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Additive Manufacturing for Large Products

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FOR
STUD.TECHN. ROAR NELISSEN LEIRVÅG

ADDITIVE FRAMSTILLINGTEKNIKKER FOR STORE PRODUKTER
Additive manufacturing techniques for large products

Oshaug Metall AS støper skipspropellere for sine kunder i offshore- og skipsindustri. Dette er store produkter, og krevende å produsere. Bedriften ønsker å finne ut om additive produksjonsmetoder kan utnyttes til å forenkle denne produksjonen. I utgangspunktet er de interesserte i alle ideer til hvordan teknikkene kan utnyttes.

Bedriften ser primært for seg at modellfremstilling er et aktuelt område for additive teknologier. Konkurrerende alternativer bedriften også ser på er direkte fresing i sand, samt fresing i PU-skum. Begge er videreutvikling av dagens ordning som er fresing av tremodeller.

I denne oppgaven skal det først gjøres en oppsummering av hva som tilbys på markedet i dag. Videre skal det gjøres en vurdering av hva som mangler og hva som kan utnyttes når dimensjonene er som på skipspropellere. Det skal vurderes om det er produktet selv eller modeller eller former som er det mest egnede stedet å begynne en utvikling, og det skal foreslås teknikker for å komme videre.

Additive teknologier for produkter i metall kan være aktuelt å undersøke for fremtidige produktmuligheter.

Miljøhensyn og muligheter for resirkulering må tas med i vurderingene.

Oppgaven skal inneholde:

- en oppsummering av state of the art når det gjelder additiv tilvirkning
- en gjennomgang av krav som stilles for de aktuelle produktene
- en mulighetsstudie, inkludert opplisting av alternative teknologier og alternative materialer med hensyn på store produkter
- en vurdering av alternativene mot kravene som stilles fra produktene
- utvikling av en konseptløsning
- konklusjon og eventuelle anbefalinger om videre arbeid

I tillegg til rapporten skal det leveres PU-journal i instituttets A3-format.

Besvarelsen skal ha med signert oppgavetekst, og redigeres mest mulig som en forskningsrapport med et sammendrag på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse, etc. Ved utarbeidelse av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelse legges det stor vekt på at resultater er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte og diskuteres utførlig.

Senest 3 uker etter oppgavestart skal et A3 ark som illustrerer arbeidet leveres inn. En mal for dette arket finnes på instituttets hjemmeside under menyen undervisning. Arket skal også oppdateres ved innlevering av masteroppgaven.

Besvarelsen skal leveres i elektronisk format via DAIM, NTNUs system for Digital arkivering og innlevering av masteroppgaver.

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ROAR NELISSEN LEIRVÅG

ADDITIVE MANUFACTURING FOR LARGE PRODUCTS

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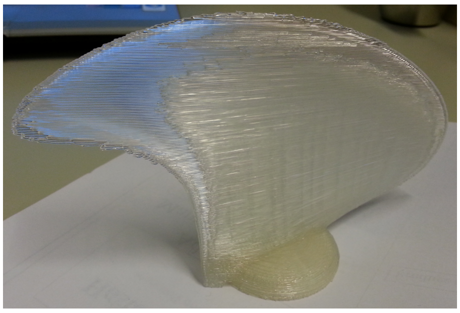

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ABSTRACT

This thesis researches the possibility and feasibility of applying additive manufacturing technology in the manufacturing of propellers. The thesis concerns the production at the foundry Oshaug Metall AS. Their products consist of propellers and other large products cast in Nickel-Aluminium Bronze. This report looks at three approaches and applications for additive manufacturing at the foundry. These are additively manufactured pattern, sand mold and end metal parts. The available *State of the Art* systems for the three approaches are listed and the systems suitability is discussed.

The systems that meet the stated criteria are selected and further discussion on the advantages and disadvantages of the additive manufacturing approach to the application are carried out for the three respective applications.

An experiment was carried out on a scaled propeller blade to measure the geometrical accuracy and surface quality of a 3D-printed pattern.

The report is concluded with the conclusion to the stated task and recommendations for further work.

SAMANDRAG

Denne masteroppgaven undersøker muligheten og gjennomførbarheten ved å anvende additive tilvirkningsteknikker i produksjone av propeller. Oppgaven vedrører produksjonen ved støperiet Oshaug Metall AS. Deres produkter består av propeller og andre store produkter støpt i Nickel-Aluminium Bronse. Denner rapporten ser på tre tilnærminger og anvendelser for additive tilvirkningsteknikker ved støperiet. Desse er additivt tilvirket modell, sandform og metalldeler. De tilgjengelige systemer for desse tre tilnærminger er listet opp og egnetheten blir diskutert.

Systemene som møter kravene blir valgt ut og videre diskusjon rundt fordeler og ulemper med additiv tilvirkning for å løse de tre respektive tilnærmingene til anvendelse ved støperiet.

Et eksperiment ble utført på en skalert propellbladmodell for å undersøke dimensjonell nøyaktighet og modellens overflatekvalitet på en 3D-printet modell.

Rapporten konkluderes med en konklusjon på den oppgitte problemstilling og anbefalinger for videre arbeid.

The great menace to the
life of an industry
is industrial
self-complacency.

— Joyce Carol Oates

ACKNOWLEDGMENTS

I would like to thank Mari Klokk Leite and all the employees at Oshaug Metall AS. Stein Berg Oshaug for the opportunity to write this Master Thesis for the company.

Thanks goes out to the department of Product Development and Materials, and especially my supervisor Knut Einar Aasland for guidance during the writing of this thesis.

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Last but not least thanks to my parents Jan Petter Leirvåg and Anita Nelissen Leirvåg for support during my studies at NTNU!

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ACRONYMS

AM	Additive Manufacturing
CAD	Computer-Aided Design
CNC	Computer Numerical Control
ABS	Acrylonitrile Butadiene Styrene
CMM	Coordinate-Measuring Machine
SLS	Selective Laser Sintering
UV	Ultra Violet

1

INTRODUCTION

1.1 BACKGROUND

With the rapid evolving of additive manufacturing systems the last 10 years the possibility for using additive manufacturing for large scale products has become a possibility. The additive manufacturing business business is launching new systems every year, and indeed some systems listed in this report were launched during the work on this report. An article in the news magazine *Economist* in april of 2012 sparked an interest in the technology with Stein Berg Oshaug, the company director at Oshaug Metall AS, a foundry casting high quality propellers and components in Nickel-Aluminium Bronze.

The author of this report finds the additive manufacturing technologies and possibilities very interesting, and after work at the foundry during the summer of 2012 the task of this thesis was suggested. And thusly work on this report began in autumn of 2012.

1.2 TERMINOLOGY

Additive manufacturing, Rapid prototyping, 3D-printing and printed parts are some of the terms used to describe the process of building physical objects by bonding layers of materials. In this report *Additive Manufacturing*, *3D-printing* and *printed parts* are used to describe this process. Furthermore the ASTM standard terms to describe the technological principles are used in this report. Standard terminology and a brief introduction to additive manufacturing is described in appendix A.

1.3 CHALLENGES

The main challenge for this report is to research if the additive manufacturing systems can be used for large scale applications in a metal foundry. The advantages of additive manufacturing lies in its high degree of automation and possibility to rapidly make complex products. Ideally the additive manufacturing technologies use only the material needed for a build and thusly waste products can be reduced by a large amount compared to material removal processes.

Available and usable materials for 3D-printing varies by what is available for the respective systems, and recyclability of the materials remain a challenge for some of the technological principles. A current lack of material standards concerning additively manufactured products is an obstacle for end use of these products.

1.4 OBJECTIVES

Research the different stages of production at Oshaug Metall AS, to find out where the company can benefit from additive manufactuirng technologies. List the available technologies and find out what *State of the Art* additive manufacturing systems are capable of. Suitable systems will be selected and advantages and disadvantages will be discussed before a conclusion is met as to the technical suitability of additive manufacturing for large products.

1.5 REPORT OUTLINE

The report is split into parts covering three approaches to the task. Chapter 2 covers the manufacturing requirements and criteria that needs to be met by an additive manufacturing system. The remainder of the report is split into three main parts covering three different approaches.

PART 1 Covers the use of 3D-printing for pattern construction.

PART 2 Covers the production of sand molds by 3D-printing.

PART 3 Covers the use of additive manufacturing technologies to construct metal end parts.

PART 4 Covers conclusions on the different parts and recommendations for further work.

2

MANUFACTURING REQUIREMENTS

The main production at Oshaug Metall AS is casting of propeller blades in Nickel-Aluminium Bronze. All casting is done with sand casting techniques. Cured sand molds result in the cope and drag for the casting. Pattern is removed and two or more parts of the sand cast mold is mounted together and prepared for casting. See fig 1 for an overview of the products and services offered by Oshaug metall AS. For control measurements of pattern and resulting cast product Coordinate-Measuring Machine (CMM) is used.

Outlined in this chapter are also time and dimension guidelines for process selection in part 1, 2 and 3 of this report.

2.1 CURRENT PATTERN MANUFACTURING PROCESS

This section concerns manufacturing of patterns to be used for large metal castings. The patterns need to accurately reproduce shape and dimensions of the digital Computer-Aided Design (CAD) model including volumes added to account for metal contraction and post machining of cast part. For the current approach using a pattern, the pattern can be adjusted slightly after a control measure by adding or removing small amounts of material to the pattern. Thusly the digital model does not need to be 100% correct for the current pattern manufacturing.

Patterns are made at Oshaug Metall AS in laminated plywood sections. Two plywood boards are glued together to create laminates that are cut into shape. A Computer Numerical Control (CNC) mill is used for the machining. When enough laminated plates are cut, the pattern is constructed by gluing the different parts together to form the complete pattern. CAD models are thusly already cut into layers during current pattern production. Layers are however much thicker by an order of magnitude (3-5cm layers of laminated plywood) than for additive processes. The mill used today for the wood and plastic milling operations has the following operating dimensions.

