

Direct Metal Laser Sintering (DMLS) of Titanium Alloys

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ABSTRACT

Direct Metal Laser Sintering (DMLS) is an additive laser melting technology that can be used for manufacturing functional metal components and tools in various alloys including light metal alloys, high grade steels, stainless steels and nickel and cobalt based super alloys. The DMLS method has been utilized many years in prototyping applications in various industries, including medical and aerospace industries. During recent years the main emphasis has been to qualify DMLS in manufacturing applications.

The paper reviews the latest results of the Ti-based materials development work done with EOSINT M270 laser sintering machine. Material characterization and testing of laser processed Ti alloys are discussed and compared with standardized materials. Specific requirements for powder materials used in the process are described.

developed. Laser is one of the most critical components in an EOSINT M laser sintering machine. The early machines used CO2 lasers and it was a technical limit for the ability to develop new materials and processes. The latest generation of EOSINT machines use fibre lasers which allows the development of a whole new range of metal alloys like stainless steels, cobalt and nickel based superalloys, light alloys like aluminium and titanium, precious metals and even refractory metals.

In the beginning, many different terms were used for the basically same layered manufacturing principle. EOS chose the term DMLS to emphasize the fact that in DMLS only metal powders are used and the manufactured part consists only of metal. However, even DMLS is somewhat misleading because the process is full melting. During recent years the term Additive Manufacturing (AM) has gained more popularity and seems to be forming as an industrial standard.

INTRODUCTION

DMLS was introduced in 1995 and it was the first commercial process for direct processing of metal powders. The main target was already then to manufacture net shape metal parts for industrial use. The first alloy was a proprietary bronze based alloy with specially designed metallurgy. Chris Bocking describes the beginning of DMLS very well in his article in The Laser User [1].

Since the early days the technology has been dramatically further

ADDITIVE MANUFACTURING – THE PRINCIPLE

All additive manufacturing methods utilize the same main principle. Two-dimensional layers are manufactured and stacked to create three-dimensional parts. How this is done in practice depends on the hardware and process used. Picture 1 shows the EOS way to do this. The parts are created on top of the building platform. The dispenser platform is the metal powder reservoir. The

recoater system is used to distribute thin layers of powder on the building platform. Laser scanning is used to 'weld' the metal particles together to create a two-dimensional structure. The two-dimensional layer is simultaneously also fixed to the previous layer. The result is a fully dense three-dimensional object.

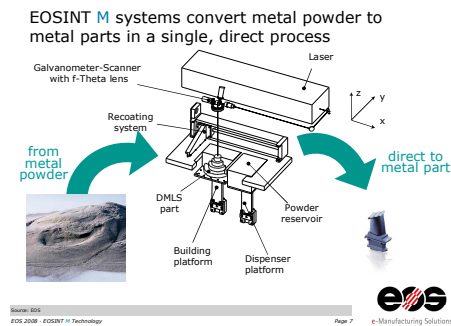


Figure 1. Schematic description of the DMLS process.

ADDITIVE MANUFACTURING – THE ADVANTAGE

The main driving force for the introduction of layered manufacturing was the greatly increased freedom in design. This was recognized first in manufacturing of prototype parts. Product development departments enjoyed the easiness in modifying designs, removing much of the manufacturing constraints and being able to produce new designs as well.

All this led to formation of a new type of industry, rapid prototyping. New companies started to manufacture rapid prototyping equipment, software and materials. Prototype manufacturing companies improved their services.

However, the real benefit is in manufacturing. By utilizing the increased freedom in design it is possible to gain real cost reductions. This can be done at least in two different ways:

1. Additive manufacturing of complex parts. The cost

reduction can be for example much lower raw material consumption because additive methods have very little waste; or improving the efficiency of the manufacturing process chains by automation

2. Increasing efficiency in the final process by using additive manufacturing parts. Typically these solutions consist of internal or surface structures which are impossible to manufacture by conventional means. Some examples of these solutions include increased fuel efficiency in engines, and biomedical and catalytic effects on surface structures.

Figure 2 shows a case study where many of the additive manufacturing advances were gained in a single part. Many of the features in the part are very difficult to manufacture by conventional means. Being able to produce the part hollow allows as much as 57% weight reduction compared to the corresponding bulky design. In addition, the manufacturing cost of the DMLS part is estimated to be about 90€ whereas the machined one costs about 400€.



Figure 2. Ti64 part. One section removed to reveal internal structure. Courtesy of HIPP medical AG.

DMLS ALLOY DEVELOPMENT

DMLS is essentially a laser welding process with the difference that instead of joining prefabricated parts, in DMLS a full three-dimensional structure is formed using single weld lines. As a result, the structures of the DMLS parts differ from conventionally manufactured ones. The main emphasis in EOS metal material R&D is to work with customers to match the material properties of EOS materials and conventional commercial materials so that full equivalence is reached.

Figures 4, 5 and 6 show typical structures of DMLS metal parts in "as-processed" and various heat treated conditions. Figure 3 shows an as-processed structure where the individual weld lines are clearly visible.

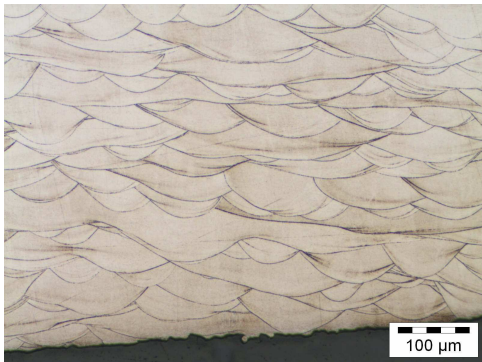


Figure 3. Nickel based superalloy in as-processed condition.

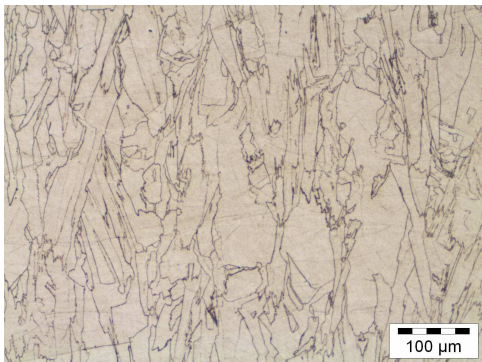


Figure 4. Nickel based superalloy in double-aged condition.

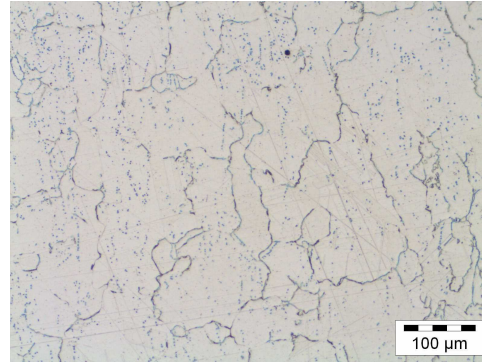


Figure 5. Nickel based superalloy in solution annealed condition.

