the rake angle, in turn affecting the chip thickness and defect area. Hence it is important to choose the starting feed per tooth (mm/rev) at least about 3 times the cutting-edge radius of the tool to avoid having extremely poor-quality holes. The PCD CX-1 drill produced the best hole qualities over a wide range of cutting data with minimum entry defect of just 2mm^2. The overall best hole quality was produced between f= 0.12mm/rev to 0.27mm/rev and Vc=100m/min to 220m/min with average defect area of 13.24mm^2. The lowest total defect area of 6.83mm^2 is produced at f=0.24mm/rev and Vc= 140m/min.

Keywords: *CFRP drilling, Composites, Hole quality, Delamination, Uncut fibers*

INTRODUCTION

Composites have been growing in their application in almost every industry one can imagine. Although composites have gained the spotlight as breakthrough material for engineering purposes in the 20th century, humans have been using natural fibre-based composites for thousands of years. Composites are heterogeneous meaning they are made of two or more constituent materials having distinct properties. The combination of which results in special physical properties. Due to its unique specific properties, composites have been trending in replacing conventional metals in various applications.

The advancement in composite materials have triggered huge demand both in terms of R&D and manufacturing in the field of aerospace and automotive engineering. In many areas in these fields, use of composites is now seen as structural and strength optimization rather than for an aesthetic purpose. In the industrial world, composite is now an a viable alternative due to its high corrosion resistant behaviour. Properties such as high strength to weight ratio, high specific stiffness, and extremely light weight makes it extremely attractive. Composite materials have been a popular alternative in both structural and aesthetic applications over the last two decades. With the most popular carbon fibre and glass fibre composites being around for a while, new studies have been leaning towards an eco-friendly alternative of composite materials that can be 100% recyclable. One such relatively new material is the natural fibre composite made of Flax seed fibres reinforced with PLA.

METHODOLOGY

This study investigates the effect of cutting parameters such as feed, cutting speed and type of drill on the defects produced while drilling 2mm Flax-PLA based bio-composite material. Each bio-composite sheet of 310mm × 310mm will have 216 holes drilled with varying cutting data. After going through previous studies in machining of flax based polymer composites, it was decided that there is a need for a wider range of cutting data since there is very limited sources on drilling of these bio-composite materials. The aim is to identify the cutting data that produced the best hole quality while drilling. Since tool wear affects the hole quality, it was important to have tested several cutting data with minimum tool wear. Another factor in choosing the cutting data in this case is heat as the material could see burns if there is excess heat produced in the process.

Bearing in mind all these factors, a detailed experimental plan is developed. Each drill is tested for a range of feed rates from 0.01mm/rev up to 0.2mm/rev. The cutting speeds that are in the range of 20m/min to 220m/min (1000 rpm – 11,010 rpm). Therefore, in each panel, there is 72 different combinations of cutting data with varying feed rate and cutting speeds. With each cutting data, 3 holes are drilled making it 216 holes in each panel. The same is repeated for 4 different drills to make comparisons.

For drilling holes, the Bridgeport XR 1270 vertical CNC machine is used. A machine table with pre-drilled slots is mounted on the machine table above which the bio-composite sheet is mounted for drilling. After going through safety instructions, the program is developed with the help of the faculty. The program is developed as per the developed strategy in table 3 and table 4 and in accordance with the pre-drilled holes on the machine table. The feed rates are incremented along the row and the cutting speeds are incremented along the column. The program is written in such a way that there was a possibility to remove the tool after every 3 holes of drilling. This provided more opportunity to check tool wear regularly.

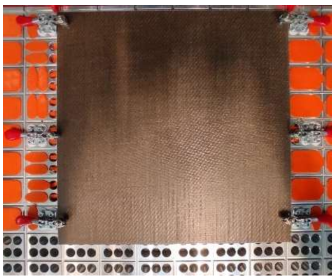


Figure 1 Machine table with pre-drilled holes

Image analysis

The process of image analysis uses a sequential order of modules that are implemented and is primarily based on input image of the drilled holes along with additional information such as the scale and size of the image in pixel/mm and the error of measurement value. For this study, a Basler Ace- acA1440-220uc camera is used to capture the images of the drilled holes and use it as the input for image analysis. The Basler ace comes with a Sony IMX 273 CMOS sensor that is capable of delivering 227 frames per second at a 1.6 mega pixel resolution. The sensor size is 5mm×3.7mm with a resolution of 1440px×1080px.

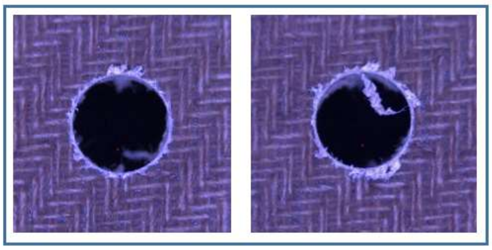


Figure 2 Images from the camera

Once all the images are captured, a MATLAB script is written to perform image processing to identify and calculate the area of defects around the drilled hole which will be the primary distinguishing and comparison factor in the analysis. All images holes both on the entry side and the exit side are captured and saved along according to the cutting data used. While using MATLAB to carry out image processing. The image is first converted from RGB to greyscale from which it is then converted to binary, black and while image. The intensity of colour grading allows us to craft the values such that all the defects are detected. It was also taken care in each case that no non-defect attributes are detected in the image processing. Once the image is converted to binary, the defect area is depicted in white, and the area of the white pixels can be calculated. This is our defect area around the hole.

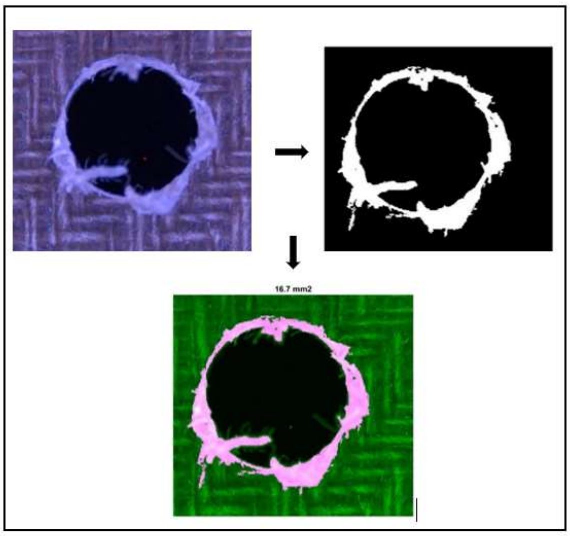
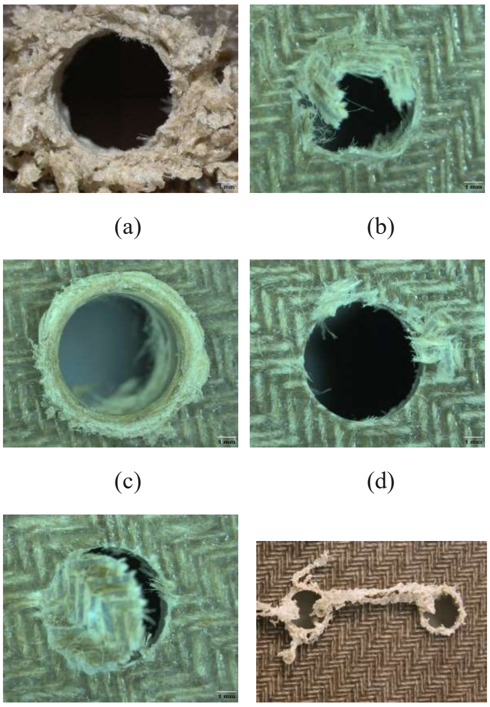


Figure 3 Image processing using MATLAB

RESULTS AND DISCUSSION

After benchmarking 4 drills over 72 combinations of cutting data, the defects that are produced while drilling bio-composite materials are analysed and classified into 7 types namely Spiralled Crown Burrs, Transient Burrs, Uniform Cylindrical Burrs, Fracture Burrs, Exit Burrs with Drill Cap, Inter-hole Longitudinal Burrs and Uncut chips which needs to be taken in consideration while choosing the cutting data and the type of drill used.



(a) (b) (c) (d) (e) (f)

Figure 4 Types of defects seen (a) Spiralled crown, (b) Transient burrs, (c) Uniform cylindrical burrs, (d) fracture burrs (e)Exit burr with drill cap (f) Interhole longitudinal burrs

PVD coated drill

The 2 flute PVD drill, has a mean cutting-edge radius (R) of 13.06µm. The tool wear and the change in cutting edge radius was negligible in our case. When a feed per tooth of 0.01mm/rev is used which corresponds to 5µm/rev per tooth, the ratio of feed per tooth(f_t) to the cutting-edge radius(R), f_t/R= 0.38 which is less than 1. In such a case, the rake angle becomes negative and hence the chip thickness is high and so is the defect area. As we increase the feed per tooth, the ratio f_t/R increases keeping the rake angle positive and consequently produces low chip thickness. Say for a feed rate of 0.04mm/rev, f_t = 20µm/rev. The ratio f_t/R = 1.53 which is greater than 1. Here is where we start seeing better quality holes being produced. There is a feed rate window from 0.04mm/rev to 0.1mm/rev where holes with good quality were produced. With the cutting speeds, better hole quality. The example of defect area behavior wit feed is shown in figure 3. It is seen that the good operating window of cutting data with the PVD tool is from feed rates 0.04 to 0.1mm/rev and cutting speeds 50m/min to 180m/min where the average total defect area is about 35 mm^2. It can also be seen that the effect of cutting speed has much lower significance than compared to the feed rate. The lowest entry, exit and total defect area produced is 6.53mm^2 at Vc=50m/min, f=0.06mm/rev, 19.27mm^2 at Vc=20m/min, f=0.18mm/rev and 30.57mm^2 at Vc=80m/min, f=0.1mm/rev. Due to the type of defects at exit surface are transient burrs, they need additional deburring process. Hence the total defect area in case of PVD is chosen to minimize in order to minimize the amount of deburring process.

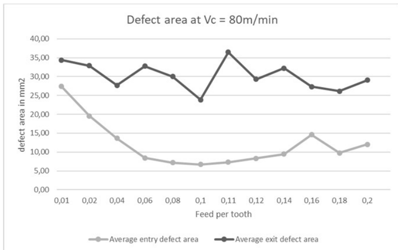


Figure 5 Example of defect area behaviour with feed with PVD

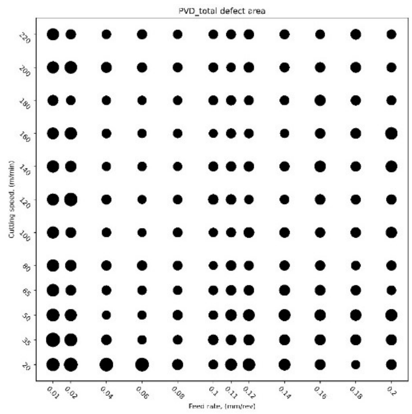


Figure 6 bubble of total defect area with varying feed rate and cutting speed for PVD drill

PCD CX-2

The entry defect area has a similar trend which can be observed while increasing feed from 0.01mm/rev to 0.2mm/rev through all the cutting speeds used. There is a drastic drop in the entry defect area as we increase from 0.01 to 0.04mm/rev. This is because of the relation between the cutting-edge radius of the tool to the feed rate used. As mentioned in section 3.2, the cutting-edge radius of the PCD CX-2 drill is 4.1µm. The tool wear and increase in cutting edge radius was negligible in this case too. When a feed of 0.01mm/rev is used, it is 10µm feed with 5µm/rev of feed per tooth, which results in the ratio of feed per tooth to cutting edge radius (f_t/R) is less than 1, making the rake angle negative and hence increasing the chip thickness producing poor quality holes. With an increase in feed(µm/rev), the ratio f_t/R increases and becomes greater than 1 for a feed rate of 0.02mm/rev(f_t=10µm/rev). The rake angle therefore is now positive and has lower chip thickness. As we increase the feed to a value greater than 3 times the feed per tooth(µm/rev), much better hole quality is produced. In this case, at a feed rate of 0.04mm/rev, we get the lowest defect area. There is a very small upward trend from f=0.04mm/rev up to 0.2mm/rev.

With the CX-2 drill, the entry defect area is weighted more than the exit and total defect area. This is because the constant drill caps formed at the exit surface at all cutting data. The area calculated at exit depends on the amount of the drill cap covering the hole at the time of measurement. Hence the entry defect area becomes a more reasonable choice to be considered. As it can be visualized in the bubble plots of entry defect area in figure 8, the good operating window of cutting data with the PCD CX-2 drill is from feed rates 0.04 to 0.08mm/rev over the entire range of cutting speeds where the average entry defect area is 9.7 mm^2. It can also be seen that the effect of cutting speed has much lower significance than compared to the feed rate. The lowest entry defect area produced is 6.7mm^2 at Vc=50m/min, f=0.06mm/rev.

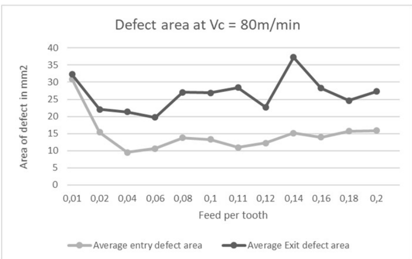


Figure 7 Example of defect area behaviour with feed with PCD CX-2

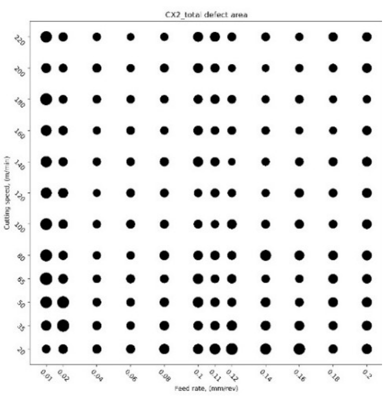


Figure 8 bubble of total defect area with varying feed rate and cutting speed for PCD CX-2 drill

It can clearly be seen that better-quality holes are produced with the CX-1 drill with the lowest defect areas when compared to the other drills used. Compared to the change in defect area with feed, the change is cutting speed has very less effect of the defect area. The behaviour of defect area with change in feed is very similar to all the cutting speeds used. The entry defect area has a similar trend which can be observed while increasing feed from 0.015mm/rev to 0.2mm/rev through all the cutting speeds used. There is a drastic drop in the entry defect area as we increase from 0.015 to 0.06mm/rev. This is because of the relation between the cutting-edge radius of the tool to the feed rate used. As mentioned in section 3.2, the cutting-edge radius of the PCD CX-1 drill is 4.3µm. The tool wear and increase in cutting edge radius was negligible in this case even after running a tool wear test for another panel of 216 holes. When a feed of 0.015mm/rev is used, which is 15µm feed with 5µm/rev of feed per tooth since the CX-1 has 3 peripheral cutting edges, results in the ratio of feed per tooth to cutting edge radius (f_t/R) is less than 1, making the rake angle negative and hence increasing the chip thickness producing holes of poor quality and larger area of defects. With an increase in feed(µm/rev), the ratio f_t/R increases and becomes greater than 1. Say for a feed rate of 0.03mm/rev(f_t=10µm/rev). The rake angle therefore is now positive and has lower chip thickness. As we increase the feed to a value greater than 3 times the feed per tooth(µm/rev), much better hole quality is produced. In this case, at a feed rate of 0.06mm/rev (ft=20 µm/rev), we get much lower defect area. It is also interesting to see that from feed rate 0.06mm/rev up to 0.3mm/rev, there was no significant change in the defect area as seen with other drills used.