X: 2000 mm

Y: 3000 mm

Z: 1000 mm

The current setup gives a guideline for target dimensions of the additive solutions. Some of the products manufactured by Oshaug Metall AS today are not as large as the propeller blades. Technologies

PROCESS	TIME IN HOURS
CAD modelling, rod placement and mill path creation	7,5
Milling of rods and gluing of workpiece	7,5
Complete milling of pattern	10
Control measurement in CMM	2
Post-processing and lacquering	5
Total process time	32

Table 1: Time consumption during current pattern production.

with build volumes smaller than this are still considered in this report for use for smaller products and for modular solution designs. This mill is the current geometrical limiting factor for pattern production, and thusly also a geometrical limit for single part in remaining production. Largest cast as of january 2013 is casting of NiAl-Bronze of up to 2,5 tons.[24]

2.1.1 *Time Consumption*

Time consumption for a present day pattern production process. Example times for a propeller blade pattern with a final cast weight of approximately 400kg. See table 1. Normal delivery time of a finished casting is 4-5 days. By using overtime an express delivery of 2-3 days can be achieved.

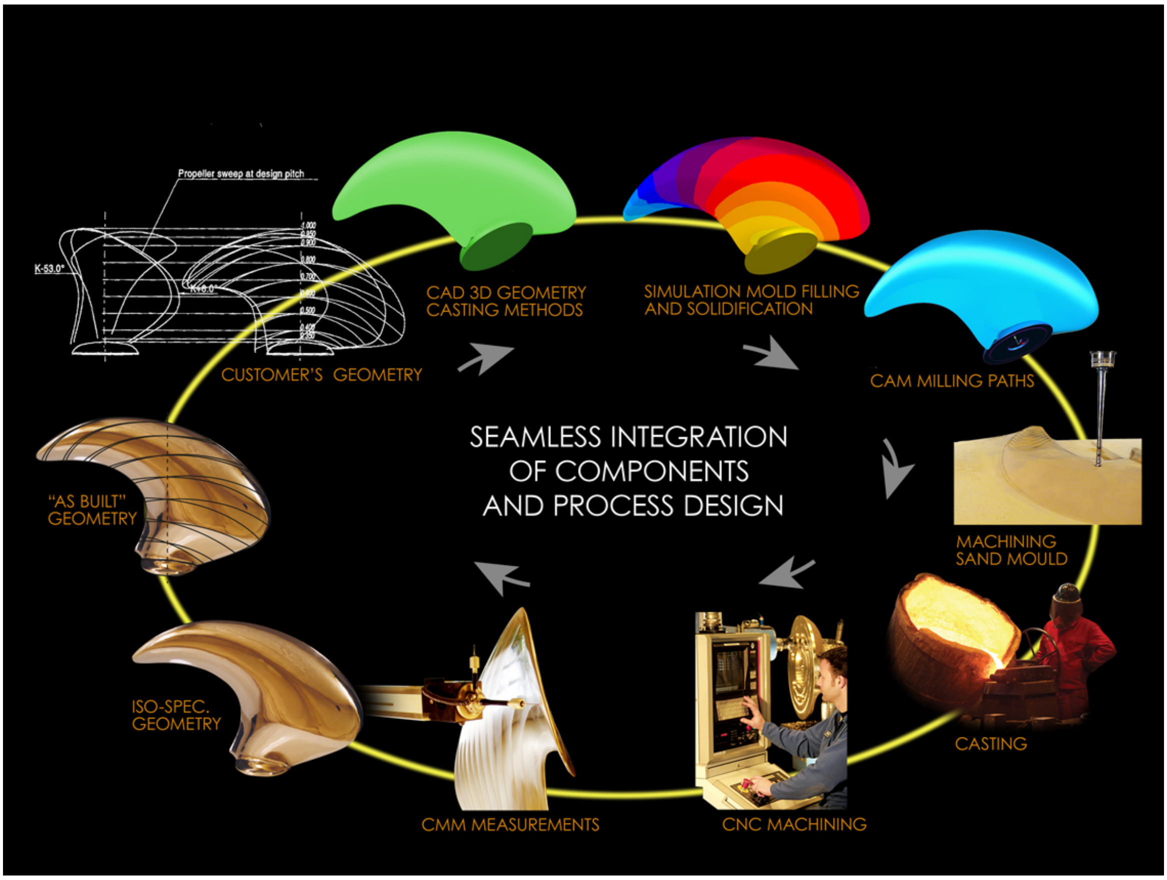
This example gives a time consumption guideline for selection of alternative solutions.

2.1.2 *Strength Criteria*

During the production the pattern needs to be transported by cranes. A threaded hole is included in the wood pulp material for the fitting of a steel ring. This hole needs to be strong enough to support the weight of the pattern and additional forces occuring during sand mold construction.

Strength criteria for an additive pattern depends on the pattern weight and strength of the selected material. Factors affecting criteria for a new pattern includes furthermore; intended number of uses, transportation need and geometrical placement of a lifting hook.

(a) Example products made by Oshaug Metall AS.



(b) Process Overview.

Figure 1: Overview of the services and products offered by Oshaug Metall AS.

2.1.3 *Surface Quality*

Surface quality of the pattern needs to be sufficient as to not make an imprint on the cope or drag. There is not a set demand or limit for the surface quality. The cast products are machined after casting. Surface quality thusly needs to be adequate as not to hinder metal flow during casting.

2.2 MANUAL SAND MOLD PRODUCTION

Sand molds are made by filling sand cast boxes (flask) with sand and letting the sand mixed with binder cure around the cast pattern. See fig. 13 for a overview of a general sand casting process.

2.2.1 *Manual Production of Sand Mold at Oshaug Metall AS*

Sand molds are made manually by filling the flask with sand and letting it cure around the pattern. The sand is manually being compressed around pattern, inlet and feed features not part of the cast pattern, to ensure that there are no unintended voids in the cast mold. After the manual filling of the flask is completed the molds are left to cure.

After curing the cast pattern and other feature patterns are removed and the mold is prepared manually for casting. The mold is visually checked for defects and loose dust and particles are removed. All moisture in the mold is removed by coating the mold with a flammable liquid that is burned off. The flask parts are then mounted together to create the complete mold ready for casting. After casting the sand mold is removed by vibration and recycled. Flasks are then ready for reuse.

2.3 PRODUCTION VOLUME

During daily production at Oshaug Metall AS the production of sand molds varies according to order reserves. On a given day with one workshift cope and drag are constructed for 2-6 propeller blades, 3-8 propellor boss and 3-5 other castings. Number of mold boxes are dependent on cast weight and size of the product. At max capacity the foundry can use three shifts, the capacity increases with about 2,5 times the capacity of one shift. In the planning for a new foundry the target capacity aims at 1500 tonnes per year using one workshift. Production days are estimated to be 225 days per year.

This gives a production capacity per day of 6666 kg of cast products. At present the only material cast is Nickel-Aluminium Bronze.

CRITERIA	LIMIT	MUST	WANT
Dimensional accuracy		X	
Surface quality		X	
Build envelope on par with current mill [mm]	2000*3000*1000		X
Build speed [hours]	32	X	
Build volume [kg]	6666	X	
Handling strength	Material dependant.		X

Table 2: Summary of manufacturing Criteria.

2.4 SUMMARY OF MANUFACTURING CRITERIA

This chapter concerns the present processes and production. However the listed criteria must be regarded as guidelines for the evaluation of the applicability of additive technologies. This is due to differences in for example the degree of automation and unsupervised operation.

Table 2 offers an overview of the criteria and limits that need to be taken into account during the evaluation of Additive Manufacturing (AM) systems in this report.

Part I

ADDITIVE MANUFACTURING OF SAND CAST PATTERN

Additive manufacturing to rapidly produce high quality pattern for sand casting.

3

STATE OF THE ART PATTERN MANUFACTURING

The following table lists system manufacturers offering machines using non-metallic materials. All machines using foundry sand are listed in chapter 6.

3.1 PROCESS FEASIBILITY

Listed in table 3 are system manufacturers offering machines using non-metallic materials. Chinese manufacturers are listed in table 4. All machines using foundry sand are listed in chapter 7. This listing does not include all available printers that use non-metallic materials, only the largest ones. Technologies with a build volume larger than 300*300*300 [mm] are included to cover technologies that may be offered with larger build volumes in the future.

Manufacturers with series of machines in different sizes, where all sizes are above minimum build volume, are listed with only the largest entry of the series. The different manufacturers use different technologies and materials available vary according to technology.

3.1.1 *System Manufacturers of Non-Metallic 3D-Printers*

Overview of the system manufacturers of the systems listed in table 3. This section addresses material and suitability of the different available systems.

3.1.1.1 *Stratasys*

Israeli company Objet and american company Stratasys merged to one company at the end of 2012. Wohlers and Caffrey [42, Page 115] The new company continues to use the name Stratasys.

The Fortus series is based on the material extrusion principle, and is the largest comercially available of the type. Stratasys uses the name Fused Deposition Modeling on their technology. The largest machine, Fortus 900mc can build models in different engineering plastics [31]. For example different types of Acrylonitrile Butadiene Styrene (ABS).

The Eden family of printers uses a material jetting, called Objet Inkjet technology. It can use inkjet-based photopolymers ranging from rigid to rubber like. These 3D-printers resemble normal inkjet printers in appearance and working principle. [30]

COMPANY	MODEL NUMBER	BUILD VOLUME [MM]
Stratasys	Fortus 400mc	405*355*405
Stratasys	Fortus 900mc	915*610*915
Stratasys	Connex500	490*390*200
Stratasys	Eden500V	490*390*200
Stratasys	Objet1000	1000*800*500 [33]
3D Systems	iPro 9000 XL	1500*750*550
3D Systems	ProJet HD 5000	550*393*300
3D Systems	sPro 60 SD, HD, HD HS	381*330*457
3D Systems	sPro 140, HS	550*550*750
3D Systems	sPro 230, HS	550*550*750
3D Systems	ZPrinter 850	508*381*229
EOS	EOSINT P 395	340*340*620
EOS	EOSINT P 760	700*380*580
EOS	EOSINT P 800	730*380*540
Sintermask	Zorro	300*200*800
Aspect Inc.	RaFaEl 550	550*550*500
CMET Inc.	Rapid Meister NRM 6000	610*610*500
CMET Inc.	EQ-1	610*610*500 [2]

Table 3: System Manufacturers currently offering printers that use non-metallic materials. Wohlers and Caffrey [42, Appendix C and D]

Furthermore the Connex series of printers is material jetting system that is multi-material. The machine combines the print materials to produce a wide range of material quality and types. This enables for example rigid parts with rubber details in one print. Objet1000 is the largest of these machines. [33]

3.1.1.2 *3D systems*

American company 3D Systems manufactures a broad selection of machines for the personal, professional and production markets. Relevant machines for this report are found in their selection of professional 3D-printers and machines aimed at direct part manufacturing.