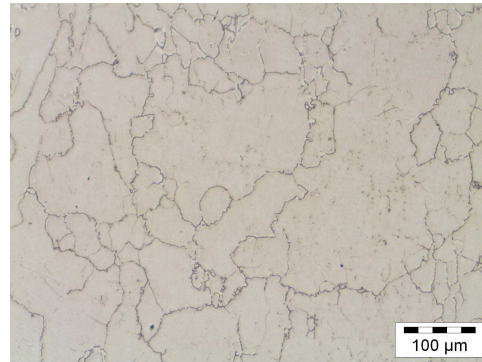


Figure 6. Nickel based superalloy in solution annealed and double aged condition.

The difference between the conditions can be seen clearly. Solution annealing changes the structure completely towards a more conventional one. Also, if aging is performed on an as-processed structure, the end structure shows much finer grain structure compared to the more "conventional one" (figures 4 and 6).

Because of the relatively short history of DMLS it is not yet fully understood what the advantages and disadvantages of the slightly different structure are in different uses. Most of the leading companies in demanding industries, such as aerospace and medical, are studying them internally. Unfortunately very little information is available in public domain.

DMLS OF TITANIUM

Being relatively expensive material, Titanium is a perfect candidate for DMLS. Very little waste and the ability to create structures very difficult for conventional methods together suggest that DMLS is a cost effective manufacturing method.

Due to the layered manufacturing principle, the structure of additively manufactured Titanium is somewhat different of cast or wrought ones. Grains tend to grow along the build axis to columns, many times taller than what the layer thickness. This is characteristic to additive methods and can thus be seen in other materials as well. Figure 7 shows an optical micrograph of EOS Ti64 sample. The columnar grains are visible. The figure includes also some measurements of the column width.

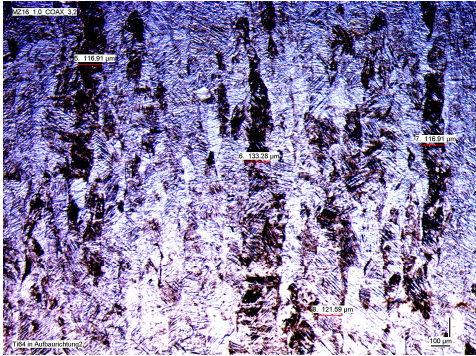


Figure 7. Optical micrograph showing columnar grains. Build direction pointing up. Etchant Weck's reagent.

Figure 8 shows the EOS Ti64 structure perpendicular to the build direction (xy plane). This time the sample has been etched with Kroll's reagent. The same columnar grains are clearly visible, now from above.

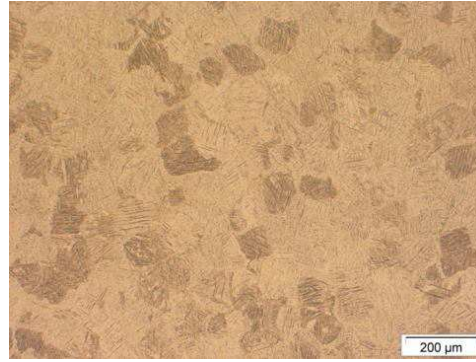


Figure 8. Etched EOS Ti64 sample. Build direction pointing toward the observer. Etchant Kroll's reagent.

MECHANICAL PROPERTIES

The critical properties of the DMLS processed parts are routinely measured both internally and also using certified laboratories. All incoming powder batches are quality assured and recorded. Instead of concentrating in the actual powder properties such as particle size distribution and chemical composition, EOS controls also the performance of all batches in a laser sintering machine. The chosen values are then declared to customers. Thus, by using released parameters and EOS certified material critical part properties are guaranteed.

Table 1 shows a tensile strength measurement of one powder batch in as-processed condition. The table includes also the same properties after three different heat treatments.

	UTS [MPA]	R _{0.2} [MPA]	A25 [%]
As manufactured	1127	1020	9.8
1h at 750°C	1036	983	10.2
1h at 800°C	1022	975	12.5
1h at 850°C	982	919	12.8

Table 1. Tensile properties of EOS Ti64 in selected conditions.

As described earlier, DMLS is essentially a laser micro welding process. Like all thermal processes also DMLS creates some residual thermal stresses in the bulk material. The lower strength and slightly increased ductility listed in Table 1 may indicate lower residual stress after the respective heat treatments.

The temperatures in Table 1 are higher than what normally is considered as stress relief for Ti64. Therefore a further microscopy study was performed to clarify if the microstructure is changed during the heat treatment. Figures 9, 10 and 11 show the microstructure after 1h in 750°C, 800°C and 850°C, respectively.

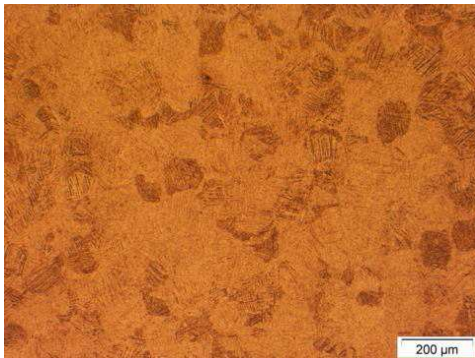


Figure 9. EOS Ti64 after 1h in 750°C. Etchant Kroll's reagent.



Figure 10. EOS Ti64 after 1h in 800°C. Etchant Kroll's reagent.



Figure 11. EOS Ti64 after 1h in 850°C. Etchant Kroll's reagent.

Comparison between the microstructures in Figures 8, 9, 10 and 11 shows that no significant changes in the structure occur in 1h at 750°C. The ductility has slightly increased. The 1h at 800°C shows small changes in the structure and slightly larger change in ductility. After 1h in 850°C the microstructure looks different and the heat treatment should no longer be considered as stress relief only.

CONCLUSIONS

DMLS has shown its capability in producing extremely complex three-dimensional parts. The Ti64 material created in the process fulfills the main international standards. Many of the leading companies in the high entry level industries such as medical and aerospace industries are working internally to qualify DMLS as a manufacturing method.

REFERENCES

1. Chris Bocking, How materials science helped develop metal laser sintering: a brief history, The Laser User, Issue 55, Summer 2009.



Direct Metal Laser Sintering of Titanium Alloys

Titanium 2010
October 4-6
Orlando, FL, USA

Olli Nyrhilä
EOS

Content

- EOS Presentation
- Definition of Laser Sintering
- Definition of e-Manufacturing
- EOS Laser Sintering Systems
- EOS Metal Materials
- Selected EOS Ti64 properties
- Selected Case Studies
- Conclusions



EOS was founded in 1989 - worldwide market leader since 2002 for laser-sintering systems

EOS History

1989

Founding EOS GmbH - Electro Optical Systems
Pilot customer BMW.

2002

Worldwide market leader for laser-sintering systems,
the key technology for e-Manufacturing™.