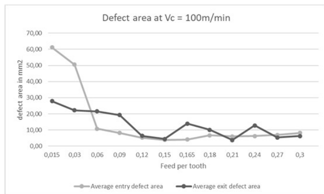


Figure 9 Example of defect area behaviour with feed with PCD CX-1

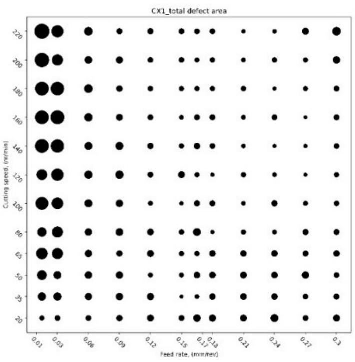


Figure 10 Bubble plot of total defect area of CX-1

HSS

In all cases, it is observed that there is a drastic downward trend in the entry defect area with increasing feed from 0.01mm/rev to 0.06mm/rev. This owes to the cutting-edge radius of the tool and the feed used. The cutting-edge radius of the HSS tool used is 6.7µm. Similar to the other drills used, tool wear and increase in cutting edge radius was negligible in this case too. When a 5µm/rev of feed per tooth is used**,** the ratio of feed per tooth to the cutting-edge radius (f_t/R) is less than 1, making the rake angle negative and hence increasing the chip thickness producing poor quality holes. Similar to the other drills, as we increased the feed per tooth(µm/rev) to a value more than 3 times the cutting-edge radius, the hole quality has a drastic change. The trend follows to be a reduction in defect area up to 0.1mm/rev and then has a small upward trendline up to 0.2mm/rev.Compared three other drills tested, HSS produced the holes with highest defect areas. High amount of spiralled crown burrs at entry, transient and fracture burrs at exit are observed. As depicted in the bubble plot, exit defect areas seem to be better than entry defects at lower feed range from 0.01mm/rev to 0.06mm/rev. Both entry and exit defect areas are comparable from feeds 0.08-0.2mm/rev. With HSS drill considering the total defect area, the comparatively better-quality holes are produced at f=0.14-0.2mm/rev and between cutting speeds of 65m/min to 160m/min with an average total defect area of 36.54mm^2. The least total defect area is produced at f=0.2mm/rev and Vc=80m/min with defect area of 25.8mm^2.

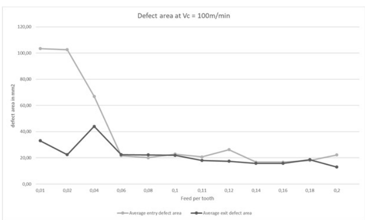


Figure 11 Example of defect area behaviour with feed with HSS

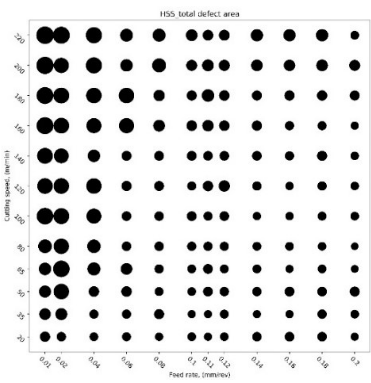


Figure 12 Bubble plot of total defect area with HSS

CONCLUSION

This study aims to investigate the effect of cutting parameters such as feed, cutting speed and type of drill on the defects produced while drilling 2mm Flax-PLA based bio-composite materials. The aim includes classifying and understanding the defects seen in drilling these bio-composites and the behaviour of hole defects over varying cutting parameters and drilling tool types.

After benchmarking 4 drills over 72 combinations of cutting data, the defects that are produced while drilling bio-composite materials are analysed and classified into 7 types namely Spiralled Crown Burrs, Transient Burrs, Uniform Cylindrical Burrs, Fracture Burrs, Exit Burrs with Drill Cap, Inter-hole Longitudinal Burrs and Uncut chips which needs to be taken in consideration while choosing the cutting data and the type of drill used.

Further, it can be said that the feed rate plays the most significant role in determining the hole quality. With increase in feed per tooth from 0.005mm/rev to 0.1mm/rev, there is first a drastic reduction in defect area (mm^2) owing to the relation between the cutting-edge radius of the tool and feed per tooth used which affects the rake angle, in turn affecting the chip thickness and defect area. Hence it is important to choose the starting feed per tooth (mm/rev) at least about 3 times the cutting-edge radius of the tool to avoid having extremely poor-quality holes.

Comparing the 4 drills used in this study, better hole qualities are produced using the PCD drills. The PCD CX-1 drill produced the best hole qualities over a wide range of cutting data with minimum entry defect of just 2mm^2. The overall best hole quality was produced between f= 0.12mm/rev to 0.27mm/rev and Vc=100m/min to 220m/min with average defect area of 13.24mm^2. The lowest total defect area of 6.83mm^2 is produced at f=0.24mm/rev and Vc= 140m/min.

FUTURE SCOPE

This study is preliminary in the area of bio-composite machining. Since there is limited scientific resources in this field there is a lot of experimental opportunities that can be looked into as future study. One such topic could involve more extensive study on tool wear by drilling large number of holes with the PCD and PVD coated drills. Rounding of cutting-edge radius of the tools can be analysed over large number of holes as it played a crucial part in determining the hole quality. The defects produced due to tool wear can be different from the defects seen due the actual drill geometry and cutting data used. This could be another addition to the study. Lastly, a study of delamination and drilling bio-composite materials of more than 2mm thickness can be a good continuation of this study.

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Redesign of a Production Dashboard under consideration of Lean and Performance Management Aspects – A Case Study

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ABSTRACT

Purpose *– The purpose of this master thesis is to test the applicability of the dashboard development procedure by Vilarinho, Lopes and Sousa (2017)[1] in the application case of a single case study at Nolato MediTor AB for a redesign of a production dashboard.*
Methodology *– This thesis was conducted in form of a case study, which allows studying the phenomenon in a realistic setting. The thesis follows the dashboard development procedure as it is instructed. As part of the procedure, semi-structured interviews were conducted..*
Findings *– The dashboard development procedure is applicable for SMEs independent of the industry. The strength is based on the intended left out of specifying exact measurements or solutions but instead, offering a comprehensible framework. It was found that the most important guideline for practitioners designing a dashboard is the close consideration of the prerequisites and the culture of the company and the alignment with the company's strategy.*
Research limitations/implications *– The research is limited by the execution as a single case study. Further was the case study only conducted with one department of the company and due to time limitations, the last step is not included.*
Keywords *– Dashboard development procedure – Dashboard – Continuous Improvement – Performance Management – Shop floor Management – Lean Management – Visual management*

1. INTRODUCTION

Dashboards are a common management tool, that often is applied in the context of the Lean Philosophy, as it combines different Lean approaches, such as performance, shop floor and visual management. Performance management focus on the affords to achieve companies' goal effectively and efficiently. The application of key performance indicators is the most popular choice to quantify company success [2]. Shop floor management places the production as the central unit of value creation and as such emphasises directing management efforts towards the production [3]. All management approaches include continuous improvement as an important aspect. Sometimes also described as Kaizen, it accentuates the importance to integrate improvement efforts into the daily business. For all those management approaches a dashboard is a tool that helps to monitor, control and adjust the course of action. The purpose of a dashboard is to display the most important information at glance [4].

In the literature, the topic of Dashboards is only covered to a limited extent. The analyses of the motivation and status of implementation, the presentation format and the selection of performance indicators have gained the most attention [4]. Lately, the advancement of digitalisation and the upcoming Industry 4.0 lead to more publications, which introduced digital or smart dashboard solutions. But those papers focus on the presentation format of a dashboard. The implementation of such requires a high maturity level of the IT infrastructure and larger investments. For SMEs, the prerequisites to implement such advanced dashboards are often not given [1]. This thesis focuses on the question: How to approach a design/redesign process of a dashboard? Which aspects need to be considered to find a company-specific solution? How to decide the content of a dashboard? This work shall contribute to finding a dashboard development approach that matches the characteristics of SMEs and offers realistic solutions for them. This aspect of the dashboard is barely covered in the literature, except for the paper "Developing dashboards for SMEs to improve performance of productive" by Vilarinho, Lopes and Sousa from the year 2017. The authors develop a procedure, which addresses the realities of SMEs and can be applied independently of the industry [1]. This thesis applied the dashboard development procedure in a single case study. In doing so this thesis aims to examine the suitability of the model. By adding a case study to the Vilarinho et.al. model this work aims to increase the validation of the model or evince possible flaws to improve the model.

2. Methodology

This thesis was conducted with the department *Produktsystem* of Nolato MediTor AB in Torekov, Sweden. The case study format allowed to pay attention to the special surrounding and consider all relevant aspects, which are given in an organizational surrounding. Moreover, does the literature accentuates the need for an individualistic implementation of a production dashboard to satisfy the specific framework of an organization.

Vilarinho, Lopes and Sousa designed a development procedure for dashboards (DDP), which is tailored for the application within SMEs and has a generalist approach. The procedure is based on the product development process by Pahl and Beitz from 2007, which is widely accepted in research and by practitioners [5]. As Pahl and Beitz also Vilarinho, Lopes and Sousa sick to the idea of four main steps.

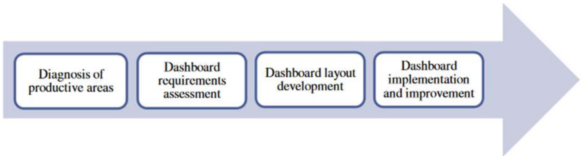

Figure 1 Dashboard development procedure Model for SMEs [1]

The steps are clear and follow a logical sequence of information acquisition over result structuring to develop an individual concept. The steps contain sub-steps to provide better guidance for practitioners, who want to apply the procedure. Still, some explanations are given but enough freedom is left to apply the model in a manner, which allows users to adapt to the characteristics of any organization. The procedure offers a compelling logic and was already successfully applied in a single case study by the authors themselves. But throughout the literature review, no further application of the model was found.

The academic contribution of enriching the methodology by another case is limited by the fixed time of the thesis. Following only the first three steps can be conducted. The final step of the implementation and improvement will be the responsibility of the case company. A further limitation is a focus on the content of the dashboard and the presentation of the information. The choice regarding the technical solution, which kind of dashboard (analogue, digital or smart) is only partly dealt with.

3. Dashboard Development Procedure

3.1. Case Company

The case study was conducted in cooperation with Nolato MediTor AB located in Torekov, Southern Sweden. Nolato AB is the mother company scoping the three business groups' medical solutions, integrated solutions, and industrial solutions. Nolato MediTor AB is part of the medical division, which reached a total operating profit (EBITA) of 457 M SEK in 2021 and makes up around a third of Nolato's sales [6]. The company has the ISO 9001 (management), ISO 14001 (environmental management) and ISO 13485 (Medical devices) certifications.

The case study was carried out in the department Produktsystem (Swedish for product system). The department was merged of formally three departments a few months before the case study. It now compasses the processes of extrusion, injection moulding, assembling processes and ISO class 8, as well as CNC cleanrooms. The product range of the Produktsystem department encompasses around fifty products of the product groups respiratory devices, injection moulded silicone parts, catheter tubes/devices and in vitro fertilization solutions. The department Produktsystem consists of 41 employees. The production is organized in a three-shift model under the week and on-demand weekend shifts. Each group has a group leader responsible for several shopfloor operators. They are supported by six machine setters (the original Swedish job title is ställare), who are responsible to maintain and repair machines as well as providing general support for the department. The department is led by a production manager.

The company is characterized by the Nolato Spirit, the cooperative culture for all Nolato divisions. For the medical division, the strategy and values are honed in the "Medical Excellence" program. It highlights the Jidoka and JiT principles. Overall, the "Medical Excellence" reflects a high customer focus and concentration on continuous improvement. Nolato MediTor AB has several lean tools in place to comply with corporate values. The production processes are standardized, and those standards are a common aid used by the shopfloor workers to meet the quality requirements and best practices. All standards are revised on a repetitive cycle. Throughout the production, the product quality is continuously controlled by random sampling and statistical process control. The strategic goals are tracked in monthly meetings under consideration of KPIs. Besides, further lean tools are applied to support the advancement of a learning company

The industry of medical supply is designated by strict laws and regulations. The majority is issued by governments, but also big players in the industry influence rules within the supply chain. The framework of the medical supply chain forces assimilation of the network. Besides the elevated quality standards, compared to other industries, the purpose of the product demands accuracy and control throughout the production and places a severe responsibility on suppliers [7,8]. These characteristics led to predominantly long-term relationships between suppliers and customers.

Correspondingly are most of Nolato MediTor's business relations long-term.

The important ISO 13485:2016 (Medical devices) certification implies neglecting CI efforts to focus on meeting the regulations and accessing risks. Consequently, the medical supply industry evolved a culture, which focused more on compliance, rather than considering Lean aspects as it became common in other industries [7]. Nevertheless, does the general trend in the economy to become more efficient also affect the medical supply chain and force manufacturers to increase productivity to stay competitive. Hence continuous improvement efforts are indispensable [8].

3.2. Diagnosis of Productive Areas

According to the DDP model, the diagnosis phase shall be conducted like an audit. The preparation phase was only a draft planning as throughout the conduction of the diagnosis the possibility to pursue finding should be given. The main pillars of the diagnoses were determined to be semi-structured interviews, observations and sighting of company documents. The insights from the execution of those pillars built the foundation for the result analysis. Those were discussed with the company for the synthesis. Contrary to the case company of Vilarinho, Lopes and Sousa, Nolato MediTor AB already uses dashboards for approximately five years. Hence the main objective throughout the diagnosis phase was to understand the current use, the motivation behind the implementation and evaluate, to which extent the usage supports the intended purpose.

The department is not using one, but three dashboards. All boards are fully analogue. Two dashboards are within the production area, each is shared by two groups within the department. They are used for shift changes. Currently, the DBs at the shopfloor areas show the production lines of the groups with the aim value of produced parts per shift. The presented info is handwritten and during the shift change meeting, the workers shall fill in the actual number of produced parts of the finished shift. Another board, located in the office area, supports the daily management meetings. Divided into, one meeting with the group leaders and senior operators and another one with the support group (production manager with quality engineers and technicians). Both are conducted shortly after each other and are led by the production manager. It has mostly prints in A4 format to follow up on the status of production regarding strategic goals. The presentation format follows the classical cross off schema of the SQDC (Safety, Quality, Delivery and Costs) approach. The categories to be found on the board are called: near miss and accidents (tillbud och olyckor), quality customer aberrations (kundavvikelser), internal delivery (interna leveranser) and internal aberrations (interna avvikelser). Further, the shift and production plan are pint on the board. Those six printouts only take about 40% of the area of the DB up. Besides the daily management board is a smaller disturbance board placed, where disturbances get written on red magnetic cards and sorted into the categories registered, started (mottagen), ongoing (påbörjad) and long-term (långsiktig). This board is follow-up only on demand and all the disturbances are registered into the quality management system.

According to the DDP semi-structured interviews were conducted to gather expectations and information from different stakeholders. At the hierarchical level of management, the production manager of the department was interviewed. Representatively for the mid-management, all three group leaders and one machine setter were selected. This stakeholder group is attending the meetings in front of the production and the daily management board. The shopfloor level was represented by three shopfloor operators. Conclusively the support group was represented by one quality engineer and a technician. The interviews were performed in person and took between fifteen to thirty minutes. The interview guideline was individually adapted to the different stakeholder groups, leading to four guidelines. The guidelines all cover the Dashboard, which the interviewee is using, asking for criticism and improvement suggestions as well as the company's strategy. The last point was included, as the management wishes for the integration of performance management on the DB. To reach content validity, a validation interview was conducted with a member of the support group.

It was found that the two dashboards in the production do not support the structure and content of the shift change meeting. During the meeting, the leaving shift shall record the number of produced units. Though an underperformance does mostly not trigger a direct reaction and barely influences the process of the following shift. In the interviews shop floor workers further reported, that they cannot influence the result. Hence shop floor workers experience discordance between the meeting purpose and the Dashboard. With the circumstance of an analogue board, the presentation of production parts per shift mostly creates a waste of double-entry bookkeeping. The analysis shows a consensus of demanding information regarding staffing, the production plan and acute deviations, which affect the scheduled production plan or the production process itself. Since this reflects the information, that is currently shared verbally in the shift change meetings. Throughout the diagnosis also occasionally information such as best practices, machine status and feedback on delivery were mentioned as helpful.

For the daily management board, the content was found to be more coherent with the meeting structure. This board is meant to support the two meetings in the morning. The prints of the used categories of the SDQC approach, plus company-specific prints, are therefore pint in the according to the meeting order on the DB from left to right and from the top to the bottom. The most obvious deficit of this alignment is the usage of only half of the whiteboard. The other half of the DB remains empty. Even though the whiteboard offers more space the current information is presented in too-small font size. In general, was the feedback throughout the interviews regarding the presented information described as valuable. Whereby the question after the most important information led to the same outcome as for the production dashboards: staffing, deviations, the production plan, plus deliveries. This prioritization is neglected by the current presentation. Moreover, did some people mention additional information, such as best practices, as interesting to put on the board. Further, it was observed, that the deviation board besides the daily management only is included in the meeting when a status of a deviation changes.

In general, it was found that the most important information in all dashboard meetings is currently shared mutually. The analogue DB causes extra work of updating and not all information is synchronized between the board. The different layouts further do not support the transfer and synchronization of the most important information through the dashboards along with the department. Regarding the aspects of visual management, it was found that coloring is not applied in an effective manner. Different colors are used, but the signal effect is not exploited. Also, the features of information at glance and drill-down for analysis are only fulfilled to a limited extent.