Amongst the professional printers the largest build envelopes offered are the ProJet 5000 and the zPrinter 850. The Projet 5000 is a material jetting system using different photopolymer build materials and wax as support material. A Ultra Violet (UV) curable acrylic plastic is offered as the build material in the ProJet 5000 [35].

The zPrinter 850 is a color 3D-printer using a binder jetting principle to make colored parts. Material offered is a high performance composite with 390000 colors available. [36]

In the production lineup of printers the largest machines offered are the iPro 9000 machines and the sPro 230, with the largest build envelope offered by the iPro 9000 XL machine. The machine uses a vat photopolymerization technology called stereolithography. Offered materials for the stereolithography production printers are a selection of curable photopolymers that can mimic known engineering plastics, for example ABS plastic. The material series are marketed as Accura SLA and RenShape SLA [27].

The sPro 230 is uses a powder bed fusion technology, called Laser Sintering. Materials offered are marketed as DuraForm [27].

3.1.1.3 *EOS*

German company EOS offers powder bed fusion printers. The technology is called Selective Laser Sintering. EOSINT 760 P is the latest offering of their large machines using powdered thermoplastics [14]. EOSINT 800 P is a similar machine that can offer high performance polymers, as one of the first of its kind. [15].

3.1.1.4 *Sintermask*

German company Sintermask offers powder bed fusion technology that they call Selective Mask Sintering. The system flashes an entire layer at the same time and offers a decrease in print time by creating the whole layer simultaneously. [29]

COMPANY	MODEL NUMBER	BUILD VOLUME [MM]
Beijing Long Yuan AFS	AFS700	700*700*500
BLY AFS	AFS500	500*500*500
Beijing Tiertime	A450	350*380*450
Guangzhou Electronic	GIET01-500	500*400*500
Shaanxi Hengtong	SPS600	600*600*400
Shaanxi Hengtong	SPS800B	800*600*400 [20]
Shanghai Uniontech	RS-600S	600*600*500
Trump P. M. Co.	Elite P5500	550*550*610
Wuhan Binhu M & E	HRPS-IV	500*500*400
W B M & E	HRPL-III	600*600*500
W B M & E	HRP-III A	600*400*500

Table 4: Chinese System Manufacturers currently offering printers that use non-metallic materials. Wohlers and Caffrey [42, Appendix D]

3.1.1.5 *Aspect Inc.*

Japanese company Aspect offers powder bed fusion machines, where the RaFaEl 550 currently offers the largest build volume. Materials offered for the system is polyamide, glass-filled polyamide, polypropylene and other plastics. [42, Appendix D]

3.1.1.6 *CMET inc.*

Japanese company CMET offers vat photopolymerization machines. The Rapid Meister 6000 machine and its succesor the EQ-1 [2] uses epoxy and acrylate as the build materials. [42, Appendix D]

3.1.2 *Chinese System Manufacturers*

See table 4 for a listing of chinese system amnufacturers.

3.1.2.1 *Beijing Long Yuan Automated Fabrication Systems*

Automated Fabrication Systems offers machines based on powder bed fusion technology. Their largest non-metallic printer is the AFS700 using materials polystyrene, polypropylene and wax. [42, Appendix D]

3.1.2.2 *Beijing Tiertime Technology Co. Ltd.*

Beijing Tiertime offers machines using the material extrusion technology. Their largest printer is the Inspire A450 using ABS plastic as material. [39]

3.1.2.3 *Guangzhou Electronic Technology Co. Ltd.*

Guangzhou Electronic Technology offers machines based on a vat photopolymerization technology. Their largest system is the GIET01-500 using photopolymer materials. [42, Appendix D]

3.1.2.4 *Shaanxi Hengtong Intelligent Machine Co. Ltd.*

Shaanxi Hengtong Intelligent Machine offers machines based on vat photopolymerization technology. Their largest printers are the SPS600 and SPS800B machines using photopolymer materials. [20] [42, Appendix D]

3.1.2.5 *Shanghai Union Technology Co. Ltd.*

UnionTech offers vat photopolymerization machines in their RS range of machines. Their largest machine is the RS-600S (RS6000) and uses epoxy photopolymer as material. [21] [42, Appendix D]

3.1.2.6 *Trump Precision Machinery Co.*

Trump Precision Machinery offers machines using powder bed fusion technology. The systems can use thermoplastic elastomer, polyamide and polypropylene. The largest machine in the series is the Elite P5500. [3] [42, Appendix D]

3.1.2.7 *Wuhan Binhu Mechanical & Electrical Co. Ltd.*

Wuhan Binhu Mechanical & Electrical offers three different technologies. [42, Appendix D] The HRPS series is a powder bed fusion process with the largest machine being the HRPS-IV using plastic powders for material. [7]

The HRP series uses the sheet lamination technology. The build material is resin coated paper. [5] The HRPL series uses a vat photopolymerization technology. The build material is epoxy. [6] [42, Appendix D]

3.1.3 *Future Concepts and Hybrid Solutions*

Refering to chapter 9 and 14 of this report, systems using metal and sand as build material are offered with a larger build envelope than currently available for the non-metallic systems listed in this chapter. These systems are evidence of scalability of the available technologies.

For the listed state of the art technologies an increase in build envelope increases the potential candidates substantially. Build envelope size criteria limits the candidates to a select few of the available systems. Following this reduction of candidates available materials are also reduced to the materials offered for these currently largest systems.

The currently largest systems suitable for pattern manufacturing are based on vat photopolymerization. Belgian company Materialise[1] has developed an inhouse stereolithography machine, the Mammoth SL. The largest Mammoth SL machine has a build envelope of 2100*700*800mm [22], however they do not sell the systems, only the services of these machines.

A new concept to increase part throughput and decreased machine cost is High Speed Sintering[2]. This technology involves sintering of entire layers in 2D profiles using an infra-red lamp. Compared to a Selective Laser Sintering (SLS) machine, an EOS P360, the production time for 1050 parts was reduced from 59,78 hours to 18,75 hours with High Speed Sintering.[16] This technology is similar to the techniques offered by Sintermask mentioned in section 3.1.1.4.

3.1.3.1 *Mega Scale Additive Manufacturing*

The currently largest applications of AM technology is used in architecture and construction engineering. For example construction engineering projects on large scale automated systems using ceramic materials to build structures and components. *Contour Crafting* is an example of large scale application of AM technology for construction of complete structures and buildings. *Contour Crafting* is a variant of the material extrusion principle where the layer steps are smoothed using a controled side trowel to create the correct contours between layers. [4]

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[1] http://www.materialise.com/

[2] http://www.lboro.ac.uk/microsites/enterprise/e2hs/technology/high-speed-sintering.html

4

ADDITIVE MANUFACTURING PATTERN PROTOTYPE

During the work on this report an experiment with a pattern manufactured additively using a vat photopolymerization process was carried out. See appendix B for the experiment plan.

The goal of this experiment was to establish dimensional accuracy of a 3D-printed prototype pattern and surface quality concerns in regards to sand mold making.

4.1 PROTOTYPE SPECIFICATIONS

The model was ordered as epoxy stereolithography. Choosing epoxy during ordering gives Materialise the choice of selecting the most applicable material for the model to be manufactured. They select the material from their available stereolithography materials. The material chosen by Materialise for the model was Protogen White. Stated accuracy for the process is +/-0,2%(min +/-0,2mm)[1]. See the material selector at Materialise On-Site for the data sheet.[25]

The model is a scaled model of an existing propeller, using a scaling factor of 0,25. Stereolithography was chosen due to available build envelope size and price. Model is printed hollow with an infill pattern of 0,3 mm. Drainage holes were plugged. Finishing was chosen to be minimal, only removal of support structures was performed. This is in line with the experiment goal of finding out the usability of an as printed pattern. Surface quality of the model can be seen in figure 3.

4.2 METHOD

The model dimensions were measured with a CMM-machine to find the dimensional accuracy. See fig. 2 for the measurement setup. The company has no set standard for the minimum accuracy of the patterns. Typical values during control measurements are (+/- 0,5mm). This is for pattern of full size milled in plywood.

The model went through the normal steps for the creation of a sand mold at Oshaug Metal As. The process of making the mold will not be detailed in this report as the mold creation process is not relevant to this experiment and includes core knowledge at Oshaug Metall AS. However a short summary of the process is given in chapter 2.2.

Stated goal of this experiment is to research the impact of pattern surface quality on the sand mold. Creation of the sand mold followed

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[1] https://materialise-onsite.com/en/TechnologySelector/Technologies

the current process of creating the sand mold with no additional steps or further changes.

This was done to observe if the model could be used with no process step changes in current sand mold production. The process steps affecting surface of mold is depicted in fig 4 to 11.

A casting was performed to check surface quality of the cast product.

4.3 RESULTS

4.3.1 *Dimensional Accuracy*

Measuring results. Dimensions on the model differ somewhat from the nominal model. This difference is larger than the stated accuracy of the service provider.

STATED ACCURACY (min +/- 0,2mm)

MEASURED ACCURACY (+/- 1-2mm)

Both the author and the machining manager at Oshaug Metall AS, John Gulla, find the measured difference in accuracy to be too large. There is an order of magnitude difference between stated and measured accuracy.

There may be multiple causes for this. The measurement was taken more than one week after arrival of the model. During this period the model was passed around and handled by multiple individuals at the company, for example during presentation of the experiment plan before execution of this experiment.

This can furthermore be evidence that the material of the printed model is not sufficently geometrically stable for the geometry of this pattern.

4.3.1.1 *Recomended Followup to the Experiment*

Repeat the experiment at a larger scale, for example using a scaling-factor of 0,5.