2009

60 Mio. € Revenue in FY 2008/2009
Approx. 300 people

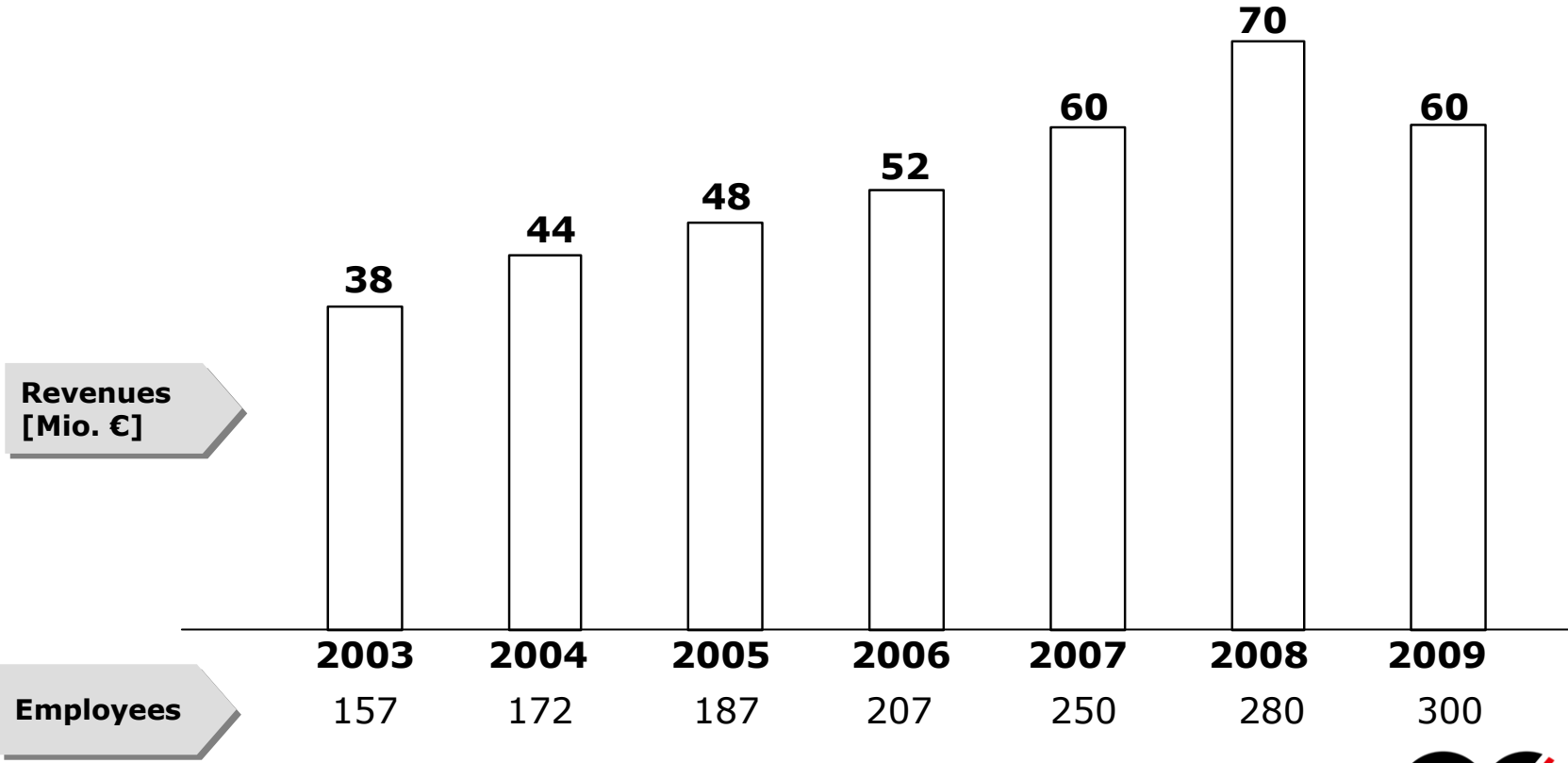
Philosophy

Application oriented solutions for numerous industries
Technology leader for high-end Rapid Prototyping, Rapid
Tooling and Rapid Manufacturing Systems.
Joint solutions with customers.



In the crisis of 2009 EOS still had a good stand – All set for future growth

EOS gross revenue and employees [2003 - 2009]

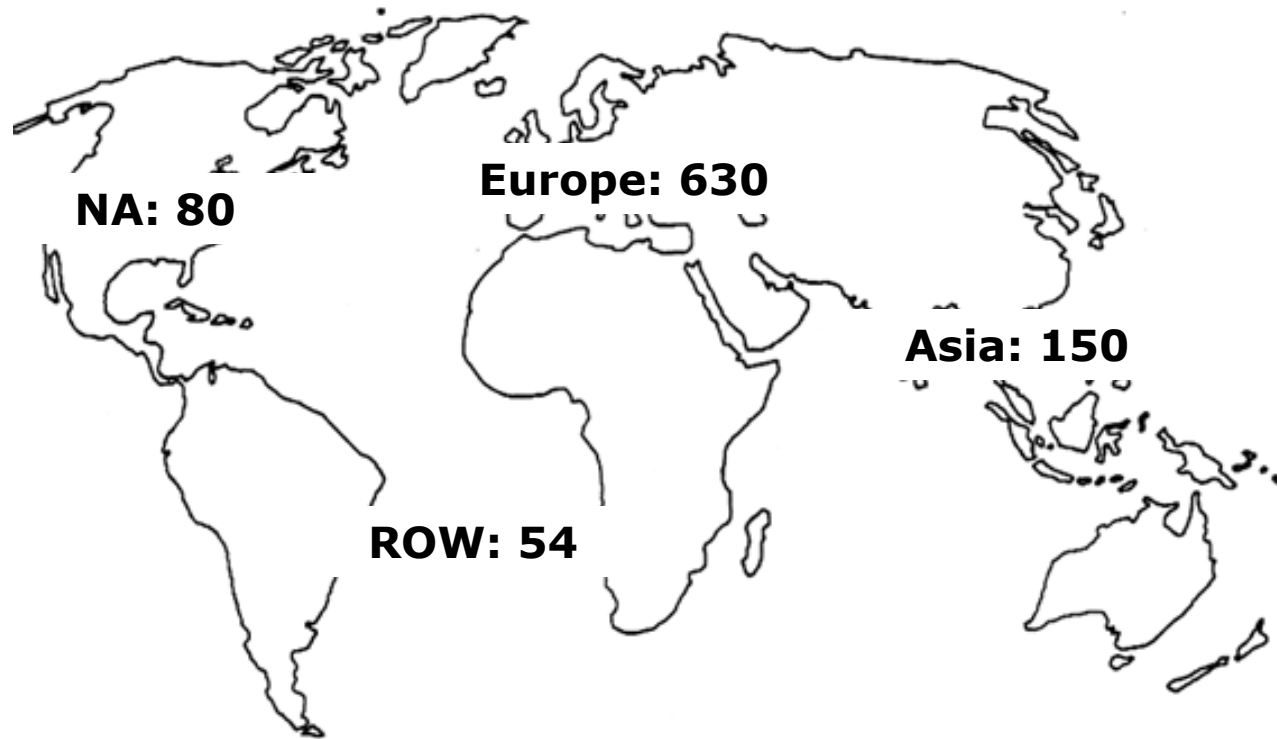


Source: EOS



EOS is the worldwide market leader with an installed base in global key regions

EOS worldwide 2010 – > 900 systems installed



Customers from various industries all over the world rely on EOS technologies

Sample EOS customers (incomplete)