To consider the idea of including performance management on the dashboard the Medical Excellence program was studied. Compared to the observations and interview statement it became noticeable, that the company strategy is not vivid throughout the entire company. Where the high customer focus is acknowledged by all employees and a central part of the daily business, the holistic cooperation strategy is leaking the same close follow-up. An analysis of the applied KPIs uncovered some inconsistencies. To enable goal-oriented performance management with consideration of the vertical company integration the KPIs need to be aligned with the overall strategy and demand an identified communication. The current level of IT majority and the organization of the performance management in monthly management meetings currently demote a senseful integration of KPIs on the dashboards.

For the synthesis, the results were summarized and presented to the responsible managers of Nolato MediTor AB. The findings were appraised by the management that without any adaption the requirement assessment could be conducted.

3.3. Dashboard Requirement Assessment

The requirement assessment is the translation of the results from the diagnosis phase into statements, how the dashboard should be designed. It shall reflect the reality of the organization. Hence constraints, realistic wishes, and other aspects, of the scientific state-of-the-art need to be considered. Two tables for the different dashboards for the daily management and the production were issued to list the requirements under the categories: purpose, user characteristics, functional and visual features and content. The requirement tables build the foundation of the layout design phase.

3.4. Dashboard layout development

To create a high recognition value between the daily management and the production DBs a guiding consideration was to create a uniform design. Nevertheless, the flexibility to modify the layout according to the different stakeholders had an important influence, as it also allows easier adaption during the implementation and improvement phase. The current system of the daily management board is designed to reflect the meeting structure. It was found to be beneficial and was tried to be maintained with the modification of the content since also important theoretical principles, as presenting the most important info at the top-left corner and middle of the board. Under those considerations, a design suggestion was created.

To gain a structure a matrix structure of 3 x 3 was chosen, with categories for the rows. The top row category is p*lan* and contains the shift plan at the top left field next to the production plan. As Nolato MediTor places outstanding importance on the customer focus the row was complemented by the existing check-up paper for delivery (interna leveranser), which follows the SDQC schema. According to the purpose of detecting and counteracting any influences that compromise quality or endanger customer focus, the second row focuses entirely on *disruption*. The first field is dedicated to aberrations and contains two of the SDQC charts, which formally had their own field on the dashboard. They are quality customer aberrations (kundavvikelser) and internal aberrations (interna avvikelser). As the derivations, that affect the daily business, are of prior interest in the center field of the board a small table shall list them. The columns list the derivation registration number from the quality system, a short description in form of a keyword, the processing status represented in colored dots, the processing datum, counteractions and the responsible employee. As derivations are handled in the quality system the possibility is given to gain more information over the system and on the board, only the acute derivations are shown. For the implementation, the last column of disruption is meant to remain free for now. It can be used for notes. The last category for the bottom row is *CI & safety*. The left field is for best practice and has no defined format on how information shall be presented. The center bottom field also stays without a layout specification but is meant to present information about Lean measurements or important announcements. The dashboard is completed with the SDQC sheet for near misses and accidents (tillbud och olyckor). The safety information was never mentioned throughout the interviews or in any other conversation as important. It indicates a safe workspace, where the employees experience their workplace as safe. Nevertheless, safety needs the room to be discussed and represented at daily meetings if an incident happens. The production dashboard shall follow the same layout only, that the top right field is meant for notes instead of deliveries. Also, the aberrations are not presented with the SDQC schema at the left middle field but leave space for notes.

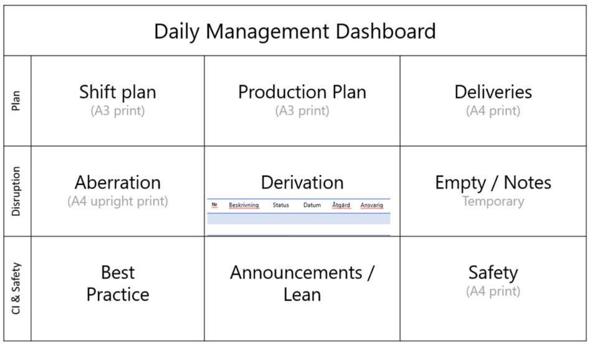

Figure 1 New dashboard layout for the daily management board

The wish of the management to integrate performance management was not complied, with since the current performance measurements do not match the focus and original purpose of the dashboards. Still, the wish for better integration of the performance management was honored by the design of a development horizon. It consists of three steps and can be started straight away with the implementation of the new dashboard design. It shall help to achieve a better vertical communication of the strategy by deepening the knowledge and understanding of the Medical Excellence program and its translation into KPIs. Further, a more detailed production monitoring is suggested. It complements the current system with aberrations and derivation with the implementation of failure groups. The groups shall track the process performance by counting disruptions and classify them into failure groups. The failure groups once introduced shall become part of the dashboards. Therefore, they shall be displayed in form of a table in the free field of the *disruption* category. Here the workers shall track disruption causes with the table in the manner of a tally sheet. Over the mid-term view a technical solution, that allows the tracking of the time failures took to get a more precise picture of the disruptions would be advantageous.

4. CONCLUSION

The process of a dashboard design is important to achieve a sustainable dashboard, which presents meaningful content supporting a company's strategy, culture and processes. The dashboard development procedure by Vilarinho, Lopes and Sousa offers a first attempt at closing the gap in designing dashboards. Throughout the application, all steps given by Vilarinho, Sousa and Lopes were perceived as intuitive and logical. The model gives a framework to consider all important factors of the development process. Under the given limitation of only performing steps one to three, it can be assumed that a satisfying solution can be developed with the DDP. The new design of the dashboards for Nolato MediTor AB takes the needs of all stakeholders into consideration and pays attention to aspects of visual management, lean management, and important principles of dashboards.

Generally, it was not possible to support the case company to the same extent as Vilarinho et.al. did in their case by adapting the information system and sheets. In accordance with the statement of Yigitbasioglu, the thesis focuses on mapping the right content for *Produktsystem* rather than the technical solution of how the information is presented exactly. Steps which require longer arrangements as cultural change or adaption or change of the information system were laid into the responsibility of Nolato MediTor in form of suggestions of the development horizon. To sustain the purposeful use of the dashboard a continuous follow-up of the contents and technical solution is required.

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Investment alternatives and operational changes in the production of perforating punches

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ABSTRACT

The report identifies and investigates possible investment alternatives and operational improvements to the production of perforating punches. The analysis is conducted for a leading Swedish manufacturer in the industry. First, an analysis of the company and its customers is performed, followed by a study of the current production capabilities. Based on this investigation, key investments opportunities are identified and analyzed. Finally, possible managerial and operational changes are addressed and discussed.

The findings highlight the link between investments and operational management, and how they are interdependent. Specifically, the report identifies the importance of lead times in this industry, and proceeds to propose both investments and managerial changes which would improve these lead times. A total of four investments are analyzed, which significantly impact lead times, product quality, production capacity and production cost. Three of these investments are found to be advisable, whilst one requires further investigations. Finally, changes to corporate management and operations management are discussed. The proposed changes include an increase in production volume, the implementation of the 5S methodology and the strategic change of focusing on increased sales volumes.

1 INTRODUCTION

The market for industrial goods is getting evermore international, subjecting suppliers to increased levels of competition. For production facilities located in the western hemisphere, this generally implies competition with low-cost alternatives. As a result, manufacturers often need to cut costs and/or focus on the quality of the products and services in order to remain attractive on the market[1]. Investments in new production methods and technology is often necessary but is generally costly and require integration with existing equipment.

The report[2] on which this summary is based, investigates the current production capabilities of Gerdins Cutting Technology AB (Gerdins), a leading supplier of cutting dies and perforating punches (punches) in the Nordic region. The company has a long history of producing tools for the shoe-manufacturing and printing industries and have a strong customer focus. At Gerdins, quality, lead times and flexibility are regarded as very important in relation to the customers.

The purpose of the report is to investigate the current production in the punches department and identify both possible investment alternatives and possible operational changes. This is done with the purpose of optimizing the process in relation to production cost, lead times and quality. Furthermore, an analysis of the proposed investments is performed. The report focuses on investments deemed interesting for the company and answers the following research questions:

- Which investment alternatives are worth considering?
- Which effect will these investments have on production cost, product quality and lead times?
- Which investment alternatives are advisable for the company?
- Which changes to corporate and operations management are advisable?

2 METHODOLOGY

A variety of sources are used, including the corporate Enterprise Resource Planning (ERP)-system, interviews with all related personnel and measurements performed by the author. The collected data is then analyzed using different models, including an Activity Based Costing (ABC)-model[3] for the calculation of production cost. The steps of the method used are shown below. The calculations and analyses in their entirety are the product of the author.

1. General analysis of the company with the purpose of identifying and quantifying core customer needs and return demands on bound capital.
2. A detailed analysis of production costs and lead times for representative products.

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3. Identifying possible investment alternatives and operational changes based on the previous analysis.

4. Evaluating investment alternatives.

5. Reflecting on the interdependence of proposed investments and operational changes.

3 RESULTS AND DISCUSSION

3.1 GENERAL RESULTS

Customer demands on punches vary between product segments and between individual customers. For products targeting the shoe manufacturing industry (the leather segment), the competition is largely based on the product unit price. Meanwhile, for products targeting the printing and packaging industries (the graphic segment), other factors, such as the lead time, are of importance. The report finds that the average customer is willing to accept a maximum time from order placement to order shipment, of 5 workdays. Further, it is found that Gerdins fulfills this customer demand for 35-30% of the orders, if orders modified by the customer are included. If modified orders are excluded from the statistic, the delivery reliability is improved.

3.2 COST REDUCTION

Based on demands posted by the customers and stockholders, a number of operational and managerial changes are identified and discussed. For some product dimensions in the leather segment, it was found that the production cost could be decreased by 77-78%. This is achieved by increasing the machine utilization and batch sizes. Based on this finding, the author recommends that sales volumes be increased, even at expense of the average sales price. The marginal production cost consists largely of material costs, which at present constitute about 15% of the production cost. Furthermore, the risk of products becoming obsolete is negligible and the production currently has overcapacity. Therefore, the author recommends that a push-production[4] be adopted, rather than producing against order. This significantly reduces the production cost and reduces customer delivery times as it implies larger stock values. It is advised that any over-production shall be sold on new markets at reduced prices. As such, new markets are made available to the company and the risk of reduced sales margins on current markets is kept low. Offers received by the company indicates that it is possible to sell sufficient volumes, at profitable prices, on new markets.

Furthermore, it is found that the investment in a new production machine could reduce production costs for the remaining product groups of the leather segment, mainly by reducing the need for manual labor. The new production machine proposed also implies a significant simplification of the production process as it allows for the removal of several production steps and machine groups. A feasibility study conducted by the author, using approximated values, shows an expected Internal Rate of the Return (IRR) of 28.7% and an expected payback time of 3.6 years, significantly better than the returns demanded by stockholders. It is therefore advised that a further analysis be conducted with regards to a new production machine. Finally, the investment in a production machine accessory[5] is advised as its usage would significantly reduce the production cost and increase production capacity.

3.3 LEAD TIME

The report concludes that the lead time can mainly be improved in two ways. Firstly, by increasing stock levels, the probability that an order may be sent directly from storage, increases. Furthermore, the cost of bound capital[6] increase induced, is not significant, in relation reductions in production cost and improved delivery time.

Secondly, an investment in a hardening furnace is proposed and investigated. It is found that this investment leads to a significant production lead time reduction, from 11.3 days to 3.5 days, for the cases investigated. This production lead time reduction is of importance to delivery times, since it is not deemed possible for the company to have all of its approximately 3000 products in stock. It would also allow for the company to regain control over this crucial production step,and thereby the product quality. The report finds that an investment of up to 1 750 000 SEK can be accepted by the company, provided its return demands.

4 CONCLUSION

The report identifies and investigates investment alternatives and operational changes to the production of punches. The company is advised to invest in a hardening furnace and production machine accessory. The investment in a new production machine is also identified as a promising investment, but requires further analysis.

Furthermore, the company is advised to increase stock volumes and implement push-production. Additional investments and operational changes are advised in the full report[2].

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Design of cost-efficient joining solution for a composite-metal structure

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Abstract

With an increasing awareness of environmentalism, the transportation sector is also understanding its duty to protect the natural resources given to humankind. For the sector it is increasingly important to decrease the weight of transportation vehicles to save fuel and electrical energy. For a severe weight reduction Volvo Buses plans to launch a lighter bus structure in the coming years. This includes sandwich structures made of PUR foam with glass fibre reinforced plastic skins. The purpose of this work is to design joining concepts between the Sandwich Structure and the metal frame/ chassis of the bus. The work is restricted by several constraints given by Volvo. There are 4 different design concepts created and evaluated. The concepted designs include inserts in the sandwich structure, adhesives used on the skin of the composite, metal flaps introduced in the core material and a micro pin solution that is introduced in the glass fiber layer of the sandwich structure. The evaluation includes a numerical analysis on if and how the composite withstands applied loads from the introduced joints. It also describes failure modes that need to be considered for in-depth analysis of the designs. Further the designs are compared from a cost perspective. The final design decision is based on a multi objective decision analysis. It compares the weight, costs, mechanical behaviors, and other constraints of the designs simultaneously. The analysis results in the recommendation on choosing the Adhesive Design to introduce as the preferred joining option. As the work only gives a preliminary design, the Adhesive Design must be analyzed and adopted more precise before introducing it in a final product. ***Keywords:*** *Composite Sandwich Structure, Design, Inserts, Adhesives, Micro-Pins*

1. Introduction

Volvo Bussar AB is a Swedish multinational bus manufacturer offering people transport solutions. Their product range extends from city buses to coaches, chassis and services on the domain of safety as well as productivity. In the first half of 2021, Volvo was leading the Western European electric bus market with 188 sold vehicles. Within the Volvo Group, the Buses subsidiary aims for the highest greenhouse gas emission decrease by targeting a reduction of 40% in the year of 2030 (baseline 2019). Adjustment screws to reach those goals are inter alia combustion efficiency, aerodynamics and weight. Since concepts like green steel are not omnipresent on the market, composites are a quite in demand for two main reasons. They are by some factors lighter and emit between 43-55% less CO2 during the production. Glass fibers Reinforced Polymer (GFRP) are in particular attractive because of the more favorable price tag in comparison to Carbon fibers Reinforced Polymer (CFRP).

The parts of interest are located at the backside of the city bus Volvo 7900E. Figure 1 globally shows the dimensions of the rear cap as well as the bumper and side pillars. In the current version of the 7900E, the rear cap consists of an ABS cover that is installed on a steel cage which comes along with a substantial weight increment compared to composite solutions. The follow-up of the city bus will feature a rear cap completely made from a GFRP and Polyurethane (PUR) foam sandwich panel resulting in an estimated weight loss of 37%. Although the chosen PUR foam is a closed-cell-structured, the sandwich panel is closed at all ends to maintain consentient stiffness at every surface point. Apart from the composite part, both ferrous and non-ferrous structural parts involved in the joining operation. Next to the rear edge of the side window, extruded aluminium pillars serve as the direct contact point for the rear cap.

Figure 1: Backside View Volvo 7900E

Under the roof, a rounded hollow steel beam has the same function. The according joining operation require a medium, or more particular, an interface that combines the sandwich panel with both steel and aluminium. This interface should homogenize force distributions while being rigid enough to withstand plastic deformation.

2. METHODOLOGY

Numerous engineering design methods are defined and conceptualized in literature, ranging from tried and trusted to new and innovative approaches. The domain of Design Theory and Methodology (DTM) is generally categorized in four categories along two axes which are ‘concrete vs. abstract’ and ‘individual vs. general’. Since metal-composite joints lack in particularly customized design methodologies, the focus shifts to a concrete but generalizable DTM.

As an entire design process takes more time than given for this work, the methodology has been adopted for the goals and objectives of this work. At the beginning of the design process the main issue of the current rear cap is identified. In the next step goals and a framework is established. This includes constraints for the joining design. Those are i.a. load resistance, low cost, low weight & preservation of tolerances. After conducting theoretical research, general concepts for joining sandwich structures were picked. The practical part of the work is the design itself, by reconsidering where possible loads and stresses occur the preliminary designs are gradually constructed. The next step is the analysis of the designs. It is used to compare how the inserts impact the composite. The analysis also includes the cost calculation for the different designs, to finally compare the different designs. In the comparison the constraints set in the initial phase are reviewed and evaluated. As a decision tool for the most suitable design a multi-objective decision analysis is used. Each constraint is given a percentage for how important it is for the decision and is multiplied with the outcome of the ranking. The design with the highest score is chosen to be the preferred joining design. The design process is not finished here but gives Volvo an overview which design concept should get focused on in the future.