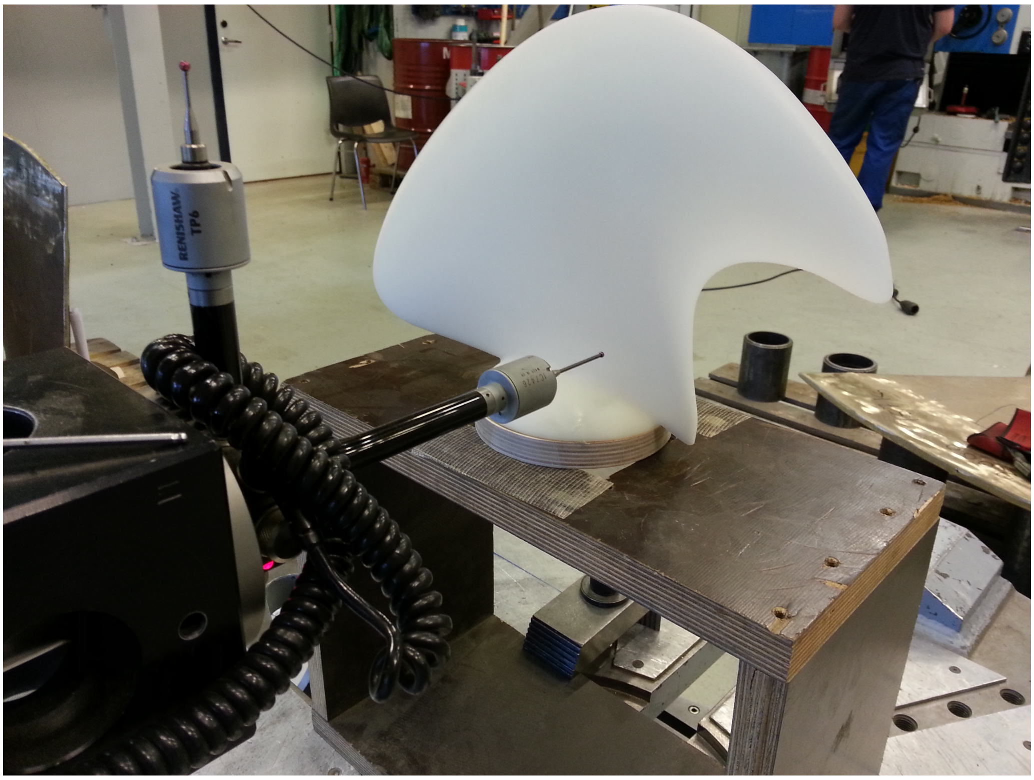
Repetition of the experiment using a different technology, for example material extrusion.

A third option could be to repeat the experiment using a different material.

4.3.2 *Surface Quality*

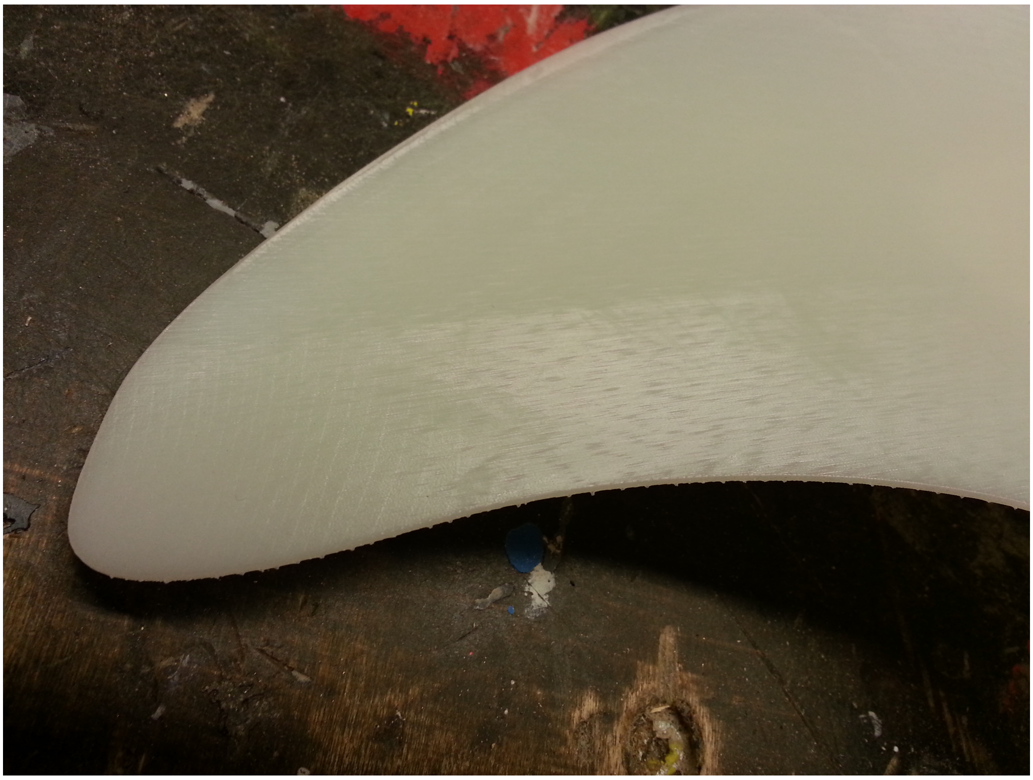
The process steps affecting surface quality can be seen in figure 3 to 12 As can be seen in figure 12, the surface quality is sufficient for direct use as a pattern. Surface quality of the finished part was on par with current methods. The experiment was stopped after casting, normally the cast skin would be machined off before end use.

(a) Appearance of the model upon arrival.



(b) Model being measured for dimensional accuracy.

Figure 2: Measuring of model before casting.



(a) Surface quality of model at the thinnest part.

(b) Surface of pattern.

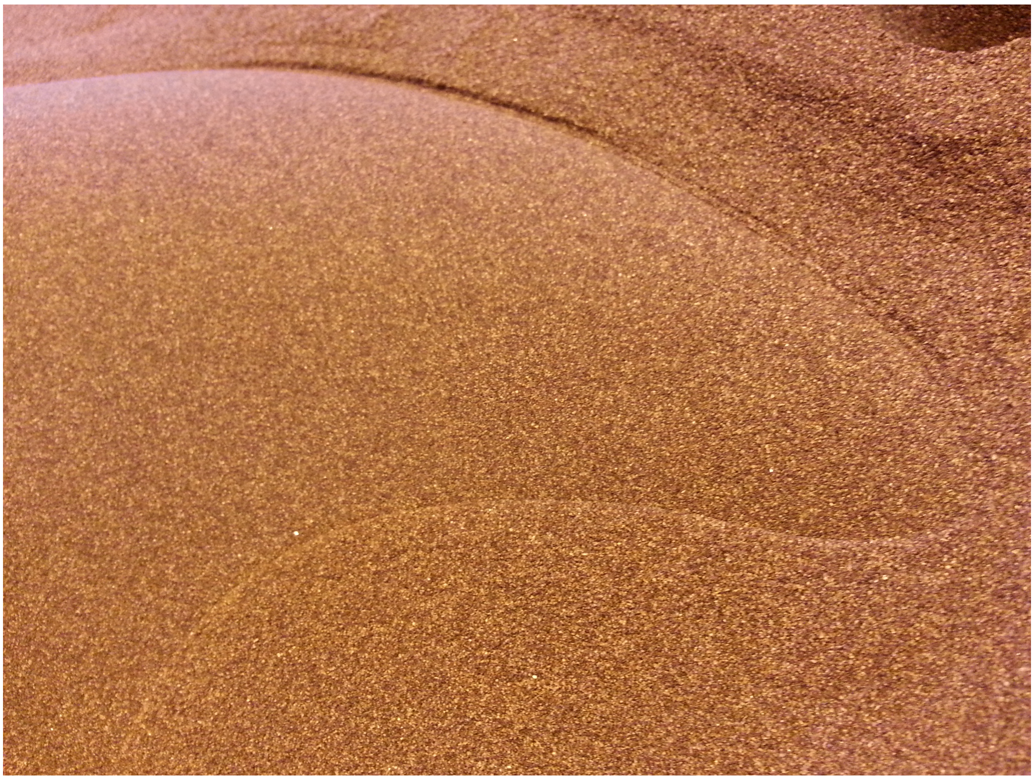
Figure 3: Surface quality of model, some stepping can be seen.

Figure 4: Slip coating to ease pattern removal from mold.

Figure 5: Air Drying of Slip coat.

Figure 6: Creating the cope and drag.

Figure 7: Pattern imprint.



(a) Surface of cope.

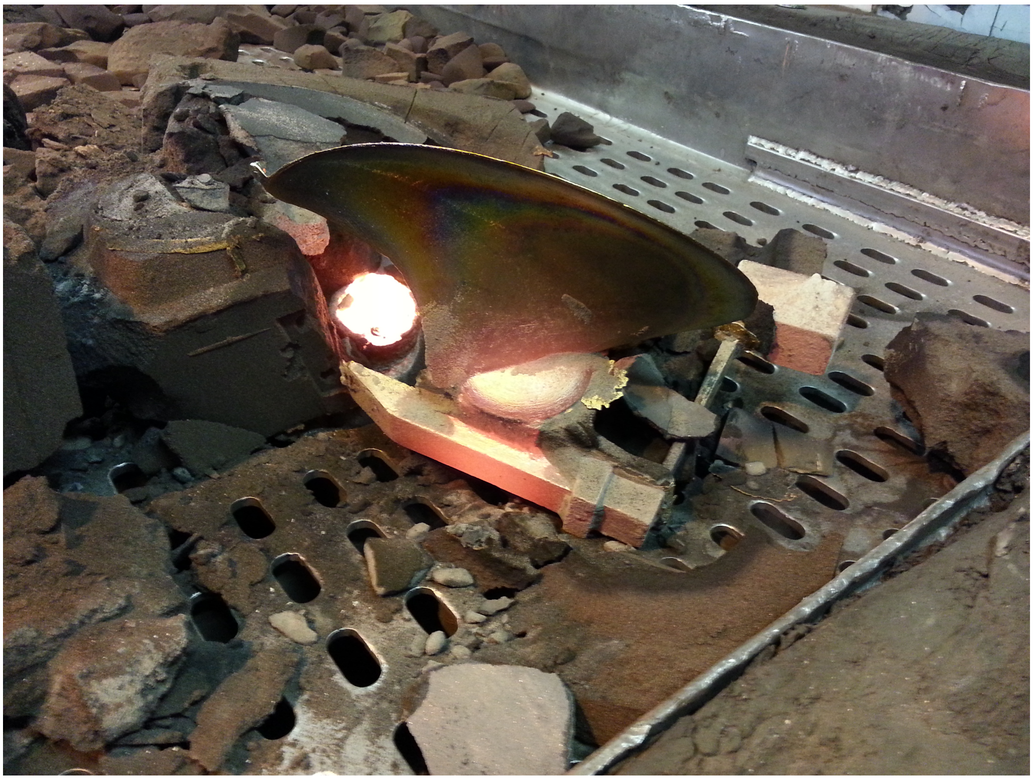
(b) Surface of drag.