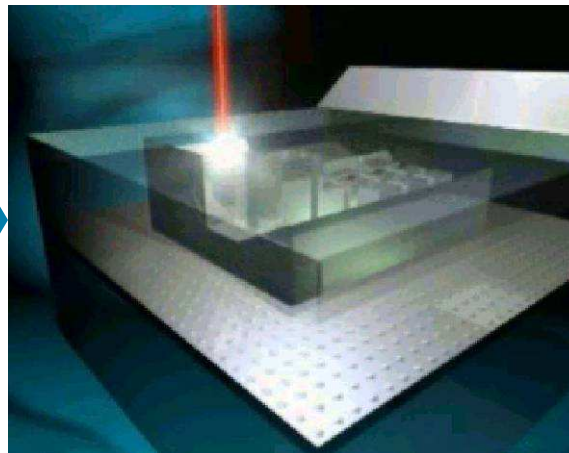


Definition of Laser-Sintering

"A family of methods which manufacture solid parts by solidifying powder-like materials layer-by-layer by exposing the surface of a powder bed with a laser beam"



Powder

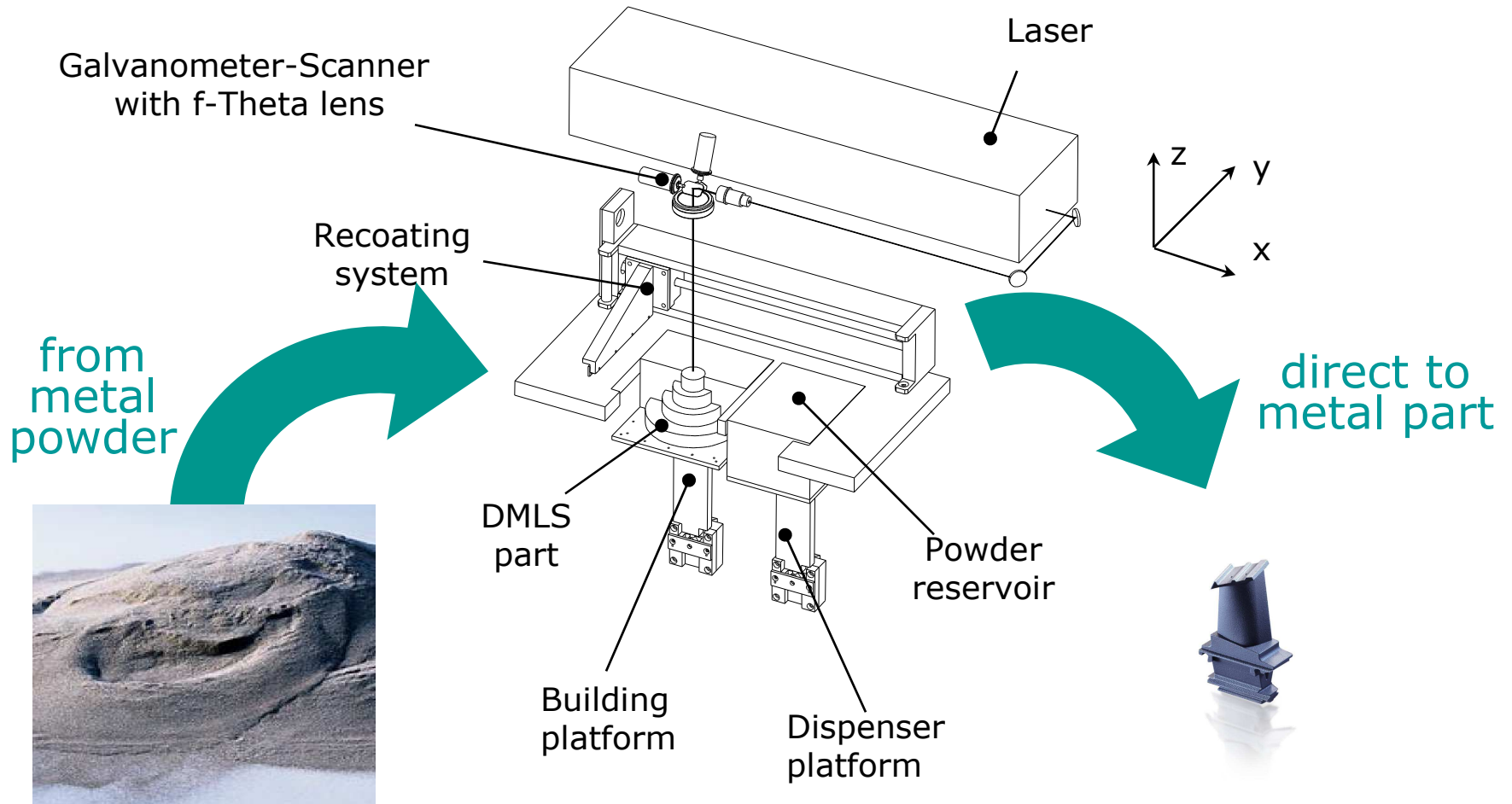


Laser-Sintering



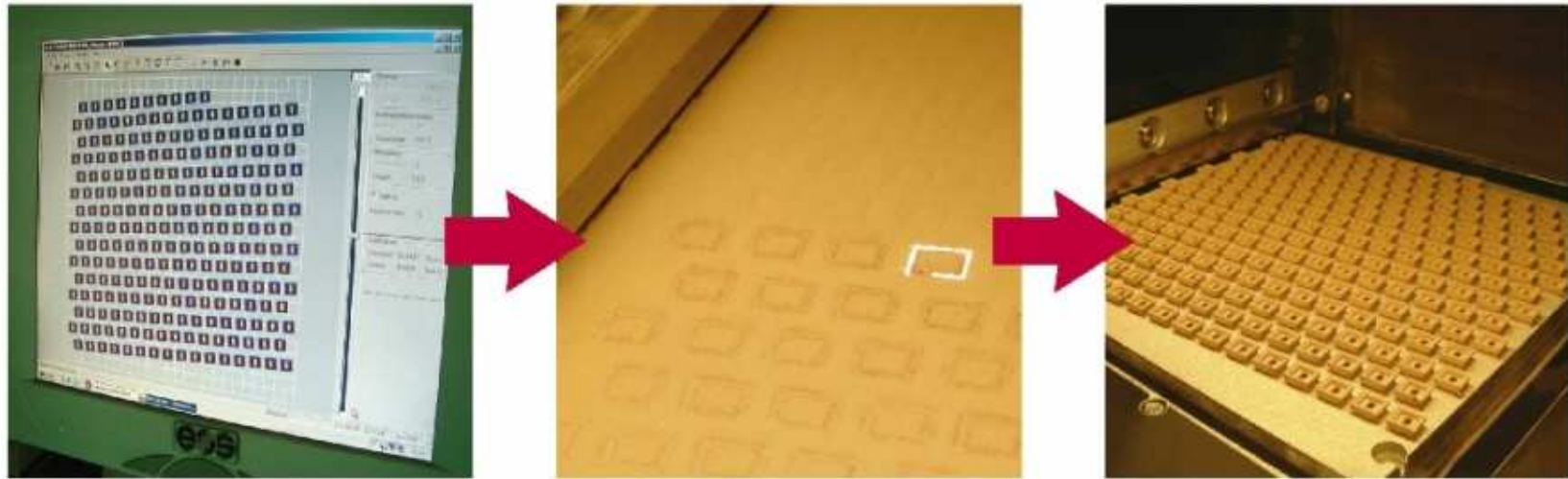
Part

EOSINT M systems convert metal powder to metal parts in a single, direct process



e-Manufacturing means the fast, flexible and cost efficient production directly from electronic data

e-Manufacturing process



From 3D Data ...