3. DESIGNS

As mentioned in the design methodology the next step after specifying the design task and specifying the constraints and technical structures as the framework is the creation of concepts and finally the design of the layout. The design also includes redesigns of the interfacing metal beams and pillars to the composite rear cap to enable the fixation of the rear cap. In the following the design concepts are described in short, without showing the global solutions.

3.1. INSERT DESIGN

As inserts are a widely used joining concepts for sandwich solutions especially in aeronautics. [1] The knowledge is used to develop joining solution for a composite rear cap of a bus. The theory behind inserts can be reviewed in the complete thesis work. Figure 2 shows a single insert setup inside the composite structure. The insert is surrounded and embedded in a potting. A bolt fixates the metallic top beam to the insert. The design

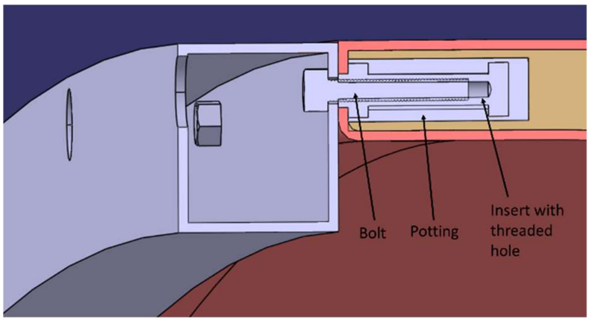

Figure 2: cross section view of insert design

includes 13 inserts distributed evenly over the interfacing surface of the composite.

3.2. ADHESIVE DESIGN

For the adhesive solution metal plates are joint to the composite part with an adhesive of the type of polyurethane. The metal plates are made of steel and are joint mechanically to the structural parts of the bus. The connection at the top includes one large plate. For the connection between the side pillar and the rear cap another interfacing metal plate is used. Figure 3 shows

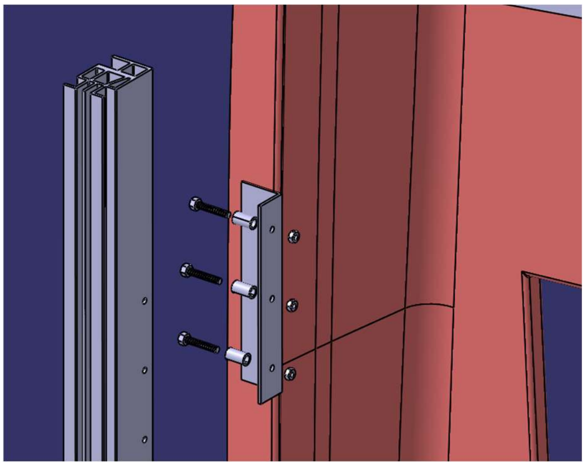

Figure 3: Adhesive L-plate with connecting side beam

the design concept, at the side pillar. The metal L-plate is glued to the composite structure and bolted to an adopted version of the side pillar.

3.3. INTEGRATED METAL FLAP DESIGN

The embedded T-bar joining solution (short: Flap Solution) is in the domain of composite-metal joints a novel approach. The T-bar is integrated into the laminate by locking it under the skin of the sandwich structure. In total, three differently dimensioned T-bars are used which attach to the two side pillars and the upper hollow beam at 13 places. The embedded T-bar joining solution (short: Flap Solution) is in the domain of composite-

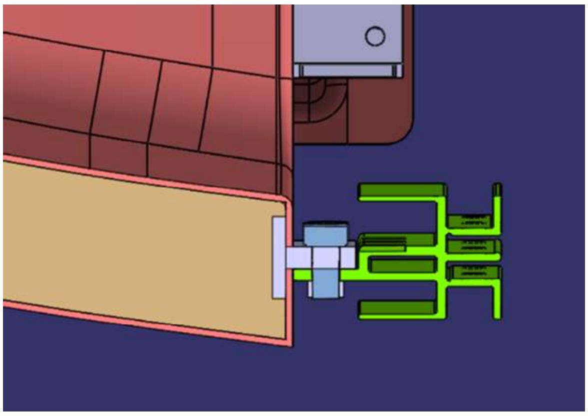

Figure 4: Section View of Metal Flap

metal joints a novel approach**.** Figure 4 shows the design concept at the side of the bus. The metal flap is integrated in the sandwich structure before the composite layers are added to the composite back.

3.4. Micro Pin Design

Additive manufactured micro pins that are cemented into the laminate of the joining structure is novel advanced joining technique. The technique is based on serval research papers and the EU funded HYPERJOINT™ system. Before resin infusion, the T-bars with a repetitive pattern of 0.5mm thick pins located under the base plate is pressed into the dry layers up to 75% of the total thickness. Figure 5 shows a zoomed view on such micro pins. On the right the joining concept is presented, where the pins penetrate the composite, and the joint is mechanically fixed to the side pillar of the bus.

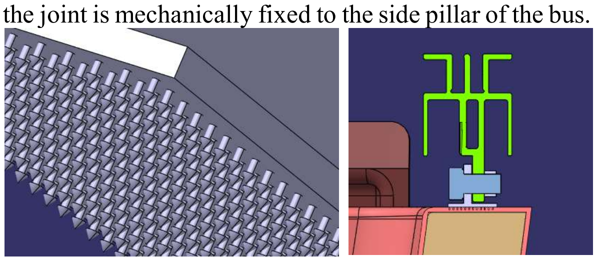

Figure 5: Micro Pins (left) and joining concept (right)

4. Design Analysis

After the conceptual designing is finished the different designs are evaluated against technical criteria. In a first step each design is theoretically analyzed by describing critical failure modes for each design. After the major risks are identified the models were numerical analyzed by developing FEM models. Due to time constraints the insert design was neglected from this type of analysis and was only theoretically reviewed. Due to the cost constraint a major decision variable for the design is the cost factor. The cost calculation was based on the following formula, where C_P are the costs to produce the different designs. The costs for the composite part are based on a quotation presented to Volvo:

$$C_{total} = C_{Composite\ Part} + C_P + C_{Transport} + C_{Assembly} \qquad (1)$$

To compare the different analysis conducted a Multi-Objective Decision Analysis was used to derive a final ranking of the different designs. A summation of different constraints and associated factors to describe the importance of each constraint is calculated for the proposed designs.

5. Results and Discussions

5.1. FEM solutions

The output of the FEM calculation compares the Von Misses stresses, elastic strain and the Tsai-Wu values. The Tsai-Wu output predicts the failure probability of composite shells. Figure 6 shows the comparison of the Von Misses stresses between the adhesive, flap and pin design. The arrow indicates where the maximum stress is located. The adhesive solution has less than half of the stress peak value of Pin and Flap solution respectively. Also, the variance of stress is less for the adhesive solution which implies collective failure instead of local

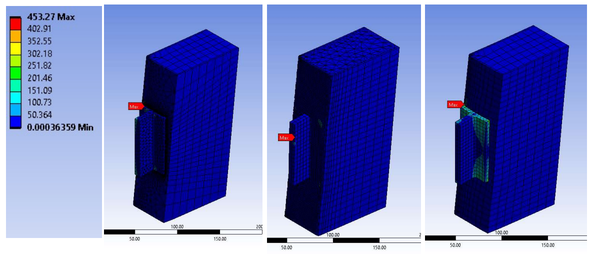

Figure 6: Von Misses stresses for adhesive, flap and pin design

failure. The failure criterion Tsai-Wu are 3,79, 0,66 and 0,85 for the Pin, Adhesive and Flap Solution respectively. This again underlies the superiority of the Adhesive solution while the Flap solution is not lagging behind.

Table 1: Comparison of Stresses

	Minimum [MPa]	**Maximum [MPa]**	**Average [MPa]**
Pin	3.6359e-004	453.27	18.745
Adhesive	4.1968e-004	209.73	8.8173
Flap	7.1281e-004	437.13	5.2525

5.2. Cost Calculation

The results of the cost calculation are found below. Figure 7 shows the general cost for the different joining systems. There are three estimated production times (min, mean and max). Depending on the estimated production times the lowest cost design changes. The concrete numbers can be seen in the written thesis as well as more information about different costs. For the minimum production times the Insert solution is the cheapest design. The Adhesive and the Flap Solution are slightly more expensive. The highest cost has the Pin design. The In the case of the realistic mean production time the ranking changes. Here the Adhesive design is the cheapest followed by the Insert and Flap design.

For the maximum production there is a clear trend of the adhesive design having the lowest costs. The cost for the insert solution is now the highest, similar to the pin solution. This is because the potting of the inserts and its handling have a high impact on the production time when handled individual.

5.3. *Multi Objective Decision Analysis*

For the decision analysis the constraints are each valued with a factor. The factor expresses how important the constraint is for the decision. For a final decision the rankings for the different constraints are each multiplied with the associated factor. The design with the lowest sum of all multiplications is the preferred choice. The work includes different results, where the one is focused on a low cost and the other also includes the weight as a major factor. Table 2 shows the results for the cost dominant calculation, where 60% is based on the cost constraint. Due to the lowest costs of the adhesive solution, it is clearly the best option with the lowest score. Followed by the flap solution with a slightly higher score.

Table 2: Decision Matrix with focus on production costs

	Insert	Adhesive	Flap	Pin	Factor
Weight	1	4	3	2	0,1
Cost	3	1	2	4	0,6
Strength performance	2	2	1	3	0,1
Supply risk	2	1	1	3	0,1
Reparations	2	1	2	2	0,1
Sum	2,5	1,4	1,9	3,4	1

6. Conclusions

In the light of the research question and the set constraints, the provided joint system solutions are all viable in its nature and presumably viable in the given configuration. Since the design process involved arguably all theoretical parts of the MVP design cycle once, the further design development is certainly subject to iterative change and refinement. The optimizing character of this however lies in the guidance towards designs rather than the execution of another whole design cycle. Four systems have all the potential to be chosen based on the set selection criteria. Since the objective is to design a cost-efficient design that satisfy all the other set selection criteria, the top-scoring solution is either the adhesive or the flap system. It is worth to mention that the weight of the system in relation to its mechanical performance is a second guiding variable that puts the adhesive system to an unprecedented first place.

As described in the methodology the work only gives preliminary design models. The next step for Volvo is therefore the selection of one single design to fully analyse. According to the input data used in this work the adhesive solution would be chosen. If Volvo uses their companies input data another design might be favourable. Therefore, it can be useful to improve the cost calculation and its input values before choosing a design.

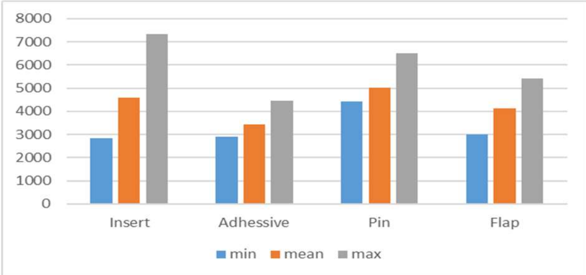

Figure 7: General cost comparison (in Sek)

Acknowledgements

We wish to express our most sincere gratitude and appreciation for our supervisor at Volvo Buses, Inegbedion Michael Ehimenmen, who invested a lot of time in questioning us and helping us through the design process. We are also very thankful for our academic supervisors, Dr. Volodymyr Bushlya, Dr. Christina Windmark and Dr. Ola Flodén for guiding us through the work and who were always available when needed. We also would like to show our deep appreciation towards Volvo Buses for funding the execution of this work and giving us the opportunity to work inside this great company. A special thanks goes also to our wonderful colleagues at the Chassis Frame department at Volvo Bus who listened and criticized our presentations, always answered any questions we had during the work and made us feel welcome at the company. This especially includes the head of the department, Sanna Eliasson who handled all our organizational questions.

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Robotic machining of aluminum alloy:

evaluation of performance and part accuracy

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Abstract

The automated machining is typically performed by CNC (Computer Numerical Control) machinery due to the high stiffness and accuracy provided by these machines, which are expensive and comparably big. For softer materials, such as aluminum, machining is possible using the less stiff industrial robot arm. This is attractive because the robot arm has a much lower cost than CNC combined with a larger work volume. Machining packages are now available for several robot brands, enabling robots to read and execute CNC G-code. It is particularly beneficial for small and medium enterprises. Robot arms are, however, less stiff and strong, resulting in less accuracy.

In this thesis, the idea was that by using the IRB 2400 robot to mill typical process paths to evaluate the performance and part accuracy in robotic machining of aluminum alloy. A pre-study towards a standard proposal for measuring robotic machining performance was performed.

Proper process parameters for robotic milling were applied, and the robot's task was to repeatedly mill parts in different postures. The path accuracy, microstructure, and milling forces were analyzed. Results showed that the posture of the robot has a significant effect on path accuracy. With a proper posture, the path accuracy could be under 0.01mm.

1. Introduction

Automated machining (that is deflashing, deburring, milling, etc) is typically performed by CNC machinery due to the high stiffness and accuracy provided by these machines. For softer materials, such as aluminum, machining is possible using the less stiff industrial robot arm. This is attractive because the robot arm has a much lower cost than CNC combined with a larger work volume. Machining packages are now available for several robot brands, enabling robots to, for instance, read and execute CNC G-code directly.

Despite robots being so welcomed in the industry, they are still not well prepared for processes such as cutting and milling. According to the International Federation of Robotics (IFR), 72.7% of all industrial robots are used for handling and welding. Only 2.0% of industrial robots are used for the machining processes [1].

This is due to numerous reasons, for example, poor structural stiffness and unexpected vibrations are the main obstacles. Others like gear ratio, chatter, and backlash are also potential influences. They together affect the path accuracy and repeatability of the robot, resulting in poor part performance.

Stiffness is the extent to which an object resists deformation in response to an applied force. It is an important indication for informing the stability of the robot. For a 6R industrial robot, every joint stiffness is different from each other. Their stiffness also highly depends on the load magnitude and the posture i.e. the angle value of every joint. There are usually two ways to find out how much the stiffness is, establish a theoretical stiffness model or measure it experimentally. However, a stiffness model is extraordinarily complicated and the result of it has a large difference from the actual one because the model is highly related to the surrounding work environment. In addition, it is also hard to simplify a stiffness model because it is based on a varying Jacobian matrix. Besides, different robots must have a diverse stiffness model, which makes it even harder to establish a generic model for all 6R industrial robots. So, in such a circumstance, the experimental measurement is applied in this study.

As for the vibration in milling, it is composed of force vibration and self-excited chatter. The forced vibration could be caused by the clash between milling tool teeth and the workpiece. The clash causes a time-varying external force that acts on the milling tooltips. The unbalance of a rotary member or a servo motor instability is also an example of forced vibration [2]. The self-excited chatter is caused by the repeated milling of a previous wavy-cut surface, resulting in micro-variations of chip thickness. As the chip thickness varies, so does the force [2]. Therefore, a time-varying force is generated. One of the best ways to improve robot machining performance is from the external force point of view because it is the basic issue. Either reducing the force or controlling it in an acceptive range would minimize the errors of accuracy to an extent.

In this study, a test methodology for performing a robotic machining performance test and analysis of test metrics would be researched with the use of the ABB IRB 2400 robot and other measure equipment. The purpose is to find out how well the path accuracy could the robot give under different work environments such as various workpiece placement, different machining process data, or different cutting features.

2. Methodology

The process of the experiment is first to build a CAM model by using Fusion 360 and then generate a RAPAID code used to control the robot. If the simulation in RobotStudio has no problem, the next step is to send the program to the robot. While the robot doing the process, both the force sensor and the Nikon metrology system are capturing data at 1000Hz and 100Hz frequencies respectively. All the data captured will finally be transferred to a laptop to be processed by using Matlab. The illustration of the procedures is shown below in Figure 1.

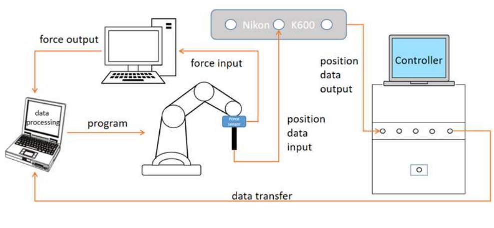

Figure 1: Illustration of the experiment

After the process parameters are confirmed, they are used to mill a square in three different positions as Figure 2 shows. The distance between the robot's center and the center of Location 1 is 1350mm, 1569mm of Location 2, and 1570mm of Location 3. To get data not only from a 2D plane but also from a 3D space, Location 3 is designed to be perpendicular to the horizontal plane. Thus, it is more comprehensive to evaluate the milling performance of a robot.