Figure 8: No evidence of imprint on either cope or drag.

Figure 9: Coating of the cope and drag.

Figure 10: Burning of residue to remove moisture from mold.

Figure 11: Surface ready to cast.



(a) Resulting Cast.

(b) Resulting Cast with gating system removed.

Figure 12: No evidence of imprint on cast propeller blade.

5

ADDITIVE MANUFACTURING PATTERN SOLUTION

An additive solution for pattern manufacturing needs to meet a strict set of criteria to be a feasable alternative to the pattern manufacturing process employed at Oshaug Metall AS today. The criteria are listed in chapter 2.

This section aims to explore the possible systems and solution approaches possible with additive technologies and associated software. Advantages of the additive processes are highlighted and their suitability for the targeted application is researched.

Known disadvantages are discussed and relevant technical concerns are targeted with regard to an additive manufacturing approach to the construction of cast patterns.

5.1 EXISTING ADDITIVE MANUFACTURING SYSTEMS

Build volume is the main criterion for the systems considered in this report. Selection amongst the systems listed in chapter 3 of this report due to this criterion leaves only the largest systems available. None of the currently available non-metallic systems listed here can offer a build envelope larger than the dimensions of the CNC-mill in use today. See table 3 and 4. However most of the production at Oshaug Metall AS concerns products with smaller dimensions than the maximum dimensional limit listed in chapter 2. AM technologies can offer a more effective solution for the most geometrically complex parts manufactured at Oshaug Metall AS.

Any solution using the systems available requires the use of a modular approach to meet current maximum dimensional criteria. This does not automatically disregard these systems due to the possibility of making all modules in the same build. Production of modules are in line with current production where the pattern is constructed in layers, with the exception being the current possibility to manufacture full length parts. Using a modular approach may also increase the time used during model preparation, and an increase in post-processing time due to the added need for assembly.

Additional applications are relevant for complex products of a smaller scale than max dimensional capacity.

COMPANY	MODEL NUMBER	BUILD ENVELOPE [MM]
Stratasys	Fortus 900mc	915*610*915
Stratasys	Objet1000	1000*800*500 [33]
3D Systems	iPro 9000 XL	1500*750*550

Table 5: The largest printers using non-metallic materials. Wohlers and Caffrey [42, Appendix C and D]

5.1.1 *Suitable System Candidates*

The systems considered here are the largest machines offered based on the different technological principles. Table 5 shows an overview of the systems considered for AM pattern manufacturing. These are the respectively largest systems available for each technological principle. These systems can be aquired as of february 2013, thusly machines where only the products of the machine can be bought are excluded here.

The largest available vat photopolymerization system is the iPro 9000 XL from 3D systems see table 8, the largest available material jetting system is the Objet1000 from Stratasys see table 7 and the largest material extrusion machine available is the Fortus 900mc from see table 6. Build speed of the Fortus 900mc depends on layer thickness and part size. The extrusion principle extrudes build material and support material through a nozzle, and thusly the layer print speed differs by the geometry of the layer. Using a mode with thicker layers increases build speed for the 900mc model. The same goes for the Objet1000 using a material jetting principle, build speed varies by geometry and thickness of layer. For the iPro9000 XL the whole build envelope is swiped each time, and there is no difference in layer build speed in regard to layer geometry.

The largest powder bed fusion machines have a build envelope of around 600*600*600mm for available non-metallic systems. However, powder bed fusion machines are scaled up to a larger build envelope in existing systems using metal powders, foundry sand and wax for investment casting. See chapter 7 for a solution proposal involving large powder bed fusion based systems.

Layer thickness controls surface quality and minimum wall thickness of a part. Surface quality also depends on part orientation.

FORTUS 900MC		
Build speed		Geometry dependant.
Accuracy		+/-0,89mm or +/-0,0015mm per mm
TERMINOLOGY	STANDARD TERM	COMPANY TERM
Technological principle	Material extrusion	Fused Deposition Modeling

Table 6: Excerpt of the system specifications for the Stratasys Fortus 900mc.[17]

OBJET1000		
Build speed		Geometry dependant
Accuracy		0,02-0,085mm for feature below 50mm. 0,3mm for full model size
TERMINOLOGY	STANDARD TERM	COMPANY TERM
Technological principle	Material Jetting	Objet Connex

Table 7: Excerpt of the system specifications for the Stratasys Objet1000.[32]

IPRO9000 XL		
Drawing speed (borders)		3,5m/s
Drawing speed (hatch)		25m/s
Accuracy[mm]		min -0,05 max -0,15
TERMINOLOGY	STANDARD TERM	COMPANY TERM
Technological principle	vat photopolymerization	Stereolithography

Table 8: Excerpt of the system specifications for the 3D Systems iPro9000 XL.[34]

5.2 ADVANTAGES OF ADDITIVE MANUFACTURING SYSTEMS

5.2.1 *Time Consumption for Additive Manufacturing Processes*

Additive technologies offer the possibility for long stretches of unatended operation. In addition, model preparation offers a time reduction since there is no need to set machine tool paths. CAD model preparation listed as process step 1 in the additive manufacturing process overview, will still consume roughly the same time. Time consumption during additive manufacturing processes is handled differently. In table 1 time consumption for pattern production is summed up to a total of 32 work hours included mill time and post-processing.

5.2.2 *Material Utilization and Handling*

Additive technologies have an unchallenged degree of material utilization compared to all material removal based technologies. Material handling issues may be a concern but is highly related to which technological principle is used. Oshaug Metall AS already have extensive experience with powdered materials handling and recycling through the use of sand and binder in daily production. Further discussion on material handling concerns with AM technologies can be found on pages 52 and 53 in the book *Additive Manufacturing Technologies - Rapid Prototyping to Digital Manufacturing*. Gibson et al. [12, p. 52-53].

5.2.3 *Extended Options through Software*

With the geometrical freedom offered by additive manufacturing, new design possibilities become available. A pattern can be constructed with a large degree of empty internal space, filled with a lightweight and material saving lattice structure. Software to automate this process are available. Control programs for slicing of the CAD models and the machine control software can include a feature to control the infill pattern of the printed part. The following are a few of the companies offering software to utilize the new possibilities offered by additive manufacturing technology and their respective software.

WITHIN TECHNOLOGIES: Within Enhance[1].

NETFABB: Selective Space Structures and Netfabb professional[2].

PARAMOUNT INDUSTRIES: Conformal Lattice Structures[3].

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[1] http://www.within-lab.com/

[2] http://www.netfabb.com/

[3] http://www.paramountind.com/conformal-lattice-structures.html

MATERIALISE: Offers a complete software suite for additive manufacturing[4].

5.3 DISADVANTAGES OF ADDITIVE MANUFACTURING SYSTEMS

A disadvantage shared by all additive manufacturing techniques is steps between layers. Steps occur in various degrees on a product depending on the surface slope and part orientation in the machine. A skilled operator can minimize the impact of stepping on a part by orientating the part according to where the most complex surfaces are on a part. Steps can also be removed during post-processing.

Advantages of additive manufacturing are diminished for simple open geometries. Mass production techniques are faster and cheaper for simple geometries. For products where mass customization is key, additive manufacturing can greatly improve efficiency. Additive technologies are best suited to very complex geometries that are either currently hard to accomplish, or previously impossible to manufacture.

Propeller geometry consists of accurate and advanced 3D surfaces. However a cast propeller blade is a massive metal component with no internal features, and this is reflected in the pattern. An additively manufactured pattern solution needs to cover the criteria for the main production at Oshaug, which is a large propeller blade with large curved surfaces and no complex internal cavities.

Current available systems are too small for full length pattern. This can be circumvented by adopting a modular design solution. A modular design introduces an added assembly stage of pattern production. Assembly of the model needs to be solved by either introduction of a new material in the form of a bonding agent or geometrical features like snap fit fixtures. Manufacturing of modules can offer a better utilization of build volume but can also increase build time due to more individual parts needed to be manufactured, resulting in possibly more complete builds to manufacture one pattern.

5.3.1 *Competing Alternatives*

Increasing complexity of product geometry increases the advantages of additive technologies, for simpler geometries traditional material removal technologies should be considered. For the openly curved geometry of the propellers using the existing mill with a foam material could be a faster solution.

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[4] `http://software.materialise.com/`

5.3.2 *Recyclability*

The additive manufacturing systems ideally use only the material it needs to build a part. Some material might be stuck to the part, for example partly sintered material. Unused material during production can be reused for the next build and should be resubmitted to the machine. Other sources for extra material use include the use of support structures during part construction. These are removed in post processing.

Recyclability of used models differ by available materials. Nylon materials can be recycled, but not as easily as some of the other more common thermoplastics such as ABS or the polycarbonates used in material extrusion machines. The thermoset polymers used for example in vat photopolymerisation processes cannot be recycled. Gibson et al. [12, p. 382]

5.3.3 *Additive Manufacturing on Demand*

Companies like Materialise, Voxeljet, ExOne and Shapeways offer additive manufacturing as a service. Service like this was used for the prototype ordered for the experiment in chapter 4.

Part II

ADDITIVE MANUFACTURING OF SAND MOLD

Additive manufacturing of sand molds without the need to construct patterns, resulting in ready to cast sand molds.