... to laser-sintering ...

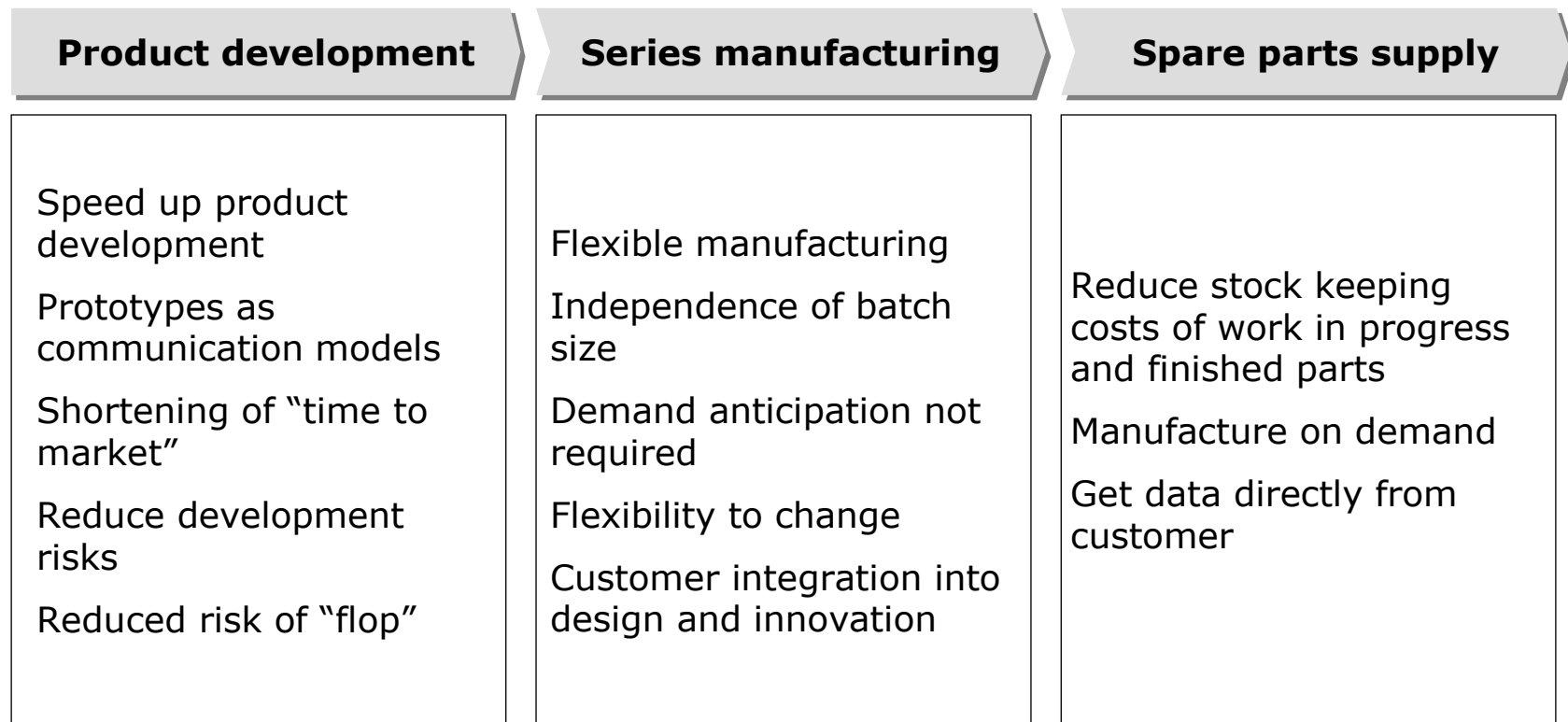
... to the final product

Laser sintering allows increased freedom in design



Laser-sintering can be the manufacturing method during the entire life-cycle

Laser-Sintering in the product life cycle



EOS offers the most modern laser-sintering systems for plastics in the market

EOS plastics laser-sintering product line



EOSINT P 760



EOSINT P 395



FORMIGA P 100

Pictures not scaled

Source: EOS



e-Manufacturing Solutions

The EOSINT M 270 for the direct laser-sintering of metal is a market leading system