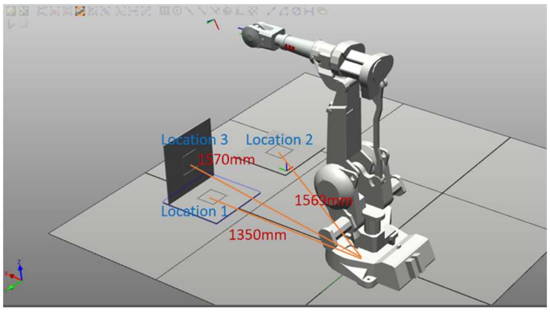

Figure 2: Design of the experiments

For each Location, the process is repeated twice. One for air movement, which means that the milling tool cuts nothing but air. And the other one is for the real cut i.e. cutting aluminum material. The reason for such a design is for comparing the performance of the process with and without cutting material. The performance of air motion includes the errors of the robot itself and the vibrations of the spindle etc. Therefore, by comparing them, we can know more precisely how the robot acts during the process.

To generate a couple of generic paths, several milling features are selected according to BS ISO 10791-7:2014, as shown in Figure 3. Due to the thickness of the prepared workpiece, only the first 5 mm thickness of the drawing is milled in this experiment.

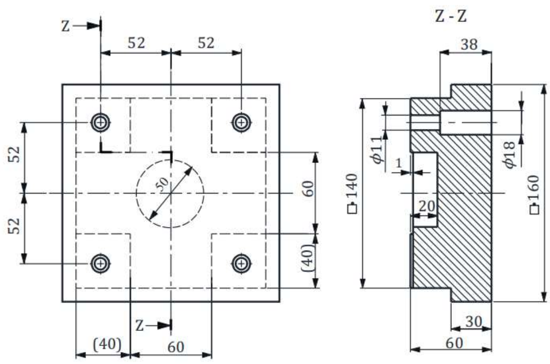

Figure 3: ISO 10791-7, M1-160

3. RESULTS AND CONCLUSION

Figure 4 summarized the average, maximum, and minimum path errors of the process with 1.8 and 1.44 cc/min MRR. It clearly shows when the milling force points to a low-stiffness direction, a large deviation will occur, like in Line 2 and Line 4. The difference could be large as 1mm. However, if the force points in a high-stiffness direction, a great performance can be achieved as small as 0.026 mm. Since the parameters for this case were out of the limits that the robot could manage, the path accuracy is not good enough to accomplish a finish milling task. Besides, the milling force could be very high, as shown in Figure 5. These data clearly show us what is the consequence if we choose the parameters that are beyond the limits of the robotic milling process.

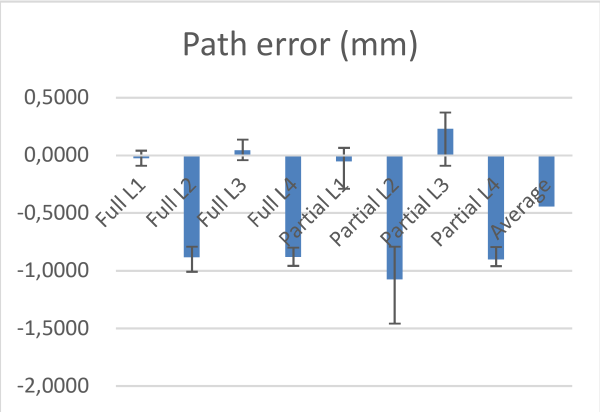

Figure 4: The path error summary of MRR 1.8 and 1.44 cc/min

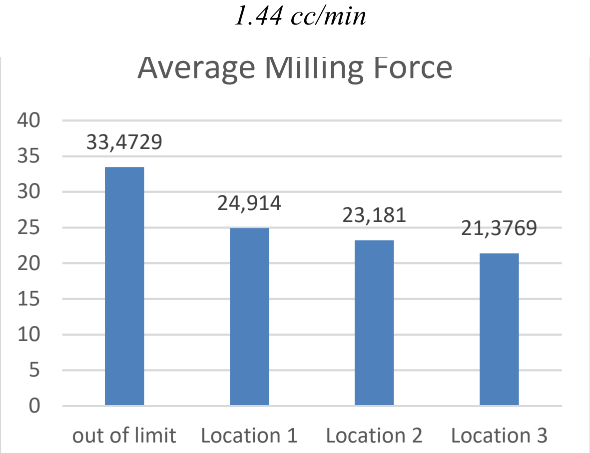

Figure 5: The average milling force

On the contrary, in the case that proper parameters are chosen, the path accuracy has been significantly improved, more than 10 times smaller than before, as shown in Figure 6. The errors are under 0.09 mm, and they can be nearly 0 along the high-stiffness direction. The average error is around 0.037 mm.

Better performance can be achieved if a more steady posture is chosen. The average path error is 0.0086 mm and 0.0096 mm in Location 2 and Location 3 respectively, as illustrated in Figure 7 and Figure 8. Especially in Location 3, the path accuracy is quite steady and the largest error is not more than 0.04 mm. It means the robot does great in Location 3 with such a posture. It could be because the weight of the milling tool compensates for the external forces during the milling. Since the tool's weight is much larger than the milling forces, it cannot be forced to displace itself.

To conclude, the evaluation method used in this study is capable of indicating how well a robot could be in the milling process. The important thing is to find the suitable process parameters that fit the robot. With a proper posture of the robot, the performance can be as good as what CNC does to aluminum.

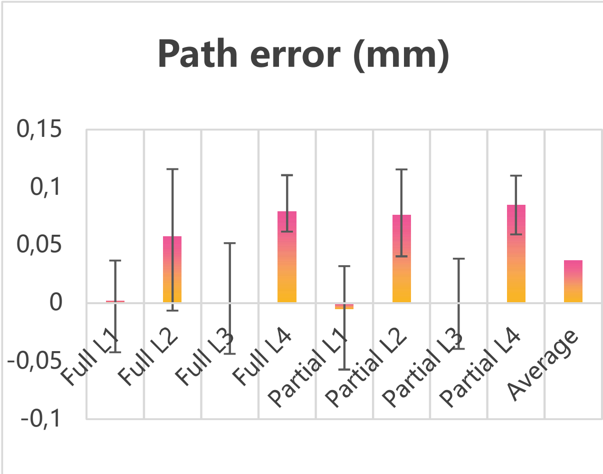

Figure 6: The path error summary of Location 1, MRR 0.48 cc/min

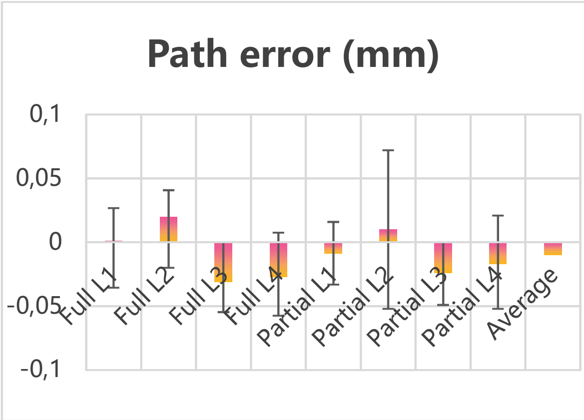

Figure 7: The path errors summary of Location 2, MRR 0.48 cc/min

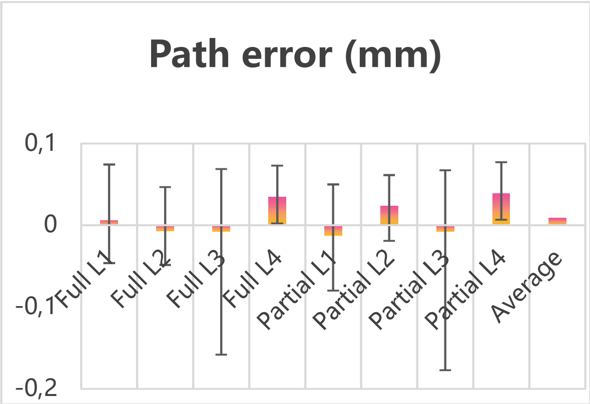

Figure 8: The path errors summary of Location 3, MRR 0.48 cc/min

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All of the work presented henceforth was conducted in the Robot Lab at Lund University. The project and associated methods were approved by the supervisors, Mathias Hagge and Anders Robertsson, from Computer Science and Control Departments, and examiner, Jinming Zhou, from Industrial Production Department.

This thesis is an original, unpublished, independent work by the author, Jingxin Zhang.

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A Study of tool wear behaviour during milling of Compacted Graphite Iron under dry and minimum quantity lubrication conditions

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Abstract

The search for stronger materials in the automotive industry resulted in an increased used of Compacted graphite iron (CGI) instead of gray cast iron, however the machinability of this material is more difficult and different approaches such as composition modification, improved tooling and improved cutting conditions have been attempted. This thesis project is focused on the analysis of tool wear when milling CGI while testing three different things. First, the use of Minimum quantity lubricant (MQL) using rapeseed oil as the lubricant. Second, on the analysis of the tool wear mechanisms present when the cutting speed and feed are modified. Last, is the study of the influence in tool wear of CGI aging. The results showed that MQL has a positive effect on milling while using a CVD coated tool resulting in 14-18% reduction of VB compared to dry machining using a tool wear criterion of 0.2 µm. Additionally, while abrasion was present in all cutting speeds, adhesion was very noticeable at lower speeds, while diffusion and crater wear were more common at the higher speeds due to increased temperatures. Regarding aging, results showed less cratering on a fully aged insert compared to some materials reset and aged for 4 and 11 days, but more cutting speeds would be required to make a more robust statement on the effect of aging.

1. Introduction

Compacted graphite iron has been used as an alternative for gray cast iron in the automotive industry for around 20 years. Even though it was first patented in 1949 along with ductile iron, when scientists were trying to improve the properties of gray cast iron, it was not until the late nineties when foundry techniques and computational advancements allowed mass manufacturing using CGI. Its use was increased due to the search of stronger materials that would allow companies to get increased performance of diesel engines, reduced engine size and lowered emissions, which would allow the comply with new environmental regulations [1] .

In order to make the use of CGI viable in an industrial manufacturing environment, its machinability should be improved. One way scientists have attempted to do this is by modifying the composition. Another way to attack the problem is by improving the cutting tools used, which refers to the material of the cutting tool, its geometry, the layers of coating around it and the method used to apply them. Last but not least, the improvement of machining process itself; this includes the cutting data (cutting speed, feed rate, depth of cut), the lubrication and choosing when to replace the inserts.

This project will attempt to find improvements in CGI machining by analyzing the wear types found in tools with different coatings, and at different speeds, also focusing on the effect of minimum quantity lubricant on the tool wear while also checking the effect of aging on tool wear.

2. Goals and limitations

This thesis project is focused on three different aspects of CGI machining. First, on understanding the advantages of using MQL lubrication (with rapeseed oil and this same oil with nano additives) against dry cutting under similar cutting conditions. Next, on analyzing how the degradation on different coating types (CVD, PVD) is, when machining CGI, examining wear type and interactions in the contact zone at different speeds. Finally, to study the effect of aging in the machinability of CGI.

This gained knowledge should allow people interested in machining CGI to take better decisions regarding tool coatings, cutting speeds, lubrication systems and material aging after casting. Certainly, this will result in reduced costs for companies and increased knowledge for use in labs of the department or future research by anyone interested in the field.

As the scope of this project is large, taking into account different cutting data, lubricant and tools, this thesis is focused on the tool wear, the type of wear obtained under different cutting data and with different coating constituents. Nevertheless, the author did not contemplate the surface roughness of the workpiece material. Additionally, the flank wear criterion used in this project is 0.2 mm, based on the ISO 8688-1:1989 specification, unless there was a tool failure before that occurred [2].

3. METHOD

3.1. PROCESS DESCRIPTION

The experiments consisted of machining the workpiece material (CGI) until the tool wear criterion was reached and then storing the cutting tools for further analysis. After that, the inserts were replaced, CNC code was modified to evaluate with new cutting data and a new workpiece was fixed in the machine.

The CNC code was made using conversational programming with Heidenhain Software. The code was designed to make ten passes with a depth of cut (a_p) of 0.5mm each pass. After every 0.5mm, there was a thirty second dwell time programmed to simulate conditions of machining, doing tool changes in between. This code had the possibility to make changes of the cutting speed (v_c) and feed per tooth (f_z) at the start of the program, allowing easy modification of the cutting data when new inserts were fixed on the tool holder.

Once the tool holder was taken to the microscope for inspection, each insert was assigned a number 1-6, based on a notch the tool holder had to allow clamping into the machine. From this notch, the numeration was done in counterclockwise direction as seen on Figure 3. Note that this is a reference view as the inserts used for this project were set at 90°.

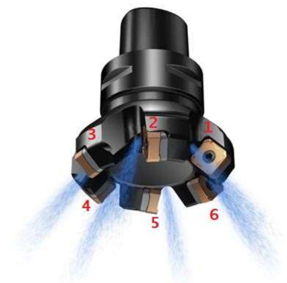

Figure 3. Numeration used on the tool with indexable inserts

3.2. CUTTING TOOLS

The first tool with CVD coating was a Sandvik Coromant Coromill® model 490R-08T304M-KL. This is part of their grade 3330, which is an all-round tool for machining cast iron in a broad range of cutting data. This insert contains three layers of coating: TiCN, Al_2O_3 and TiN, in that order from inside to outside. Additionally, it possesses 4 cutting edges and has a main cutting edge angle of 90° and a corner radius of 0.4 mm. For the analysis part of this document. this will be referred as CVD Cutting Tool CCT**.**

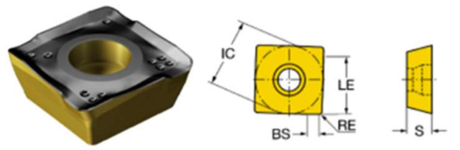

Figure 1. 3D model of the CCT (left), Insert drawing(right)

The second tool with PVD coating is part of the series *Square 6* from Seco Tools AB, the model number is XNEX080608TR-M13 MK2050, which has trigonal shape with a total of six cutting edges, three on each side. The manufacturer specifies the coating of this tool as (Ti,Si)N/(Ti, Al)N. This PVD cutting tool will be referred as PCT.

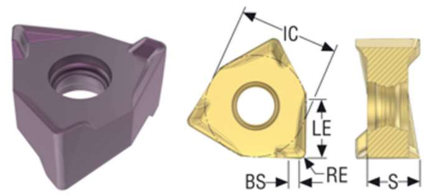

Figure 2. 3D model of the PCT (left), Insert drawing(right)

3.3. CUTTING DATA

Based on the scope of this project, one set of cutting data was selected to analyze the effectivity of MQL compared to dry machining. Other set of values were used to check the influence of v_c and f_z in the wear of the tool and the interactions. Finally, one last set is used to check the influence of aging in tool wear. These parameters used can be found in Table 1.

Table 1. Cutting data sets for the experiments

Data set	Tool	v_c [m/min]	f_z [mm/tooth]	Lubrication
1	CCT	150	0.15	MQL
2	CCT	250	0.15	MQL
3	CCT	150	0.15	MQL + GnP
4	CCT	250	0.1	Dry
5	CCT	250	0.2	Dry
6	CCT	330	0.1	Dry
7	CCT	330	0.15	Dry
8	CCT	330	0.15	Dry Reset 4
9	CCT	330	0.15	Dry Reset 11
10	PCT	150	0.15	Dry
11	PCT	250	0.15	Dry

3.4. LUBRICANTS

- **Rapeseed oil**. The selection of this was done via a recommendation of Accu-Svenska AB based on what is used in the industry for this type of material, the product identifier is Ecolubric E200L. The manufacturer describes it as cold-pressed rapeseed oil without additives which has been refined to remove fats that are not appropriate for industrial use.

- **Rapeseed oil with graphite nano particles (GnP).** This lubricant was prepared based on a previous work by a researcher of the department. In order to manufacture the nano additives, thermally expanded graphite (TEG) went through a process of sonication, which consists of agitating the particles and breaking them using sound energy. This was done using 1g of TEG in a 120ml container of 10% Alcohol solution.

The final mix was obtained using a magnetic stirrer with 0.2% of TEG in Alcohol solution in the rapeseed oil .

3.5. MATERIAL RESETTING

This part of the process consisted of putting two samples in an oven until it reached 650°C, and was kept at that temperature for 30 minutes; the temperature selection was chosen after discussion with people in the department with experience in similar experiments. Then, these pieces were allowed to cool off at room temperature inside the lab.

After four days, one of the samples was machined using v_c=330 m/min, f_z=0.15 mm/tooth, and ap=0.5 mm. A similar procedure was done for the second sample after 11 days. All the pieces used in the experiment were casted a year prior to the tests, so the objective was to perform a tool wear comparison between the reset pieces and the fully aged piece using the same cutting parameters.