6

STATE OF THE ART SAND PRINTING

As to the nature of sand casting molds some technologies for AM are immediately discarded as not applicable solution to the task. However some technologies are well suited, and indeed are already available, for making sand cast molds. Powder bed based and powder binder printing processes present themselves as the technologies with the largest build volumes available.

For this state of the art listing all available machines which use sand as build medium are considered. This is due to the limited number of available machines, and the relevance to the casting industry. For an overview of available systems sorted by build volume, see table 9.

The technologies use loose sand around the work parts as support. Some post-processing to remove loose sand may be required. The main differences in the technologies are how the machine binds the sand. For an overview of the different technology grouping see page 61.

6.1 PROCESS FEASIBILITY

For the direct printing of sand molds a selection criteria based on current pattern production will be used.

6.1.1 *System Manufacturers of Foundry Sand Systems*

This section concerns the various manufacturers of the systems listed in table 9. Material type and layer build principle are covered for all the largest available additive manufacturing systems.

6.1.1.1 *Beijing Long Yuan Automated Fabrication Systems*

Chinese company Beijing Long Yuan Automated Fabrication Systems offers a series of laser sintering machines that can use powdered sand as a medium. Available materials, according to AFS, are Casting PS, Wax, Casting Sand, Polystyrene [19].

6.1.1.2 *Voxeljet*

German company Voxeljet technology GmbH offers a series of machines using a binder jetting principle. Voxeljet offers the only machine that is larger than the current pattern mill dimensions listed on page 3. The entire series of machines use the same materials, PolyPor-

COMPANY	MODEL NUMBER	BUILD VOLUME [MM]
ExOne	S-Print	750*380*400
ExOne	S-Max	1800*1000*700
Voxeljet	VX200	300*200*150
Voxeljet	VX500	500*400*300
Voxeljet	VXC800	850*450*continuous
Voxeljet	VX1000	1060*600*500
Voxeljet	VX4000	4000*2000*1000
EOS	EOSINT S 750	720*380*380
Beijing Long Yuan AFS	LaserCore 700	700*700*500
Beijing Long Yuan AFS	LaserCore 500	560*560*500

Table 9: System Manufacturers currently offering printers that use sand as build material. Wohlers and Caffrey [42, Appendix C and D]

PMMA and Sand. [37] The PolyPor-PMMA materials are used for investment casting.

6.1.1.3 *ExOne*

American company ExOne offers two different machines, where the largest one is the second biggest machine available that uses sand as the build medium. The technology is based on binder jetting. The foundry sand is mixed with a binder component and spread over the work area. A second part of the binder material is sprayed selectively on the work area and binds the sand together. Both machines can use Quartz and speciality sands.[8]

6.1.1.4 *EOS*

German company EOS GmbH offers a laser sintering machine using foundry sand as build medium. EOS offers the use of different croning sands typically used in foundries and offers optimized sand mixture for use with their DirectCast application. [13]

7

SAND MOLD PRINT SOLUTION

Additive technologies offer a pattern free manufacturing of sand cast molds. AM sand printed molds need no additional tooling and are ready to be used in casting after removal of unused sand during printing.

7.1 ADDITIVE MANUFACTURING SOLUTION

A solution outline for future production must meet the build volume criteria and the capacity needs of the daily production. For an overview see table 2. However, most of the products manufactured at Oshaug Metall AS is of a smaller scale than their geometrical limit. A solution proposal taking this fact into account is also considered.

7.1.1 *Model Preparation*

A 3D CAD-model of the casting mold, consisting of a cope and drag and possibly more parts, needs to be constructed. This is done in current production to simulate casting and placement of risers, gating system and chill blocks.

7.1.2 *Software Solutions*

In addition to the CAD-model of the cope and drag that is made today a scripted approach to the CAD-model generation could be used. Usage of scripting could reduce the time needed to construction the CADgeometry needed. The scripts could also generate riser and gating systems. Furthermore this approach combined with AM technology could enable idealized flow geometries to be constructed in the sand mold. For example software like OpenScad[1] could be used to create scripts for automatic generating of the cope and drag boxes.

To take into account the need for chill block placement, modular construction and correct pattern geometry.

7.1.3 *Sand and Binder Selection*

All the manufacturers considered for this application use commercially availabe foundry sand. Print material compatibility with the sand and binder used in current production needs to be researched

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[1] `http://www.openscad.org/`

COMPANY	MODEL NUMBER	BUILD ENVELOPE [MM]
Voxeljet	VX4000	4000*2000*1000
Voxeljet	VXC800	850*450*continuous
ExOne	S-Max	1800*1000*700

Table 10: The largest printers using foundry sand. Wohlers and Caffrey [42, Appendix C and D]

for the available systems. In this report an experiment for pattern production was prioritized in an effort to research the usability of an additive manufacturing process. See chapter 4 for the performed experiment. This experiment could be repeated with a printed mold by one of the companies offering sand printing as a service. See section 7.4 in this chapter for a list of the manufacturers offering the printed products as a service.

7.1.3.1 *Recyclability of Printed Sand*

Unused sand during printing is removed and reentered into the system for reuse.

7.2 PROPELLER PRODUCTION

Voxeljet VX4000, see table 10 is the largest and only available system meeting todays geometrical limit. Other machines are disregarded for this application as the need for modular production would lead to the need of multiple machines to meet production capacity. A solution including applications of smaller and more complex products are covered in section 7.3 of this chapter.

The machine can operate 24/7 with a team on call during weekends. As mentioned in chapter 5, the geometry of propeller blades might be too simple in this regard for an additive manufacturing system to be the most effective solution.

The possibility to make sand molds in one piece, or ready to cast modular sections, can offer improved efficiency for products that need a separate pattern manufactured. 3D-printing of sand molds provides a patternless production of the molds.

7.2.1 *Disadvantages*

Print speed of the sand molds compared to manual filling of boxes counts againts additive manufacturing. The time used for printing a sand mold can be higher than todays manual sand mold production time, due to the fact that the sand print approach is patternless. Still,

VX4000	
Build speed	14,5 mm/h = 116 l/h
Layer thickness	0.12-0,30mm
TERMINOLOGY	STANDARD
Technological principle	Binder jetting

Table 11: Excerpt of the system specifications for the Voxeljet VX4000.[40]

VXC800	
Build speed	35 mm/h = 18 l/h
Layer thickness	0,30mm
TERMINOLOGY	STANDARD
Technological principle	Binder jetting

Table 12: Excerpt of the system specifications for the Voxeljet VXC800.[41]

S-MAX	
Build speed	59 400 to 165000 cm^3/h
Layer thickness	0,28mm-0,50mm
TERMINOLOGY	STANDARD
Technological principle	Binder jetting

Table 13: Excerpt of the system specifications for the ExOne S-Max.[38]

some of the production today uses permanent inverted pattern boxes for propeller designs that are made in larger series. These production volumes operate separate from the designs needing a customized pattern. The propeller blade shape allows for an automated alternative using a mill in a filled sand mold box to achieve the same result as a 3D-printed sand box.

Geometrical complexity of the propeller blade is simple enough for rapid manual production of the molds. This diminishes the advantages of an additive approach which is faster for very complex products. Furthermore, the relatively high production volume and size of the products would likely need multiple machines for adequate production capacity. Production capacity concerns are reduced somewhat by the company projecting a new foundry and can take the matter into concideration at an early stage.

7.2.2 *Unused Material*

Unused loose sand can be easily removed through gaps already present due to risers and other necessary features of metal casting. Unused sand is reintroduced to the machine for reuse. Recyclability of used sand cores needs to be checked for compatibility of the existing facilities at Oshaug Metall AS, or possibly the need for a separate system.

7.3 ADDITIVE MANUFACTURING SOLUTION FOR CASTING OF BOSS AND OTHER PRODUCTS

7.3.1 *Propeller Boss and Other Products*

Suitable candidates for this application is the Voxeljet VX4000 see table 11, the ExOne S-Max see table 13 and the Voxeljet VXC 800 see table 12. These are the two largest available systems using sand as build material and the only machine that uses a continous approach. See table 10 for a size comparison of the three systems.

Additive manufacturing offers the possibility for very complex product and prototype production. This can offer new possibilities in regard to realizing new designs with large amounts of undercuts and cavities in a shorter time. New market opportunities can emerge from the ability to manufacture geomtrically complex prototypes in NiAl-Bronze with a patternless approach. This allows a higher degree of designer freedom and iteration due to the removed cost of complex pattern manufacturing. Added to this is the ability of AM processes to reproduce geometries previously impossible to achieve with material removal processes. No need for tooling and a pattern furthermore gives production engineers the ability to ideally design a mold in regard to riser, gating and chill features.

The molds and core boxes can be made in the same machine simultaneously. The machines build speeds are not affected by the area of material that needs bonding.

The high degree of automation enables 24 hour operation 7 days a week of the additive manufacturing system. Interchangable build trays makes this continous operation possible. The new continous concept of the VXC 800 enables an even more uninterupted approach to mold production. The whole build area can be used for any combination of different products. The time used for pattern manufacturing can largely be used for printing the mold. Exception to this is the stages of model preparation that still needs to be carried out, and the possibility of increased model preparation time due to the need for an increased digital accuracy. See appendix A for the list of additive manufacturing process steps.

7.3.2 *Disadvantages*

Capacity problems competing with manual production. Milling in a sand box might be a feasible solution. For the patternless approach the CAD-model must include a 100% representation of the geometry including metal contraction- and machining allowance.

7.4 NEW POSSIBILITIES

Using 3D-printed sand molds open possibilities to construct large prototypes of new products. New research opportunities into new geometries and rapid production of different pattern geometries in one machine. The system manufacturers Voxeljet[2] and ExOne[3] also offer the products from their systems as a service.

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[2] http://www.voxeljet.de/en/services/products/voxeljet-services/

[3] http://exone.com/materialization/services

Part III

ADDITIVE MANUFACTURING OF LARGE METAL PARTS

Direct manufacturing of high quality metal parts with ideal geometry.

8

STATE OF THE ART DIRECT MANUFACTURING OF LARGE METAL PRODUCTS

Direct manufacturing of metal parts with additive manufacturing processes. Metal parts production with additive manufacturing technologies is an area of interest mainly for industrial use. Consumer availability of metal parts production does exist, but material choice is limited. Industrial activity and research into metal parts production and usable materials is increasing. Titanium alloys have received alot of attention. Copper alloys in additive manufacturing are being researched, mainly for use in heat exchanger applications.