EOSINT M 270



**150 M 270
operated
worldwide**

The EOSINT S 750 is used for laser-sintering croning moulding material

EOSINT S 750

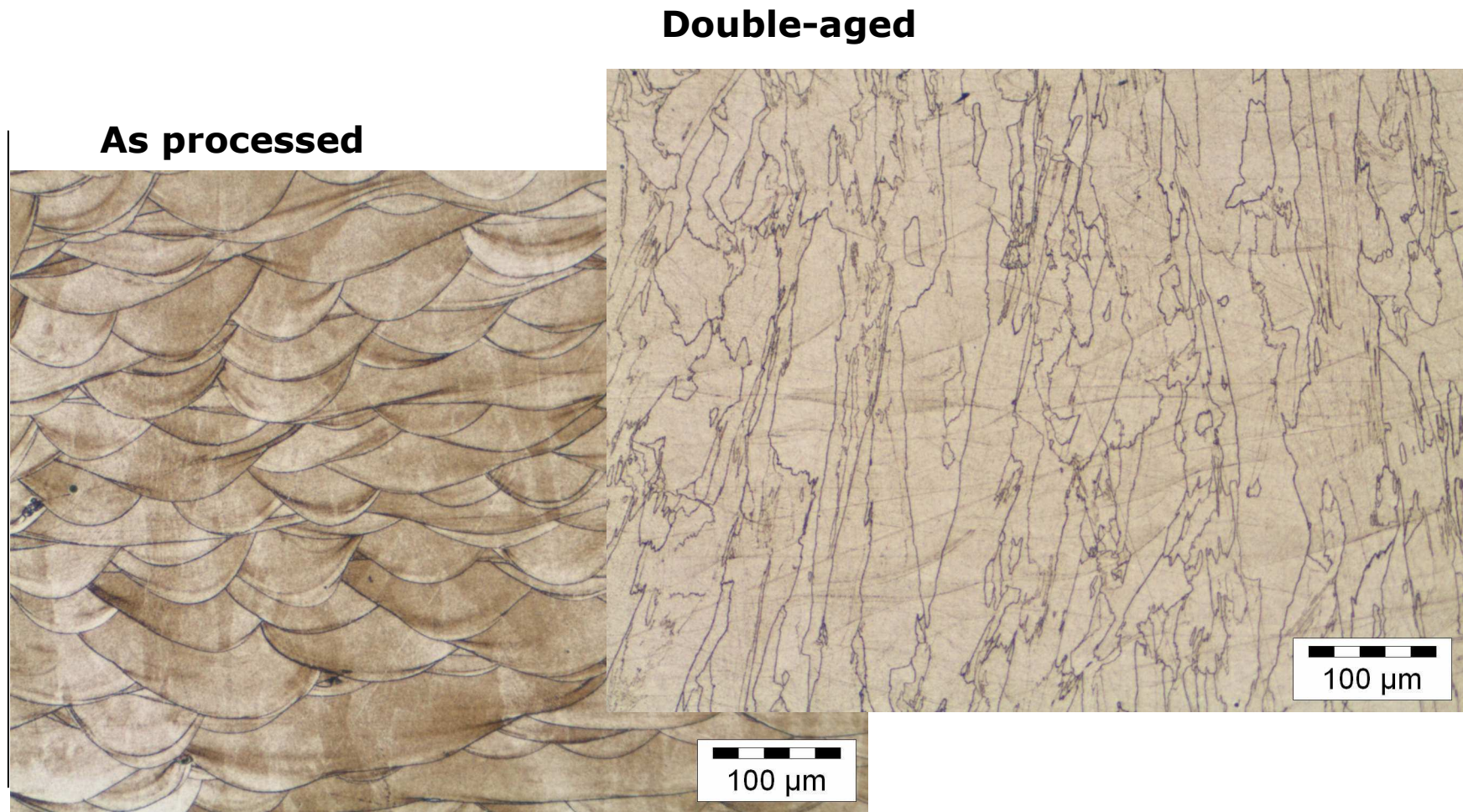


EOS metal powder materials for EOSINT M systems

Material name	Material type	Typical applications
EOS MaragingSteel MS1	18 Mar 300 / 1.2709	Injection moulding series tooling; engineering parts
EOS StainlessSteel GP1	Stainless steel 17-4 / 1.4542	Functional prototypes and series parts; engineering and medical
EOS StainlessSteel PH1	Hardenable stainless 15-5 / 1.4540	Functional prototypes and series parts; engineering and medical
EOS NickelAlloy IN718	Inconel™ 718, UNS N07718, AMS 5662, W.Nr 2.4668 etc.	Functional prototypes and series parts; high temperature turbine parts etc.
EOS CobaltChrome MP1	CoCrMo superalloy	Functional prototypes and series parts; engineering, medical, dental
EOS CobaltChrome SP2	CoCrMo superalloy	Dental restorations (series production)
EOS Titanium Ti64	Ti6Al4V light alloy	Functional prototypes and series parts; aerospace, motor sport etc.
EOS Aluminium AlSi10Mg	AlSi10Mg light alloy	Functional prototypes and series parts; engineering, automotive etc.
DirectMetal 20	Bronze-based mixture	Injection moulding tooling; functional prototypes