3.5. DATA COLLECTION

The flank wear of the inserts was obtained using an Olympus SZX7 microscope every 10 passes of 0.5 mm each. Once the flank wear criterion on the insert was reached (0.2 mm) the piece was separated for further analysis.

The samples were cleaned for a first SEM session and then also cut, embedded, grinded and polished for a second SEM session in which the cross sections were of interest. The equipment used was a variable pressure Tescan Mira3 with a FEG Schottky Electron emission source plus Energy Dispersive Spectroscopy.

4. RESULTS AND DISCUSSION

This section will cover the results obtained and explained the tool wear interactions. Due to limitations in space, only figured for one case were included. Please see the full thesis document for further information

4.1. MACHINABILITY EFFECT ON DRY VS MQL VS MQL WITH GRAPHITE NANOPARTICLES

It can be seen in Figure 4 that the use of MQL had the best results of all, reaching an engagement time of 214 minutes while being very close from reaching the tool wear criteria of 200 µm. In this case it reached 192 µm in average meaning it could have reached the next checkpoint of 224 min, but it would have required to install a new workpiece just for 10 passes. This is in average an increase of 10.6% in engagement time and a reduction in average VB of 14.9%. In the case of MQL with GnP, VB was actually higher than in the dry case, then it went slightly lower after 173 min. Another detail from this graph is that the standard deviation stayed consistent in all three cases, increasing slowly but not having a major increase in value. Figure 5 shows the isometric view of insert 3 from the MQL test at v_c=150, the most noticeable characteristic is the adhesion of CGI mainly near the flank, but also around the nose of the tool. This type of wear mechanism is common at lower speeds.

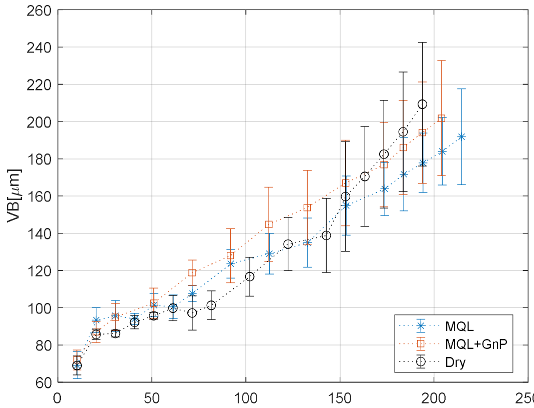

Figure 4. CTT, v_c =150 m/min, f_z =0.15 mm/tooth. a_p =0.5mm

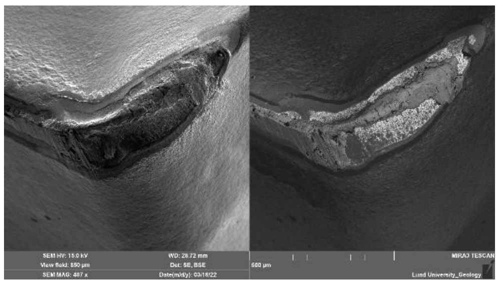

Figure 5. Isometric view with SEM: SE (left) BSE (right)

4.2. COATING DEGRADATION ON CVD AND PVD COATED TOOLS

First, a comparison is done maintaining v_c=250 m/min and varying f_z with values of 0.1, 0.15 and 0.2 mm/tooth. The first thing to notice is that when f_z=0.2, the tool did not even reach the tool wear criterion of

0.2mm, because of catastrophic failure of two inserts. The tool manufacturer specifies a working range between 0.05 and 0.15 mm/tooth for these inserts, which indicates that this tool failed due to higher cutting forces than what it was designed for.

The next case is maintaining v_c=330 m/min and varying f_z with values of 0.1, and 0.15 mm/tooth. In this case increasing f_z results in a decrease in engagement time from 55 to 32 minutes. the interactions are similar: deterioration of coating by abrasion due to high speeds, then diffusion because of the high temperatures, increasing the crater size and creating a solid ceramic made of iron carbides.

The last experiment with the CCT compared VB when using three different values of v_c, 150, 250, and 330 m/min, while maintaining the feed constant at 0.15 mm/tooth. In this case, all the tools reached the VB of 0.2 mm even though the maximum working value should be 270 m/min according to the tool manufacturer website. The engagement time is greatly increased with v_c=150 m/min, reaching 194 minutes compared to v_c=250 m/min which resulted in 61 minutes, and 32 minutes for v_c=330 m/min.

In the case of the PCT, a comparison was done using two v_c values of 150 and 250 m/min and maintaining f_z=0.15 mm/tooth. The amount of passes it reached at the lower speed is 170, compared to 70 at the higher speed. This means for the same amount of material machined at 70 passes, it would take 40% less time to do it at a higher speed but if time is not a problem (which can be in manufacturing environments), the lower cutting speed could be used to machine 142% more material.

4.3. Effect of resetting the workpiece material

With the objective of testing the effect of resetting the material, three samples machined with the same cutting speed of v_c=330 m/min and f_z=0.15 mm/tooth were used: A sample aged 1 year, a sample reset and cut after 4 days and a sample reset and cut after 11 days. the average VB of the inserts for each case was similar, however, one phenomenon that was more common on the reset samples was crater wear. In order to understand why crater wear happened more on the tools that went through the reset process, the author suggests that it could be due to microstructural changes in the CGI, and that natural aging has a good effect on machinability; which was found in similar to previous studies on gray cast iron.

5. Conclusions

Based on the results obtained from experiments at cutting speeds (v_c) of 150 and 250 m/min, feed (f_z) of 0.15 mm/tooth, and depth of cut (a_p) 0.5 mm, and the use of rapeseed oil as a lubricant, it could be said that milling CGI improves when MQL is used. The reduction in VB in comparison to dry machining varied based on the cutting speed, being 14% and 18% for the lower and higher cutting speeds respectively. Additionally, MQL with graphite nano particles was tested for one of the speeds, however, it did not improve the flank wear, and the wear mechanisms looked similar as in MQL with no extra additives.

For the CVD tool, it was found that at a lower speed of 150 m/min adhesion is more common, but as the speed is increased to 250 m/min, the increased temperature causes diffusion between the tool and the adhered material besides the abrasion and adhesion, resulting eventually in loss of the shape of the tool. When the speed increases more to 330 m/min, craters in the rake are common which causes the tools to fail once the cobalt is lost from the tungsten carbide. A higher feed than the recommended by the manufacturer was tested and it resulted in plastic deformation of the tool, plus cracks were seen in the tool coatings, which points at one of the main mechanisms of failure. The PVD coated tool had adhesion present as the common wear mechanism at speed of 150 m/min. For a speed of 250m/min, cratering was noticeable in the rake side, but adhesion was also present in different regions of the tool.

The last goal was to study how the machinability of CGI was affected by aging. For this project, the material went through a reset process in which it was heated to 650°C, kept for 30 minutes and then cooled off naturally. The experiment compared pieces aged for 4 days, 11 days and 1 year (completely aged) running at v_c=330 m/min and f_z=0.15 mm/tooth and a_p=0.5 mm. It was found that flank wear did not vary that much between these three cases, however, crater wear was more noticeable in the inserts that were not aged. In order to make a generalized conclusion, this test should be done with more cutting speeds to see the repeatability of the aging effect.

6. Acknowledgements

To the collaborators FFI, Sandvik Coromant, Seco tools, Accu Svenska. To the supervisors Vova and Rebecka. To my family for their continuous support.

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The influence of tool geometry on damping during machining

A theoretical and fundamental study

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ABSTRACT

Due to advancements in technology and incorporation with numerical control, machining processes have experienced great changes in the last decades. Numerous innovative solutions have been applied to achieve higher productivity, flexibility, and accuracy. Deep understanding of metal cutting fundamentals has brought about wider control over the obtained surface roughness, integrity, and dimensional accuracy. However, there are still some complexities in chip formation mechanisms which result in some limitations. Mechanical vibrations (chatter) are one of these limitations to improve productivity and quality in metal cutting processes. The work aims to identify the correlation between amount of flank wear and the process damping both in feed and tangential direction during the face turning of a grey cast iron brake disc. It is also desired to investigate the conventional mathematical models in chip formation theories.

1. INTRODUCTION

Chatter in machining occurs due to the dynamics in cutting process being in resonance with the neighbouring structures including the workpiece, the tool holder, and the machine tool. The damping coefficient in this phenomenon acts a vital role as if this value is insufficient, it may result in some undesirable effects including uncontrollable tool wear and surface irregularities. The work aims to clarify and describe the correlation (phase shift) between the tool motion, amplitude, dynamic forces, and acceleration, as well as generated surface topography and process damping, for a few special selected tool geometries.

1.1. DEFORMATION DAMPING

The effect of flank interaction with the workpiece surface brings about the most considerable amount of damping during a machining process. This contact would result in a certain amount of material on workpiece being deformed. This deformation will consume some amount of energy which can be supplied by the kinetic energy of the relative motion of the tool. This energy consumption due to material deformation would cause some damping effects which is regarded as “deformation damping”. The amount of deformed material is a function of micro-geometry of the insert (flank wear VB_s and cutting edge radius r_β), wavelength e_1 and the amplitude h of the workpiece surface wave, and clearance angle α (Figure 1).

The amount of deformed material can be calculated by applying numerical integration. The amount of deformed material also is a function of the position of the tool tip along the surface wave. In the current model, the

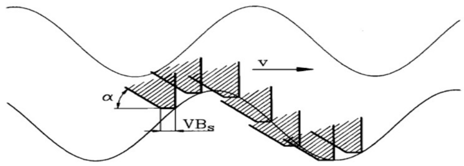

Figure 1: Motion of a cutting edge with wear during critical machining

maximum amount of material deformed through the path of the inserts indicates the process damping. The maximum amount occurs when the slope of the curve is equal to the slope of the flank face. Mathematically speaking,

$$\tan\alpha = \frac{dh_{el}}{de} \tag{1}$$

Where α is clearance angle and h_{el} is the sinusoidal function for surface waviness.

If we calculate the normalized deformed area as a function of normalized position, the result would be as Figure 2.

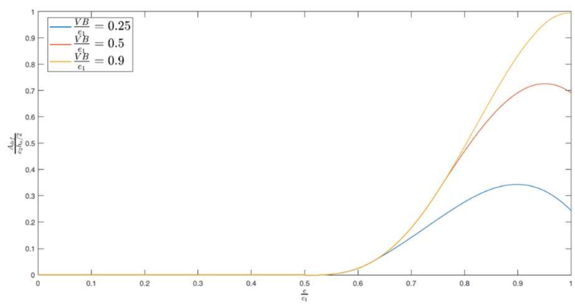

Figure 2: Deformed area as a function of tool position and flank wear

As it has been shown in Figure 2, increasing the amount of tool wear would result in higher amount of deformation and corresponding more damping. However, in the current model, there is no consideration of other machining parameters including cutting velocity. Thus, it is needed to consider other factors including the change of cutting velocity direction due to vibrations in feed direction and the effect of curvature of the waviness of the profile.

1.2. CONVECTIONAL MODELS FOR OSCILLATIONS IN FEED DIRECTION

Tobias has derived the simplest model for self-induced vibrations in feed direction by assuming the tool holder as a simple 1-DOF spring-mass-damper system in feed direction (Figure 3). The equation of motion of the tool tip would be as Equation (2).

$$F_x(t) = m\ddot{x} + c\dot{x} + kx \qquad (2)$$

Where m, c, and k are constants for equivalent mass, damping and stiffness coefficient, respectively. $F_x(t)$ is the cutting force in feed direction can be calculated as Equation (3).

$$F_x(t) = k_f \cdot a_p \cdot [h_1 - x(t) + x(t-\tau)] \qquad (3)$$

Where k_f is the static cutting resistance of the workpiece material in feed direction, a_p is cutting depth, h_1 is the theoretical chip thickness, $x(t)$ illustrates outer surface of the workpiece while $x(t-\tau)$ shows the waviness profile obtained from the previous revolution. Modifying the model, we can include the effect of cutting velocity vector's direction change owing to oscillations in feed direction (Figure 3). As a result of this, there would be an axial component of the main cutting force in the opposite direction of the feed force.

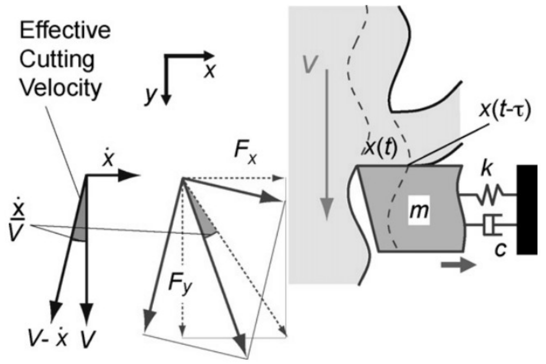

Figure 3: Influence of oscillations in feed direction on main cutting velocity

As has been shown in Figure 3, the oscillations would result in a rotation of θ in the cutting forces direction. The value of θ can be obtained as Equation (4).

$$\theta = \tan^{-1}\frac{\dot{x}}{V} \qquad (4)$$

Knowing the amount of θ is tending to zero, we can assume $\tan\theta \approx \theta$. Thus, the axial component of the main cutting force would be as below.

$$F_{y_x}(t) = -k_c \cdot a_p \cdot [h_1 - x(t) + x(t-\tau)] \cdot \frac{\dot{x}}{V} \qquad (5)$$

Thus,

$$F_x(t) = m\ddot{x} + \left[c + \frac{k_c \cdot a_p \cdot h_1}{V}\right]\dot{x} + kx \qquad (6)$$

It can be concluded from Equation (6) that the change of velocity direction would result in higher damping coefficient. However, this effect would not be noticeable in high cutting velocities.

Moreover, the effect of flank/workpiece interaction can be added by calculating the slope and curvature of the wave.

$$\frac{dx}{du} = \frac{dx}{dt}\cdot\frac{dt}{du} = \frac{\dot{x}}{V} \qquad (7)$$

$$\frac{d^2x}{du^2} = \frac{d}{du}\cdot\left(\frac{dx}{du}\right) = \frac{d}{dt}\left(\frac{\dot{x}}{V}\right)\cdot\frac{dt}{du} = \frac{\ddot{x}}{V^2} \qquad (8)$$

The derived model by Altintas is shown in Equation (9).

$$F_x(t) = a_p \cdot \left[k_f[h_1 - x(t) + x(t-\tau)] - \frac{C_i\dot{x}}{V} - \frac{\alpha_i\ddot{x}}{V^2}\right] \qquad (9)$$

Parameters α_i and C_i can only be extracted by conducting a set of dynamic cutting experiments while k_f and k_c can be obtained by a simple vibration-free orthogonal cutting tests.

1.3. CONVECTIONAL MODELS IN CHIP FORMATION

During a cutting process, the material, which is being removed, experiences a deformation in the shear "*zone*" leading to changes in the **width** and **thickness** of the chips compared to the uncut material. However, in classic theories of chip formation, it has been mostly assumed that the deformation occurs in a single plane whose angle designate the direction of the chip motion. This angle which is referred to as "*shear-plane angle* ϕ" is a function of rake angle γ and chip compression ratio λ_h. Figure 4 shows the schematic diagram of shear plane angle in a two-dimensional cutting process. According to this figure, we have,

$$\tan\phi = \frac{\cos\gamma}{\lambda_h - \sin\gamma} \qquad (10)$$

Equation (10) is totally based on geometrical relations ignoring the effect of velocity on plastic deformation of the chip and the amount of work converting to heat in the cutting process. In this work, we are also going to study the influence of cutting speed v_c on chip compression λ_h.

2. EXPERIMENTS AND RESULTS

Investigating the effect of tool micro-geometry on process damping for a continuous turning, a custom-built tool holder equipped with strain gauge sensors in two directions (tangential and axial) has been designed previously. The flexible tool holder mounted with a multi-layer coated, diamond shaped turning insert with $55°$ wedge angle β. The process has been selected to be turning of a grey cast iron brake disc while the feed direction is perpendicular to the rotational axis to the workpiece. "VDF Boehringer Goppingen model 51085" center lathe has been used to perform the process. In order to minimize pressure distribution difference along the contact length on the rake face, the same feed rate of $f = 0.4\,mm/min$ and cutting depth $2\,mm$ has been selected for all sets of experiment. The experiment has been performed for a three-stage post processing procedure.