8.1 DIRECT MANUFACTURING OF LARGE METAL PRODUCTS

This section concerns direct manufacturing of large scale additively manufactured large metal products.

8.1.1 *Selection Criteria and Definition*

In this report the focus is set on large metal products. In the interest of exploring large scale direct metal printing a selection criteria build volume of at least 300mm cubed or a 300mm+ z-axis has been used for the following process listing. See table 14. This criteria exludes technologies mainly used for small scale products and parts, but still includes available technologies for larger products. Technologies that use metals in printing of electronics with build volumes larger than this exclusion criteria are discarded as the intended use of the technology does not apply to the focus of this report.

8.1.2 *System Manufacturers of Metallic Printers*

This is an overview of the manufacturers of metal printing systems listed in table 14.

8.1.2.1 *Optomec*

American company Optomec uses the term LENS-Laser Engineered Net Shaping for their technology, which is a directed energy deposition technology. The largest offering with this technology is the LENS 850-R, using powdered metals. [26]

COMPANY	MODEL NUMBER	BUILD VOLUME [MM]
Optomec	LENS 750	300*300*300
Optomec	LENS MR-7	300*300*300
Optomec	LENS 850-R	1500*900*900
POM	DMD505D	863*863*609
POM	DMD105D	300*300*300
POM	DMD 44R	1950*2140*330°
POM	DMD 66R	3200*3665*360°
POM	DMD IC106	800 reach 6-axis robot
Sciaky	VX.2-60*60*60	720*380*380
Sciaky	VX.4-110*110*110	2032*1016*1524
Sciaky	VX.4-300*108*132	6299*1372*1473
Irepa	VC LF 300	400*350*200
Irepa	VH LF4000	650*700*500
Irepa	VI LF4000	950*900*500
Irepa	MAGIC LF 6000	1500*800*800
Concept Laser	M3 Linear	300*350*300
EOS	EOSINT M 280	250*250*325
ReaLizer	SLM 250	250*250*300
ReaLizer	SLM 300	300*300*300
Arcam	A2	200*200*350
	A2	Ø300*200
	A2XX	Ø350*380
InssTek	MX-3	1000*800*650
InssTek	MX-4	450*450*350

Table 14: System Manufacturers currently offering large build volume systems that use metal as build material. Wohlers and Caffrey [42, Appendix C and D]

8.1.2.2 *POM*

POM manufactures machines using a process they call Direct Metal Deposition (DMD) which is a directed energy deposition process. The systems are mounted on 6-axis industrial robots for the largest systems. The smaller systems are 5 axis based cnc machines. [42, Appendix C]

8.1.2.3 *Sciaky*

American company Sciaky is a welding company that offers a direct manufacturing technology they call Electronic Beam Direct Manufacturing (EBDM) a direct energy deposition technology. Thes systems are based on mounting the material deposition head on a moving platform like an industrial robot. [42, Appendix C] [28]

8.1.2.4 *Irepa*

French company Irepa Laser offers a directed energy deposition process which they call Construction Laser Additive Directe (CLAD). The system is based on the deposition head mounted on a 5-axis controlled system. [42, Appendix C]

8.1.2.5 *Concept Laser*

German company Concept laser offers a line of powder bed fusion machines using metal powders. [42, Appendix C]

8.1.2.6 *EOS*

German company EOS offers a powder bed fusion machine using metal powders. Amongst the powdered materials are bronze powders. [42, Appendix D]

8.1.2.7 *ReaLizer*

German company Realizer offers a series of powder based fusion machines they call Selective Laser Melting offering for example aluminium alloys, steel and others. [42, Appendix D]

8.1.2.8 *Arcam*

Swedish company Arcam offers advanced machines using a powder bed fusion technology using a electron beam to fuse the metal powders instead of the more common laser offerings. They call their technology Electron Beam melting (EBM). Materials offered are various high-end alloys. The model with the largest build envelope the A2XX uses titanium powder as build material. [1]

8.1.2.9 *InssTek*

South Korean company InssTek offers a directed energy deposition system using powdered metals. [42, Appendix D]

8.1.2.10 *Future Technology and Hybrid Systems*

Japanese company Matsuura hybrid metal CNC and 3D-printer, the Lumex Avance-25[1]. This system works by printing 10 layers, and then machining the contours of these layers before continuing. This gives metal parts that are accurate and with a good surface finish right out of the machine. Currently the build envelope is W250*D250 [mm] with a travel of (XYZ) 260*260*100 [mm]. [23]

Fraunhofer Additive Manufacturing Alliance[2] runs research projects in the fields materials, technology, engineering and quality. Special interst for this report is Fraunhofer ILT researching copper for metal printing. Companies are starting to offer bronze and copper alloys for some applications. For example Materialize[3] has started to offer bronze as a printable material.

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[1] http://www.matsuura.co.jp/english/contents/products/lumex.html

[2] http://www.generativ.fraunhofer.de/en/profile.html

[3] http://i.materialise.com/materials/bronze

9

DIRECT MANUFACTURING OF LARGE METAL PRODUCTS

9.1 DISCUSSION ON METAL PARTS

In Wohlers Report 2012 a overview of AM usage in different fields lists marine applications in a category with other industries, including Oil and Gas. The category totals 5,3% of the additive manufacturing usage in the industry today. Additionaly a survey detailing what all additive manufacturing systems are used for, lists that 19,2% was used for direct part production. Wohlers and Caffrey [42, p. 18]

The currently largest obstacle for widespread use of metal parts manufactured by additive technologies for direct use is a lack of standards. Committee F42 on Additive Manufacturing Technologies [1] was formed in 2009 and have so far made 4 different international standards concerning additive technologies.

The following four standards are publicized as of February 2013 by Committee F42. [9]

- F2792 Standard Terminology for Additive Manufacturing Technologies
- F2915 Standard Specification for Additive Manufacturing File Format (AMF)
- F2921 Standard Terminology for Additive Manufacturing–Coordinate Systems and Nomenclature
- F2924 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion

It is expected that new standards are in development. As of february 2013 the following subcomittees have proposed new standards[2].

- Subcomittee F42.01-Test Methods, have proposed three new standards.
- Subcomittee F42.04-Design, have proposed three standards.
- Subcomittee F42.05-Materials and Processes, have proposed fifteen new standards.

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[1] http://www.astm.org/COMMITTEE/F42.htm

[2] http://www.astm.org/COMMIT/SUBCOMMIT/F42.htm

9.1.1 *Testing Methods and Systems*

Following the lack of standards are testing systems for 3D-printed objects. Reproducable results and proper testing systems are needed for printed metal parts to be accepted in conservative engineering fields operating in hazardous environments.

Proved repeatability and consistency in the additive manufacturing process needs to be documented before they can be used in hazardous environments. As system manufacturers continue to develop machines with better control systems and increased build envelopes, non destructive testing tailored for additive manufacturing to produce data on a parts could possibly be included in the post-processing stage. For direct metal parts there is at present no applications suitable to improve the production at Oshaug Metall AS.

Marine metal products need to be classified for hazardous and corrosive environments and are subject to strict control and standards. Standards on tribology and corrosion for additively made materials are needed for any widespread use of submerged products. The Nickel-Aluminium Bronze alloy is selected for marine use due to its excellent corrosion and strength properties. Any additively manufactured part needs to meet or exceed the rigid demands that are set on the alloys used in marine environments today.

9.1.2 *Materials*

There is alot of material research and interest in the additive manufacturing of metal parts. Currently available metals for additive manufacturing include stainless steels, titanium, nickel-alloys and aluminium powders.Wohlers and Caffrey [42, Appendix E: Material Properties]

9.1.3 *Microstructures*

Additive manufacturing processes creates new microstructure in metal parts. This expands the need for established standards before any widespread use of direct metal part production.

9.1.4 *Direct Metal Part Usage Today*

3D-printed metal parts have been used succesfully in for example medical and aerospace applications where lightweight structures and biocompatibility are key factors. Metals with known biocompatibility, like titanium have been used in surgery applications.

9.2 DIRECT METAL PARTS PRODUCTION AT OSHAUG METALL AS

Direct metal printing of parts is not likely to affect Oshaug Metall AS in a market perspective due to the above stated reasons. However there is some activity concerning propeller repair at the company. This repair is performed by cutting of the damaged part of the propeller and welding on a new replacement part.

Metal printing processes can be used for automated repairs. Recommendations on metal parts 3D-printing technology for Oshaug Metall AS is to observe developments in this field of metal based 3D-printing applied to automated repair systems.

Part IV

ADDITIVE MANUFACTURING OF LARGE PRODUCTS CONCLUSION AND RECOMMENDATIONS

Discussion and Conclusion.

10

CONCLUSION

This report has looked at the technical possibility and feasibility of using additive manufacturing in different parts of the production at Oshaug Metall AS. The following is conclusions to the different approaches and recommendations for further work. A logistical and economical analysis of the systems recomended is recommended as the next step in addition to the recommendations concerning further work on the different approaches explored in this report.

10.1 PART I: ADDITIVE MANUFACTURING OF SAND CAST PATTERN

The systems found suitable for this application are the material extrusion based Fortus 900mc, vat photopolymerization based iPro 9000 XL and the material jetting based Objet1000. These are based on three different principles and have different materials available.

An experiment was carried out where a vat photopolymerisation machine was used to 3D-print a pattern. The results from this are that the surface quality is sufficient for use as pattern. Accuracy of the model differed more than stated by the system provider. No firm conclusion can be made as to the reason for this. A repeat of the experiment with a different material is recommended.

To further research these systems experiments should be carried out for the extrusion based machine and the material jetting system to map out which of the suitable systems are the most applicable for pattern manufaturing.

10.2 PART II: ADDITIVE MANUFACTURING OF SAND MOLD

This part conclusion covers two possible applications for the technology. The suitable systems found are the VX4000, VXC800 and the S-Max.

For production of sand molds used for propellor blade manufacturing only the VX4000 is large enough to meet the size criteria. However alot of the products manufactured at Oshaug Metall AS are of a smaller size than the mximum limit. Therefore the three systems can be applied for parts of the production.