Figure 4: Experimental setup

1. Collecting data from accelerometer and strain gauge sensors to calculate the tool displacement comparing it to the surface profile of the workpiece by performing face turning in which the insert moves radially towards the center of the workpiece. The cutting velocity would be varying from $150\,m/min$ to $75\,m/min$. The reason is to make resonance occur between the first two natural frequencies of the tool holder. The collected data will be utilized in signal processing so as to calculate the modal parameters and correlating the tool holder displacement with dynamic cutting forces.
2. Collecting chips for each set of machining parameters to find the segmentation distance e_2 while collecting data from sensors by conducting face turning of a brake disc.
3. Providing the workpiece with a trigger slot (Figure 4) to conduct the turning in specific numbers of revolutions and studying the surface topography (chatter marks) correlating the surface waviness with data collected from accelerometer and strain gauge sensors.

Recognizing the excitation frequency components so as to analyze if the process has reached the critical machining speed range requires knowing the natural frequency of vibration of the tool holder (with tool post) and workpiece as there are three different scenarios for chatter based on relative stiffness of the workpiece and tool shaft.

1. The first case happens when the tool holder is stiffer than the workpiece where the chatter occurs in radial direction.
2. If there is a weaker tool shaft, the chatter will be occurring in tangential and axial direction (TA plane).
3. The last case which leads to the same result as the second case is when machining a tube where the workpiece may wobble in tangential and feed directions.

Finding the vibration plane which appears during the process requires to know the natural frequency of vibrations (eigenfrequencies) of the workpiece and the tool shaft which is proportionally related to their material's Young's modulus. For obtaining the the dynamic characteristics of a system, modal analysis can be performed where the load can be applied with certain amplitude and frequency. The system response leads us to find the eigenfrequencies of the system. Calculating spectrum of the acceleration signal for modal analysis of the workpiece and the tool holder, it can be concluded that the workpiece is stiffer than the tool shaft/tool post resulting in chatter in axial and tangential direction.

2.1. VIBRATION ANALYSIS

we are going to preform frequency domain analysis of the data obtained from accelerometer and strain gauge sensors in feed and tangential direction. By analyzing, it is meant to apply Fourier transform finding the frequency components of the signal. Interpreting the frequency components during machining process is not a trivial task due to the measurement noise and disturbance forces caused by the complexity of chip removal mechanism. Chip removal process may lead to non-deterministic and impossible to model dynamic forces with random frequencies. By and large, the computational analysis aims to identify the trend of chatter frequencies in feed direction as a function of cutting velocity and the presence of process damping due to interaction of the workpiece surface and flank face for different amounts of synthetic tool wear VB_s. Applying FFT, the segmentation frequency is decreasing by reducing cutting velocity. The eigenfrequencies can be noticed as they remain constant as the cutting speed is varying. Figure 5 shows the segmentation frequency and eigenfrequencies as a function of cutting speed. As it shows, there is a linear relationship between the segmentation frequency and cutting speed. Ståhl has experimentally derived a relation between cutting speed and segmentation frequency (Equation (11)) where d_1 and d_2 are constants which are functions of material properties. Compression ratio λ_h, itself, is dependent on cutting speed v_c and theoretical chip thickness h_1.

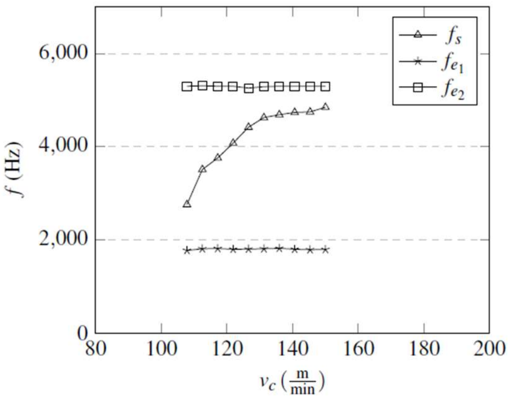

Figure 4: Segmentation frequency and eigenfrequencies as a function of cutting speed

$$f_s = \frac{v_c}{e_1} = \frac{v_c}{\lambda_h(d_2 + d_1 \cdot \lambda_h \cdot h_1)} \quad (11)$$

2.2. *Process Damping*

For finding the damping ratio, both amplitude of the tool holder displacement and the phase difference between the force and displacement signals will play a vital role. One way to estimate the system parameters (ω_n, ξ) is to find the frequency response function and estimate the modal parameters by utilizing estimation algorithms. "Least-squares rational function estimation" has been utilized to estimate the damping coefficient in which orthonormal rational polynomial basic functions are utilized so that the best solution to be found for non-linear least square problem. Not to mention, it is first required to apply discrete time integration on acceleration twice so as to obtain the displacement signal. Yet, the obtained values for damping ratio are not the real values since the amplitude of acceleration and force are not in N and m/s^2 but in volts and $g/200$, respectively. However, since we have used the same scale factors in sampling, the obtained values can be compared to each

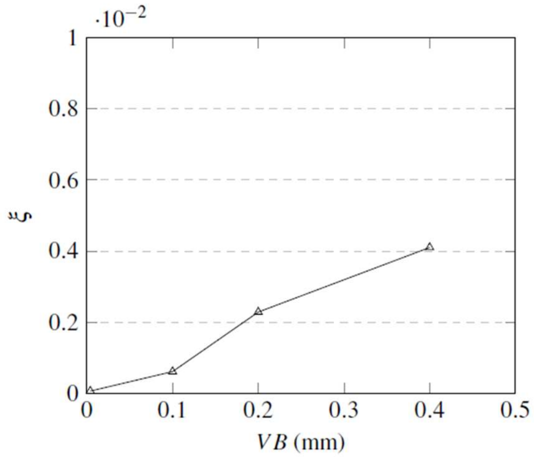

Figure 5: Process damping as a function of flank wear

other. The damping coefficient as a function flank wear can be seen in Figure 5. As has been shown, increasing amount of tool wear would result in higher damping in the process which verifies the deformation damping theory in low cutting velocities.

2.3. *Tool Shaft Displacement*

As it has been mentioned earlier, process gain which is the ratio of the output amplitude (displacement in this case) to the input amplitude (force) is another parameter can be utilized to calculate process damping. Thus, in this section, we are going to compare the magnitude of displacement of tool shaft for different amounts tool wear VB_s.

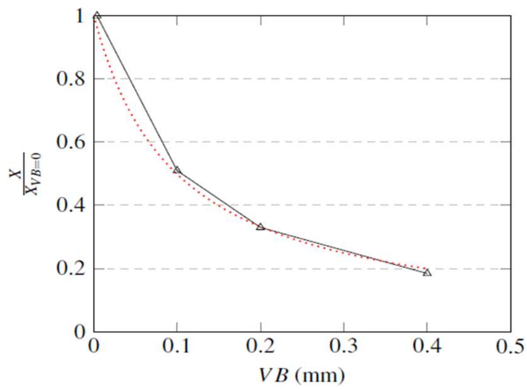

Figure 6: Tool shaft oscillation amplitude as a function of flank wear

Double-time integration must be applied to accelerometer signal to calculate displacement. One of the issues may appear in time-integration would be the presence of drift in displacement which is since the velocity and acceleration signals are not zero-mean signals. Moreover, one of the consequences of going from acceleration to displacement is that low-frequency components will be boosted. Thus, a high-pass filter must be run to avoid address this problem.

Assuming the tool holder displacement amplitude when $VB_s = 0$ as the reference value, it is possible to compare this parameter in machining when we have higher amounts of tool wear and see the effect of flank wear on process damping (Figure 6).

2.4. Chip Segmentation Analysis

In this section, the conventional models for chip segmentation will be applied for the collected chips during the tests and the results will be compared to the ones have been obtained from signal processing. The chips have been mounted in carbon filler epoxy and polished so as to be prepared for optical microscopy. The results are shown in Figure (7).

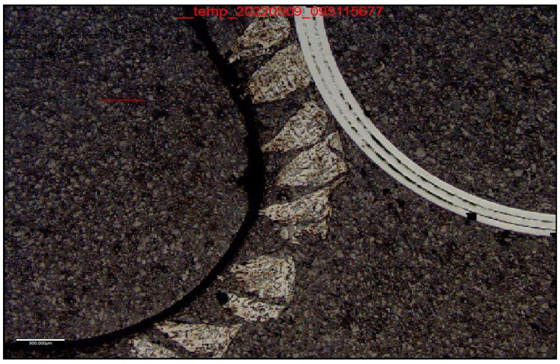

Figure 7: Segmented chip collected from machining of grey cast iron brake disc

Image processing program “ImageJ” has been used in order to find the chip segmentation area A, the chip thickness h_2, and chip contact length e_2. The process of measurement has been performed manually which may cause considerable errors in some cases. The chip compression ratio λ_h is shown as a function of cutting speed v_c. As can be seen, the chip compression ratio has a downward trend by increasing the cutting velocity.

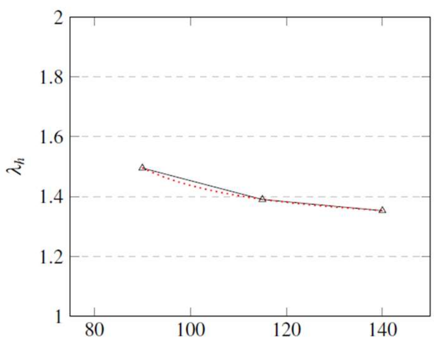

Figure 8: Chip compression ratio as a function of cutting speed

3. Discussion

Before coming to conclusions, there are a few points deserved to be discussed more.

It has been shown that the vibration frequency is increasing with cutting speed while Jan-Eric Ståhl has derived a linear function correlating chatter frequency with cutting speed and chip compression ratio (Equation (11)). However, at low cutting speeds, the chatter frequency is close to the eigenfrequency of the structure. The possible explanation for this phenomenon (increased chatter frequency) could be the increasing effective stiffness due to the machining-induced pre-loads. In low cutting speeds, ignoring the effects of temperature rise on static cutting forces due to short machining time, the process damping would increase owing to the effect of changes in cutting force direction because of oscillation velocity and the effect of profile curvature on the surface interacting with clearance face.

Brittle behavior of grey cast iron during cutting process brings about a great variation (bandwidth) in segmentation frequency. However, this variation also occurs owing to the procedure of chip segmentation. The frequency component of stress development occurring because of chip segmentation differs from those components appeared by pressure relief on the workpiece or shearing off chips.

Figure 2 shows the normalized deformed area as a function of insert position for different values of synthetic tool wear. The effect of strain-hardening also must be noted as the insert moves along the workpiece surface, a portion of the area is being deformed, has already been in contact with flank face resulting in deformations occurred before the current interaction.

Another source of non-linearity results from the changing of the contact length of the tool holder and its clamping during its oscillation. As the tool holder vibrates, due to the deflection occurs throughout the beam, the beam will lose a portion of its contact with the tool post resulting in increasing in the effective beam length for a value of $\Delta\ell$ which varies in time depending on the amount of tool holder deflection and could be in the upper or lower surface of the tool holder in each cycle of oscillation.

It has been shown that in the observed speed interval, increasing the speed would result in a drop in chip compression ratio. The strain rate can be correlated to the cutting speed by Equation (12) where L and t are the specimen length in the cutting velocity direction and cutting time, respectively.

$$\dot{\varepsilon} = \frac{\partial \varepsilon}{\partial t} = \frac{v}{L} \qquad (12)$$

Solving the differential equation, strain rate can be obtained from Equation (13).

$$\varepsilon + c = \frac{vt}{L} \tag{13}$$

On the other hand, true strain ε_t can be calculated as below.

$$\varepsilon_t = \ln\frac{h_2}{h_1} = \ln\lambda_h \tag{14}$$

Substituting Equation (14) in Equation (13),

$$\lambda_h = e^{c-\frac{tv}{L}} = \mathrm{e}^{\beta-\alpha v} \tag{15}$$

As has been proved, chip compression ratio will exponentially decrease with cutting velocity. In this study, we have measured the chip compression ratio for three different velocities. The curve fit for these data would be as follow.

$$\lambda_h = \mathrm{e}^{0.678-0.1220v} \tag{15}$$

4. Conclusion

Mechanical vibrations of tool shaft and workpiece have been argued throughout this work and the effect of micro-geometry of an insert on correlation between the dynamic cutting forces and tool holder displacement has been illustrated. In particular, the process damping has been studied during face turning of a brake disc made up of grey cast iron. Signal processing approach, surface topography and segmentation analysis has been chosen to measure tool displacement in tangential and axial direction comparing it to the cut surface waviness and comparing the frequency components of cutting forces with chip segmentation frequency.

Moreover, conventional models for chip formation and deformation damping have been challenged throughout this project. Following results have been concluded:

1. It has been shown that by increasing tool wear, while in sub-critical machining cutting speed interval, the process damping will rise particularly in feed direction due to the flank interaction bringing about workpiece surface deformed and corresponding energy waste.
2. However, it has been shown that in tangential direction the flank interaction is not a decisive factor for process damping, but the chip rigidity based on adiabatic temperature plays a vital role in energy loss in transmitting the power from tool to the layer being removed through chips.
3. The mathematical models correlating chip compression ratio with rake angle and shear plane angle has been introduced. However, the effect of cutting speed and size of plastic deformation zone has been ignored in the conventional models. Thus, the effect of speed on λ_h has been explained and a model has been derived by Astakhov (Equation (15)).

While the working material, insert micro-geometry, and machining parameters might limit the generalizability of the results, this approach can be utilized in any sets of machining in case of either single or multiple point processes. However, in this project, the same workpiece has been used to conduct the experiments. Therefore, the geometrical changes after each process might affect the reliability of the results which can be addressed by using an uncut workpiece for each set of experiment for the future.

Further research is needed to determine the effects of adiabatic temperature and deformation zones shape and size on energy losses during machining and corresponding damping effects during the process.

Acknowledgements

I wish to show my appreciation to my primary supervisor, Professor Jan-Eric Ståhl for sharing his valuable experience in production technology and material sciences leading me to finalize this project. The completion of this study may not have been possible without the provided help by Dr. Oleksandr Gutnichenko with data acquisition part of the study. I am also deeply grateful to Rebecka Lindvall for her contributions during the project specially in chip segmentation analysis part.

Last but not least, I would like to thank my parents, family, and friends supporting me emotionally to cope with the difficulties.

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Strain Rate Characterization of Packaging Materials

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ABSTRACT

This paper firstly introduced the basic knowledge of packaging materials through literature survey and focused on exploring the effect of strain rate on mechanical properties of paperboard materials. By means of tensile tests and microscopic observation, the changes of mechanical properties such as yield strength, strain and Young's modulus of two paperboard packaging materials TFA and TBA from Tetra Pak were analyzed at strain rates ranging from 100 mm/min to 10000 mm/min. The yield strengths of the samples were first increased and then decreased in this strain rate range, and the maximum value was obtained at about 1000 mm/min. The strain was basically positively correlated with the strain rate, and the Young's modulus was not significantly related to it.

1. INTRODUCTION

Tetra Pak, established in Lund Sweden, by Ruben Rausing in 1951, is one of the leading companies globally in food packaging solutions, especially for liquid food. Working closely with customers and suppliers, they provide safe, innovative and environmentally sound products. This thesis is conducted by Tetra Pak Packaging Solutions AB and is devoted to the study of mechanical properties, especially the effect of strain rate on packaging materials.

In the packaging materials, mechanical properties are very important in both fabrication of package and service. Mechanical properties of packaging materials include stiffness, tensile strength, impact resistance, tear strength and so on. Materials with good performance in the above properties, such as paperboard, aluminum foil and polymer, become suitable packaging materials and have a wide application. Paperboard provides the primary stiffness and strength for the material system, while aluminum foil prevents light and oxygen from getting in, and natural or artificial polymer layers act as moisture-proof layers and adhesives.

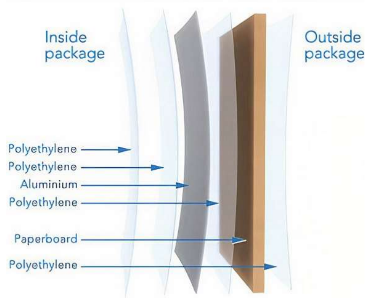


Figure 1.1: Packaging material for Tetra Pak carton packages [1]

Modern technology for fabricating the package takes place at very high rates. With the change of strain rate, mechanical properties such as yield strength, ultimate tensile strength and elongation will change. As a consequence, the study of mechanical behaviour of packaging materials at high strain rate is critically important. Literature survey on strain-rate material responses, experiments for different packaging materials and simulation are implement in this paper.

Therefore, this project has been initiated by Tetra Pak, and plays an important role in the technology development.

The objectives of the project include:

1) Carry out a comprehensive literature survey on state-of-the-art in packaging materials and the effect of strain rate on their mechanical properties.
2) Study experimentally the effect of strain rate on packaging materials used by Tetra Pak.

2. PAPERBOARD IN PACKAGING MATERIALS

The purpose of this section is to have a preliminary understanding of

1) Packaging materials for liquid food – general overview.
2) Mechanical properties of packaging materials including anisotropy.
3) Effect of strain rate on the mechanical properties of packaging materials.
4) Experimental methods for determining the mechanical properties of packaging materials at high strain rates.

Therefore, a literature survey was conducted to review the topics of previously researched knowledge.

2.1. PACKAGING MATERIALS

The packaging materials in Tetra Pak consist polyethylene and aluminium foil to protect against outside moisture, oxygen and light, which is benefit for maintaining the nutritional value and flavors of the food in the package in ambient temperatures.[1]

2.2. ROLE OF PAPERBOARD IN PACKAGING MATERIALS

Paperboard-based composites are an ideal material for packaging applications including food and beverage packaging. This is because paperboard is a lightweight cellulose fiber material with a high degree of anisotropy between in-plane and out-of-plane properties, and its high bending stiffness makes it an excellent material for packaging containers. The carton itself is made of wood fiber, and its natural properties make experimental evaluation and material modelling of paperboard and its driving laminate composites challenging.[2]

There are mainly three main sub-layers of food packaging paperboard: the top, middle and bottom layers. In order to produce paperboard with high bending stiffness and light weight, the outer layer is usually made of chemical pulp, whose mechanical and physical properties are characterized by high hardness and density. The mid layers are made from a combination of mechanical, chemical, or chemical-thermal-mechanical (CTMP) pulps to reduce thickness and are more suitable for obtaining a well-defined shape and layering profile during conversion. For the food packaging applications paperboards with a thickness of almost 350-500 µm are applied and the stiffer outer layers have thickness of 80-120 µm.[3]

3. MATERIALS AND EXPERIMENTAL METHODS

In this chapter, the materials and experimental methods of the study are described in detail. Material samples were provided by Tetra Pak and the experiments were mainly carried out at LTH.

3.1. PAPERBOARD MATERIALS OF INTEREST IN PACKAGING MATERIALS

The first experimental material is a thin paperboard utilized in a "pillow"-shaped package format called TFA, Tetra Fino® Aseptic (figure 3.1 a))[1]. From the outside, these packages look simple, but the process of manufacturing them is complex and sometimes they have trouble forming and folding them. First, a continuous roll of carton packaging material is fed into a filling machine and sterilized. The material is formed and sealed into a tube and filled, allowing it to expand. It is then shaped and sealed to maintain sterility. Finally, it is cut into individual packs. The product is filled in Tetra Pak® A1[13] and is sealed at a high strain rate, therefore, it is important that mechanical properties are tested at different strain rates for this product.

It was cut by a paper cutter into strips 100 mm long and 15 mm wide (figure 3.1 b)) for MD and CD respectively. The thickness of the sample was measured at 101 µm. The clamping areas were covered by masking tape in order to prevent samples from being damaged by grips.

Figure 3.1: a) Tetra Fino® Aseptic[1]; b) Sample size and shape description

The second experiment material TBA paperboard, which is the same as Robertsson[2] tested. This material was tested at higher strain rates than Robertsson's experiment but only cut along MD (the same size and shape as TFA material with thickness of 410 µm).

3.2. MECHANICAL TESTING

ElectroPuls® E10000 Linear-Torsion with ±10 kN force and ±100 Nm torque capacity is used for obtaining information on the mechanical properties of material. This data is used as a background for the analysis of material performance at high strain rates.

Designed for dynamic and static testing of a broad range of materials and components, it is a state-of-the-art, all-electric test instrument. It is powered by a single-phase supply and requires no additional utilities for basic operation (for example, air, hydraulics, or water).

3.3. OPTICAL MICROSCOPY

Samples of paperboard material tested in the tensile test at different strain rates were next observed under an optical microscope. The observation of fractures, fiber morphology, and wrinkles can help analyze the effect of strain rate on the mechanical properties of the material.

4. EXPERIMENTAL STUDY OF MECHANICAL PROPERTIES, MICROSTRUCTURE, AND FRACTURE OF PAPERBOARD

4.1. MECHANICAL TESTING OF PAPERBOARD

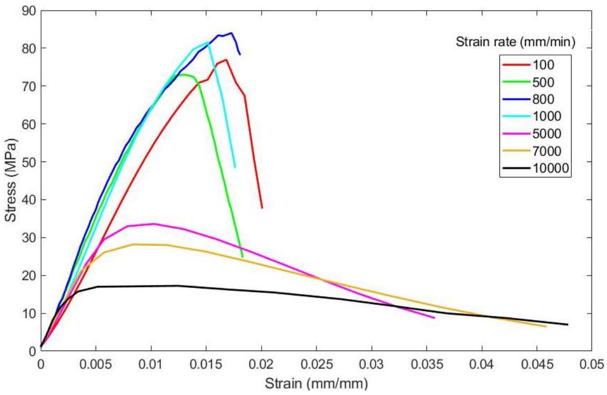


Figure 4.3: Stress-strain curve for tensile tests of TFA in MD from 100 mm/min to 10000 mm/min

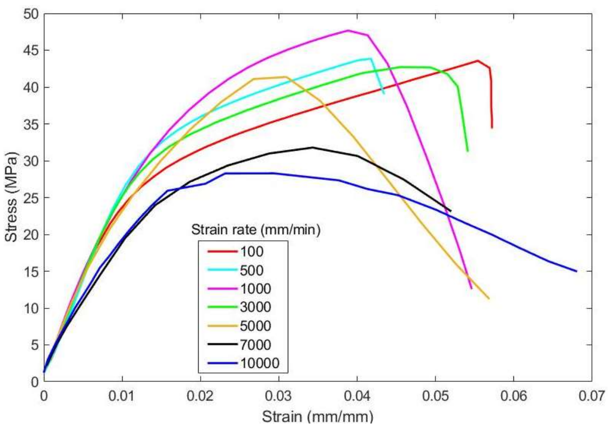


Figure 4.4: Stress-strain curve for tensile tests of TFA in CD from 100 mm/min to 10000 mm/min

For TBA material, the same experiment method was used to test its properties in MD.

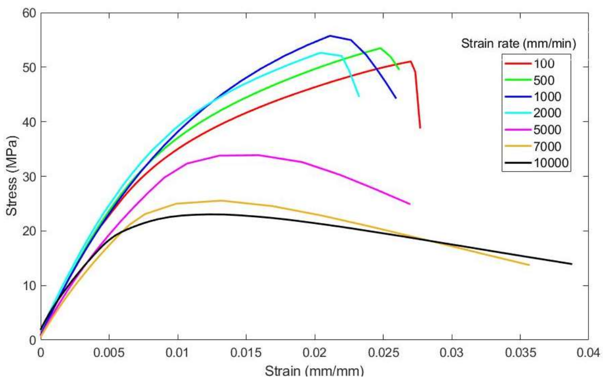
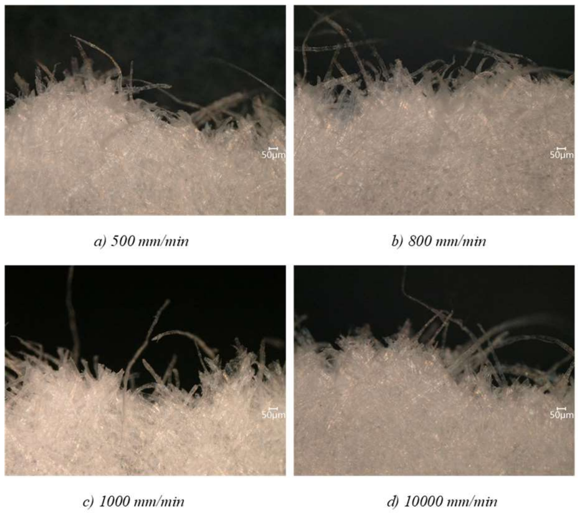


Figure 4.5: Stress-strain curve for tensile tests of TBA material from 100 mm/min to 10000 mm/min

4.2. ANALYSIS OF MICROSTRUCTURE IN TFA AND TBA PAPERBOARDS

Figure 4.6 shows the TFA samples that had been tested in tension at different strain rates observed under an optical microscope. It can be seen from figure 4.6 that the fibers at the fracture from strain rate of 500 mm/min to 10000 mm/min gradually become tidy (same lengths). The fibers were significantly extended at a strain rate of 10000 mm/min.

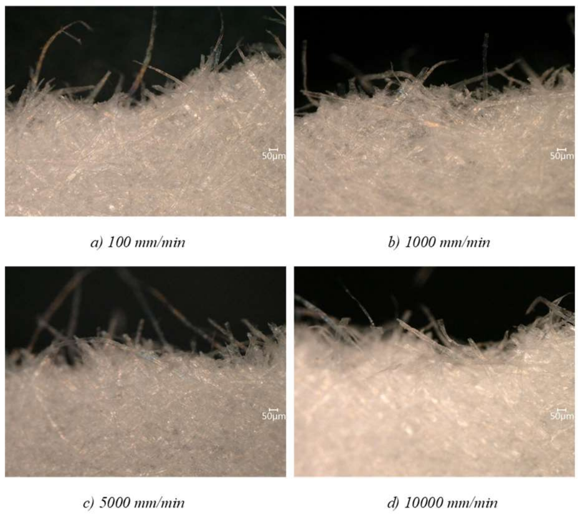


a) 500 mm/min *b) 800 mm/min*

c) 1000 mm/min *d) 10000 mm/min*

Figure 4.6: Microscopic images of TFA in MD at different strain rates

In CD, less broken fiber can be seen and the fractures of the 100 mm/min and 1000 mm/min samples are uneven while the fibers of the 5000 mm/min and 10000 mm/min samples are looser. This is similar to the condition of MD.

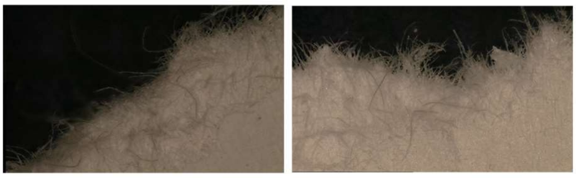


a) 100 mm/min *b) 1000 mm/min*

c) 5000 mm/min *d) 10000 mm/min*

Figure 4.7: Microscopic images of TFA in CD at different strain rates

The TBA material also had similar differences to those found above at the fracture of the samples at strain rates of 100 mm/min and 10000 mm/min. In addition, because the TBA material is relatively thick, obvious delamination can be seen in the tensile fracture at low strain rate.



a) 100 mm/min *b) 10000 mm/min*

Figure 4.8: Microscopic images of TBA in MD at different strain rates

3D images of the TFA material at the wrinkles resulting from stretching at 100 mm/min show that the wrinkles in CD are deeper and more evident, which can also be seen in next section.

a) MD b) CD

Figure 4.9: 3D microscopic images of TFA in MD and CD at 100 mm/min

For TBA samples, the wrinkles produced after stretching are less visible in appearance due to the thicker and stiffer samples themselves (darker areas is the wrinkle).

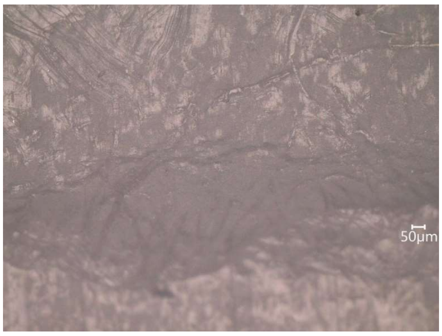


Figure 4.10: 3D microscopic images of TBA in MD at 10000 mm/min

4.3. ANALYSIS OF FRACTURE IN TFA AND TBA PAPERBOARDS

The fracture of all samples occurred in the stretching area, rather than near the grips. The fractures are all essentially perpendicular to the direction of tension. At a strain rate of 100 mm/min, the fracture of the sample is relatively rough, which is due to the fact that at low strain rate, the strain distribution is very uniform and the damage area of the specimen slowly expands toward the adjacent weakest point to form a rough fracture surface. At a strain rate of 10000 mm/min, a relatively flat fracture can be observed, which is due to the rapid expansion of the damaged area of the specimen into fracture damage. This is common to both materials.

For TFA cut along the MD, the morphology of the sample after tensile testing at low strain rates of 100 mm/min and 1000 mm/min is virtually indistinguishable from that before stretching. This is also reflected in the fact that they have a small yield strain. This is because almost no deformation of the fibers takes place, except at the fracture.

The specimens tested at 10000 mm/min have slight wrinkle in close to the area of contact with the grip.

For TFA cut along the CD, the samples tested at all three strain rates showed significant wrinkle, which became apparent as the strain rate increased. It can be assumed that this is due to the small number of fibers along this direction and the weak connections between the parallel fibers. These hydrogen bonds govern the behavior of paperboard in CD, which is less than the strength of cellulose fibers. As the parallel fibers become loose with stretching, the paperboard becomes thinner or even breaks when the few fibers that are used as a link break.

The fracture of the TBA material at different strain rates is also basically perpendicular to the direction of force, but because the paperboard is thicker and consists of different layers, the fracture is not exactly perpendicular to ZD. Slight wrinkles appeared in the samples at all strain rates, and the number increased with increasing strain rate.

5. ANALYSIS OF STRUCTURE-PROPERTY RELATIONSHIP IN PAPERBOARD MATERIALS

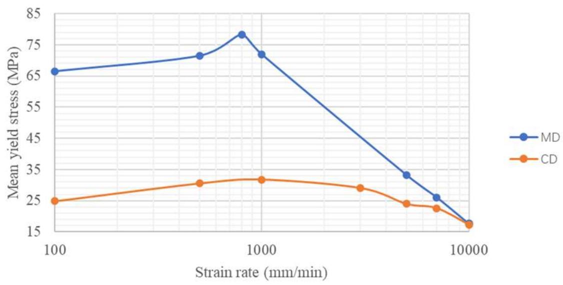


Figure 5.1: Stress-Strain rate graph of TFA (The horizontal axis is logarithmic)

According to this result, stress at maximum load in MD is obviously higher than that in CD at all strain rates. This is due to the fact that the strength of the paper fibers themselves is greater than the strength of the connections between the fibers. This is also in line with previous speculations based on the arrangement of the fibers in the paperboard material.

This may also explain the wrinkles (waves) that appear in the paper after stretching in figure 5.2. The disrupted areas between poorly connected fibers become thinner and the change in thickness causes wrinkles to develop. The morphology of the samples also varies between experimental conditions and different cutting orientations; this will be presented and discussed in the following section.

In both directions, the yield strength showed a trend of increasing and then decreasing, with the minimum value both occurring at 10000 mm/min, and maximum values occurring at 800 mm/min (in MD) and 1000 mm/min (in CD). For the strain at fracture, that in CD is higher than that in MD, and a positive correlation with the strain rate is basically shown in both directions according to figure 4.3 and 4.4, which coincides with the macroscopic and microscopic images shown in the previous chapter. No significant correlation was found between Young's modulus and strain rate.

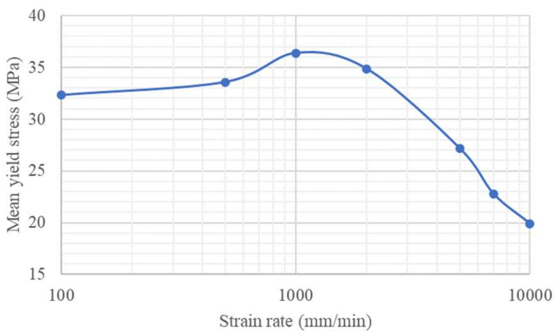


Figure 5.2: Stress-Strain rate graph of TBA (The horizontal axis is logarithmic)

The maximum value of yield strength occurs at 1000 mm/min and the minimum value at 10000 mm/min, which increases and then decreases overall. According to Figure 4.5, the strain at fracture is positively correlated with the strain rate. No significant correlation was found between Young's modulus and strain rate.

For both materials in all directions, the relationship between stress and strain is initially linear (elastic deformation) and when the stresses both reach a certain value becomes non-linear (plasticity deformation). In addition, the yield strength and strain rate of both materials have a similar variation path (first increase and then decrease), and the strain rates for achieving the maximum yield strength are in the range of 800 to 1000 mm/min. The minimum yield stress always appears at 10000 mm/min and is lower than that at 100 mm/min. At higher strain rates, localized damage and weak zones are generated at multiple locations within the material, and the overall ultimate strain of the material grows[14]. This is also reflected in the multiple wrinkles of the samples at higher strain rates, which can be seen more clearly in CD of the TFA material (figure 4.12).

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Mechanical Engineering Sciences

2022