Recommended further work includes research into the compatibility of sand and binders used in these systems with the current and future sand and binder used at Oshaug Metall AS.

An experiment should be carried out to research the suitability of these sand molds with casting of Nickel-Aluminium Bronze, by ordering a sand mold from one of the companies offering the products from the above systems as on demand services.

10.3 PART III: ADDITIVE MANUFACTURING OF LARGE METAL PARTS

No suitable systems was found for this application as of february 2013. The main obstacle found for this is the lack of standards and testing methods required for end use of AM metal parts in hazardous environments in the marine industry.

Part V

APPENDIX

A

APPENDIX A

Additive manufacturing technologies and 3D printing are relative new technologies and there exists alot of different technologies and terms describing the various existing technologies and variations.

The basic principle for all the technologies are that they build a physical object by joining layers of material using automated systems for delivery of these materials. This document gives an overview and description of terms and technologies referenced in this thesis.

A.1 OVERVIEW 3D-PRINTING

3D-printing, Additive manufacturing and rapid prototyping are just a few of the many terms describing the layer based approach of building and manufacturing products. 3D-printing uses a digital CAD model for the product geometry. To create the physical model, material is deposited in different ways to create layers that bind together to form the finished product. For all the additive technologies we can set up eight steps common to all categories of AM as listed in Gibson et al. [12, Chapter 3]. The following is a list of the eight steps.

1. Conceptualization and CAD
2. STL convert
3. File transfer to machine
4. Machine setup
5. Build
6. Remove
7. Post-Process
8. Application

A.1.1 *File Formats*

3D printers and rapid prototyping systems uses file formats where a CAD model cut into layers. Different file formats exist where stl has been the most used and the de facto industry standard. Increasing possibilities and demands in the industry calls for a new format that includes information about color, texture and future innovations in the additive manufacturing field.

A.1.1.1 *STL*

3D Systems native stereolithography format. The format describes the surface of a three-dimensjonal object as a tesselation of triangles. Contains no information on colors, textures and other features applicable to CAD models. This format has been the industry standard the last three decades.

A.1.1.2 *SLC*

Stratasys own format for their fused deposition modeling technology. The format describes the countours on, and the thickness of, each build layer.

A.1.1.3 *AMF*

amf-standard comittee f.42 additive format including colors etc. [10]

A.1.2 *Categorization of Technologies*

The main difference between the technologies for 3D-printing are how the layers are made and what materials are used. Different systems for sorting the technological principles exist.

In Gibson et al. [12] the technologies are split into seven categories and many other sorting systems exist. Service providers and system manufacturers refer to their respective technologies with their own definition. For manufacturer listings company provided description is added. This report follows the categories and definitions listed in F42.91 [11]. These categories are listed in the following section.

A.2 STANDARD TERMINOLOGY

ASTM Comittee F42 have released a terminology standard on additive manufacturing. The following is a technology grouping structure that is used in this report. For convenience and accuracy the following are the standard definitions quoted as written in *Standard Terminology for Additive Manufacturing Technologies*.[11]

A.2.1 *Binder Jetting*

> An additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials. [11]

A.2.2 *Directed Energy Deposition*

An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. [11]

A.2.3 *Material Extrusion*

An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice. [11]

A.2.4 *Material Jetting*

An additive manufacturing process in which droplets of build material are selectively deposited. [11]

Overview of AM technology categories.

A.2.5 *Powder Bed Fusion*

An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. [11]

A.2.6 *Sheet Lamination*

An additive manufacturing process in which sheets of material are bonded to form an object. [11]

A.2.7 *Vat Photopolymerization*

An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated photopolymerization. [11]

APPENDIX B

B

B.1 PROTOTYPE ADDITIVELY MANUFACTURED PATTERN

Construction of an additively manufactured pattern to observe the impact of process factors related to the layer based building of products. The experiment aims to research and expose advantages and possible problem areas by using additive processes to construct a pattern for advanced casting procedures.

Casting of Nickel-Aluminium Bronze is a difficult and advanced process due to the metallurgical behaviour of the alloy. These processes are not covered by this report as they are the core knowledge at Oshaug metall AS. Present day pattern production is described in 2.

Experimental scale model of a propellor blade, printed in plastic.

B.1.1 *Experiment setup*

A scale model of a complex propellor blade supplied by Oshaug Metall As has been prepared for printing by conversion to STL-format. The propellor blade model was chosen due to it being a finished blade with existing measurements of the finished blade. This gives an excellent control for accurate comparison of the different pattern construction techniques. The printed bladepattern will be a uniformely scaled model of the real blade by a known scaling factor. The following are requirements for the experimental pattern.

A. Plastic type, strength and cost.

B. Dimensional accuracy of pattern as printed without post processing.

C. Aesthetic appearance of experimental pattern as printed.

D. Minimum size and scale of pattern to suit both printing and casting process to be used in experiment.

E. Process choice, guided by material choice and cost.

B.1.1.1 *A*

For this experiment material is selected by availability of large build volume and price. At Materialise [1] they provide services to print large scale products in various plastic types. Their online ordering system

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[1] http://www.materialise.com/

gives an discount for direct online ordering. Shapeways [2] offers larger volume with laser sintered nylon (Polyamide PA 2200). Models in the nylon material are priced by volume, and larger models get a volume discount within certain rules. The most flexible and fastest solution is delivered by materialise.

B.1.1.2 *B*

Dimensional accuracy will be measured as the first stage of the experiment. This is not expected to be a problem. Problem areas concerning dimensional accuracy is related to material creep during building and material warping due to internal stresses.

B.1.1.3 *C*

The model will be used in promoting the company after the end of the experiment. Aesthetic apperance as printed is therefore a factor. With a small layer thickness, this should not be a concern for a model of this scale. If necessary model can be coated with a clear coat after the experiment to keep as printed aesthetics.

B.1.1.4 *D*

This report concerns the use of AM technologies for large products. The model also needs to be large enough for a proper cast to be performed with the model as pattern. Other concerns for AM technologies like layer thickness and minimum wall thickness is of minor importance for this model. Limiting factors are build volume of readily available service providers for printing, and minimum size for a castable pattern.

B.1.1.5 *E*

For this experiment process choice is mainly guided by available technology, price and material selected. Processes are generally concidered because a promoted ability to manufacture models sufficient size for this experiment. Build size rules defined elsewhere are not taken in to account for this experiment. This is due to the prototype being a scale model of a fullsize propellor blade.

B.2 EXPERIMENT PLAN

Experimental setup using Materialise [3] online ordering. Suggested progression plan assuming all stages and processes are feasible economically and logistically.

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[2] `http://www.shapeways.com/materials/strong-flexible/`

[3] `http://www.materialise.com/`

1. Upload model, selection of material and appearance characteristics.
2. 4-5 days model print time.
3. Shipping to Norway form Materialise production facilities in belgium.
4. Upon arrival model should be ready for experiment directly.
5. Documentation of model as delivered.
6. Control of model dimensions.
7. Production of sand cast mold.
8. Documentation of sand mold and 3D print model effects on sand mold.
9. Casting of blade.
10. Documentation of finished cast and end results.
11. Results are included in the report.

C

APPENDIX C

Metal sand casting is a broad field with its own terminology. This appendix covers a listing of some of the casting terminology used in this report.

C.1 METAL CASTING TERMINOLOGY

PATTERN A model of the part you want to cast.

MOLD MATERIAL Material the mold is made of. For example sand and binder.

COPE Upper half of the mold

DRAG Lower part of the mold

FLASK The box around the mold.

CORE For example a sand core representing a cavity in the finished casting.

RISER AND FEED Supplying the cast with metal during cool down contraction.

CHILL BLOCKS Metal parts placed in the mold to control solidification.

CONTRACTION ALLOWANCE Extra volume of metal to supply the cooling and contracting metal.

MOLD CAVITY The cavity left after removal of the pattern.

GATING SYSTEM Control of metal flow from the pouring basin to the mold cavity.

POURING CUP OR BASIN Where the molten metal is poured into the mold.

PARTING LINE Line between the cope and drag.

PARTING AGENT Chemical to ease the removal of the pattern from the sand.

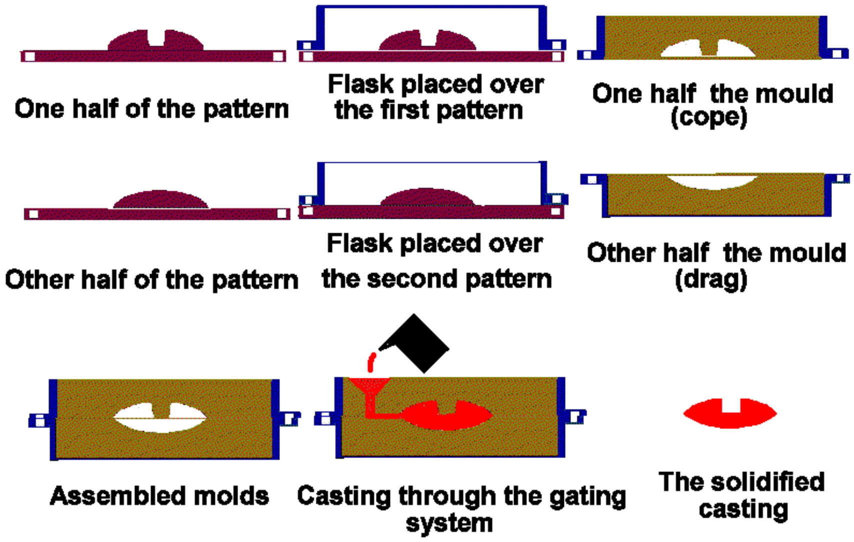

Figure 13: Overview of a general sand casting process.

C.2 PRODUCTION TERMINOLOGY

Sintering - bonding (fusion) of compacted metal powder at temperature lower than melting, but sufficient for bonding. Kalpakjian and Schmid [18, p. 685]

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DECLARATION

I declare that the work presented here is, to the best of my knowledge and belief, original and the result of my own investigations, except as acknowledged, and has not been submitted, either in part or whole, for a degree at this or any other University.

Formulations and ideas taken from other sources are cited as such. This work has not been published.

Trondheim, February 2013

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