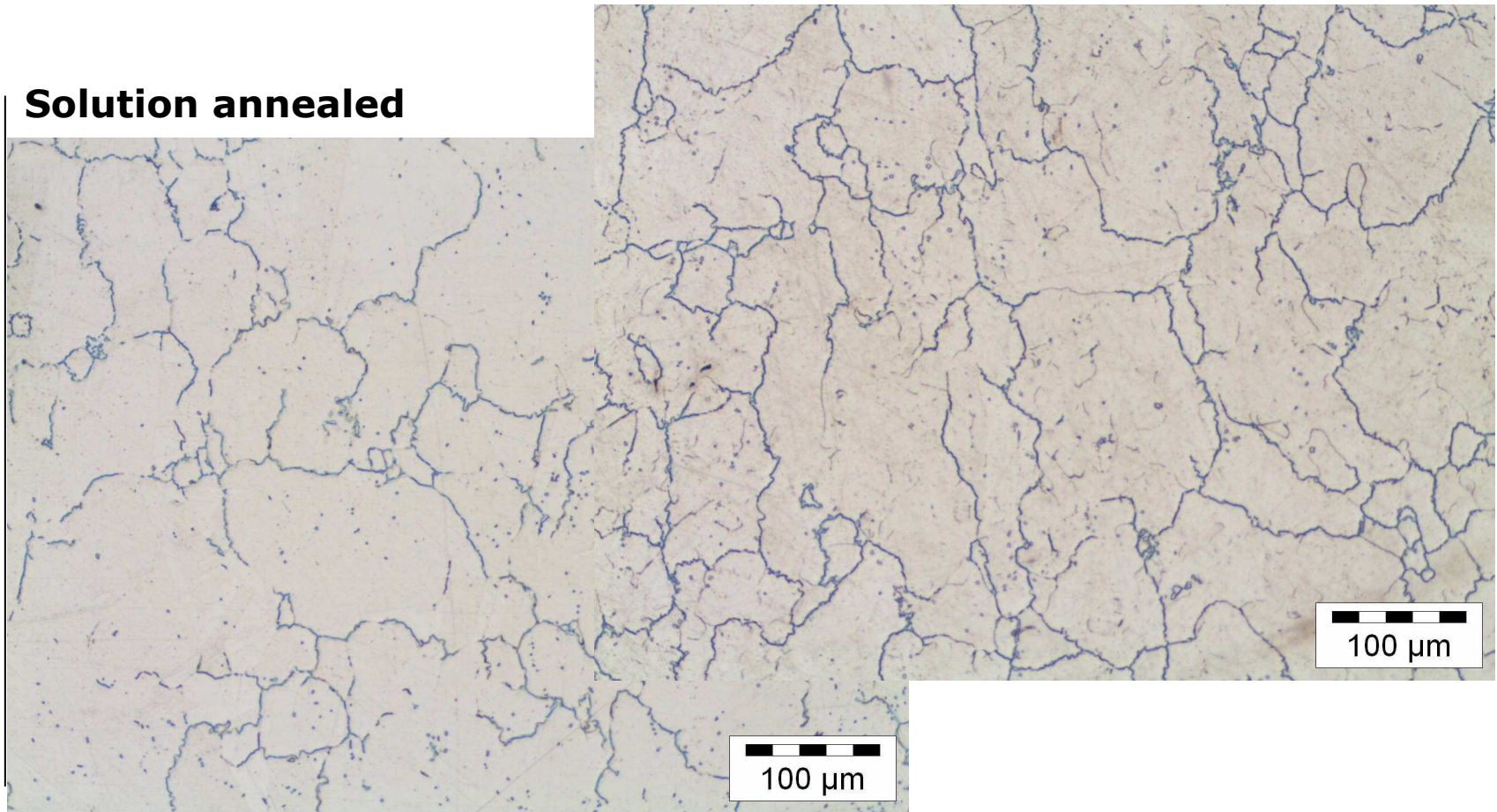
Structure of DMLS HX parts



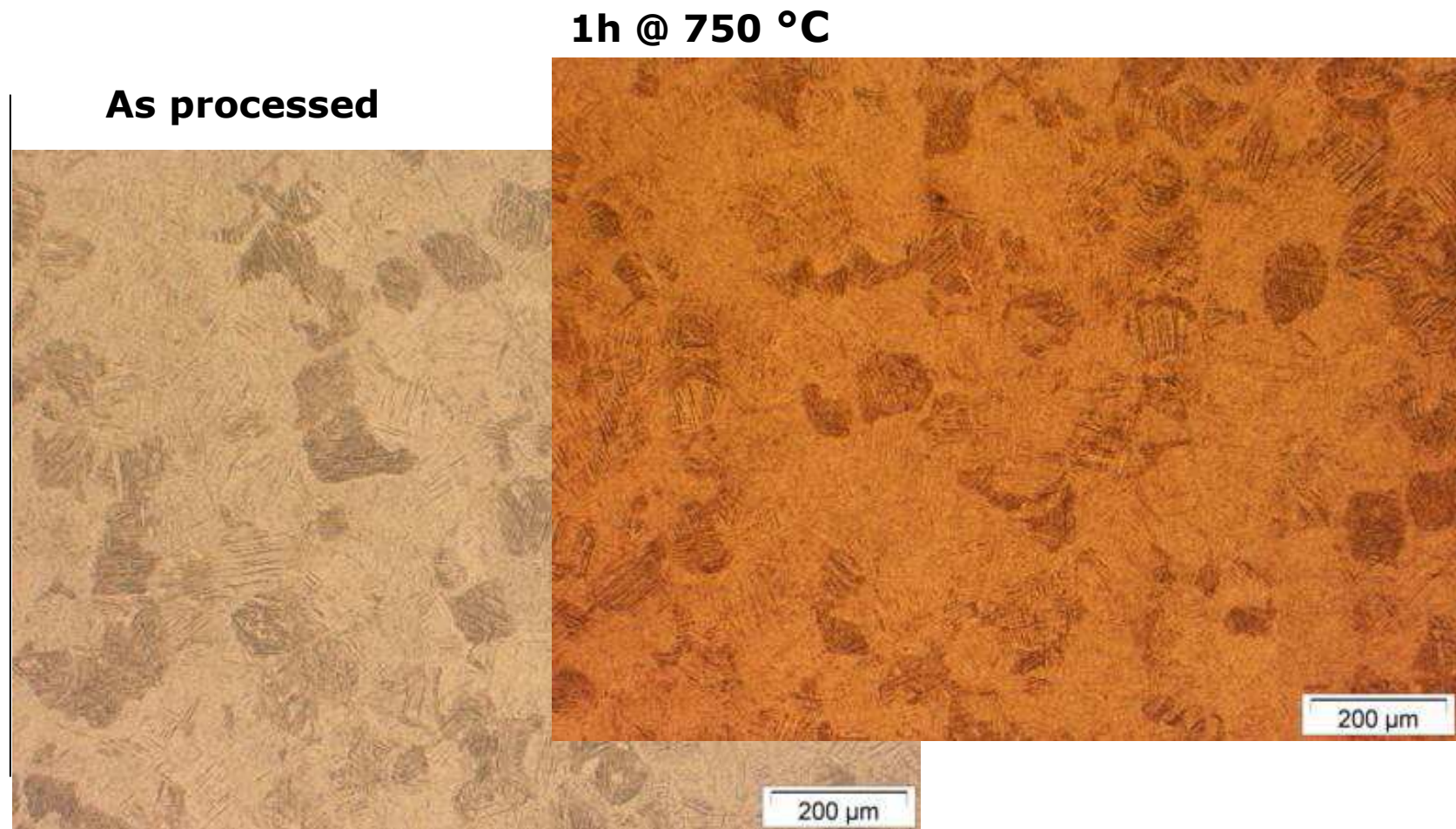
Structure of DMLS HX parts

Solution annealed & double aged

Solution annealed

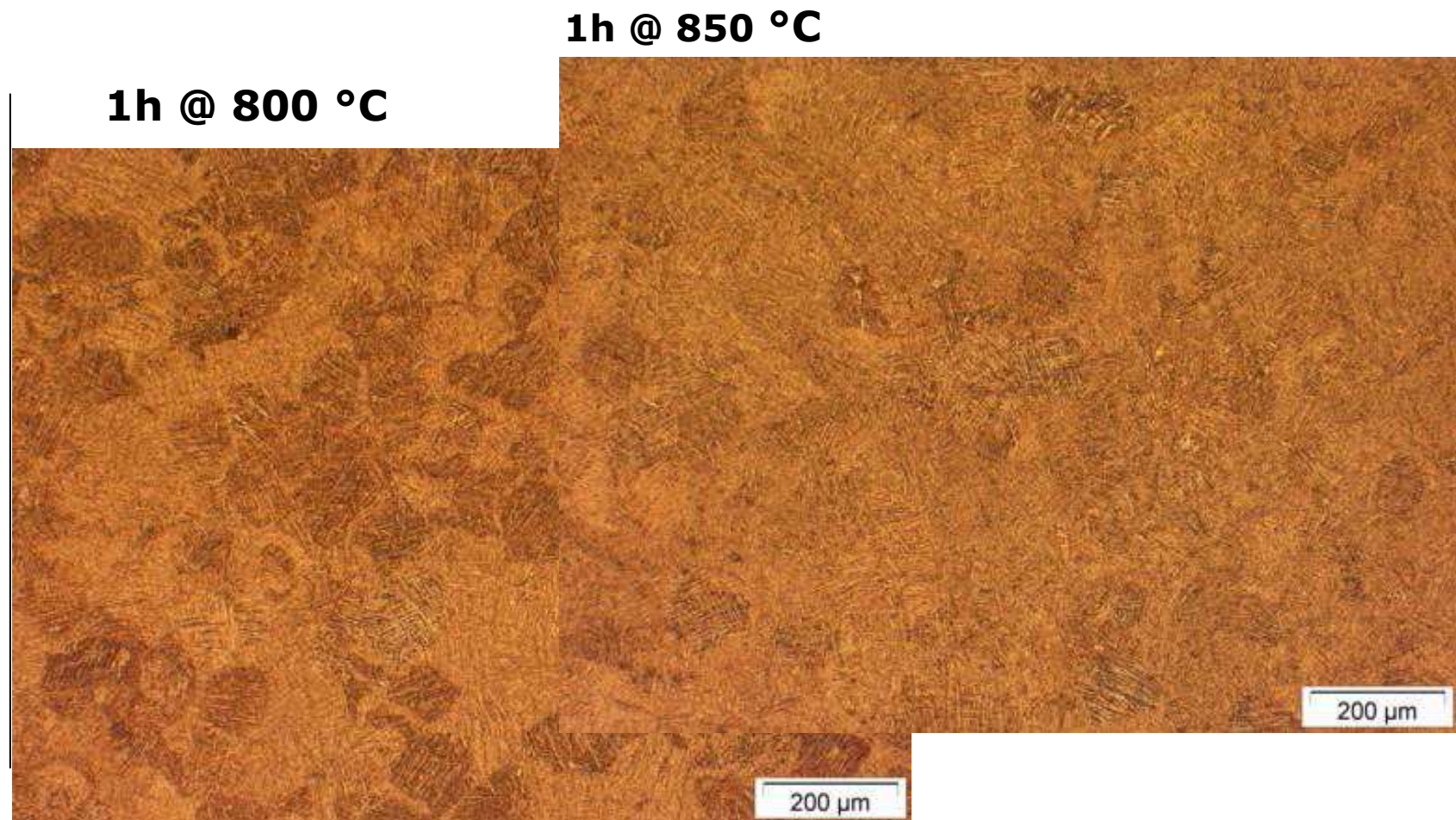


Ti64 microstructure



Source: EOS. Etchant Kroll's reagent

Ti64 microstructure



Source: EOS. Etchant Kroll's reagent

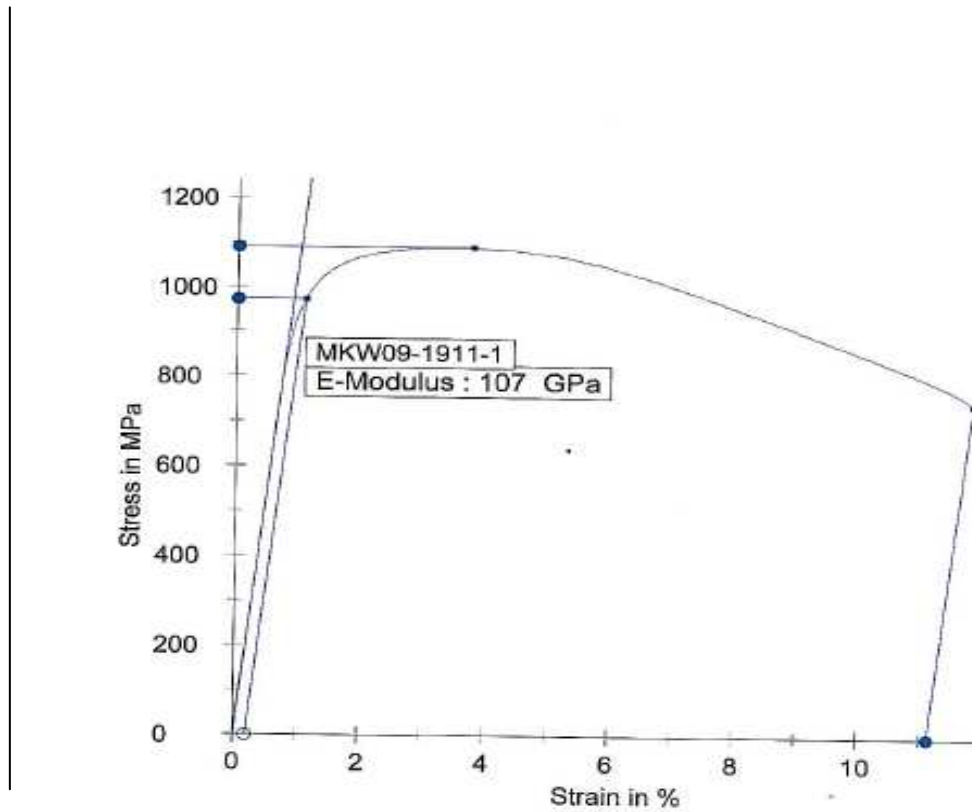
EOS Ti64 mechanical properties

An example of one lot of material

	UTS [MPA]	R0.2 [MPA]	A25 [%]
As manufactured	1127	1020	9,8
1h at 750°C	1036	983	10,2
1h at 800°C	1022	975	12,5
1h at 850°C	982	919	12,8

EOS Ti64 tensile graph

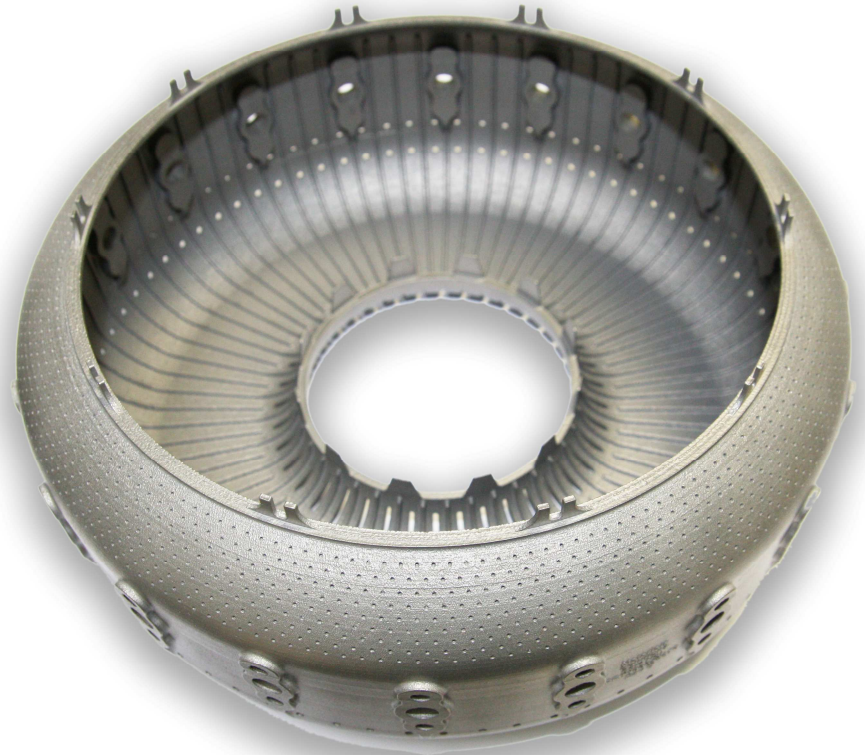
One sample from the examined lot of material



Selected case studies

Aerospace Demonstration part

- EOSINT M enables product optimization for aerospace devices with new design concepts
- Aerospace part design
 - high complexity
 - thin walled
 - Large size (max Ø 248mm ~10 inches)



Thin walled turbine combustion chamber, produced on EOSINT M 270, material EOS StainlessSteel PH1.

Materials Solutions

Rapid development to meet environmental challenges

Source: Materials Solutions

Page 22



e-Manufacturing Solutions

Selected case studies

EOS NickelAlloy IN718

—IN 718 is a newly developed product for DMLS-process

—Process and material development started in 2008

—Pilot testing started in 2008

- 1 pilot customer in USA
- 2 pilot customers in Europe



Stator ring built in EOS NickelAlloy IN718



Selected case studies

Product optimization for aerospace devices with new design concepts

Requirements:

- production of a turbine wheel prototype

Solution:

- EOS NickelAlloy IN718
- produced on EOSINT M 270
- 20 µm layer thickness
- building time: 6h 44min
- heat treatment: 19h
- polish and machining: ca. 6h

Result:

- dramatic reduction in time 2-3 day vs. 12 weeks
- cost reduction, min. 80% less
(mould for wax injection €6,000, investment casting for 10 turbine wheels ca. €1,000)



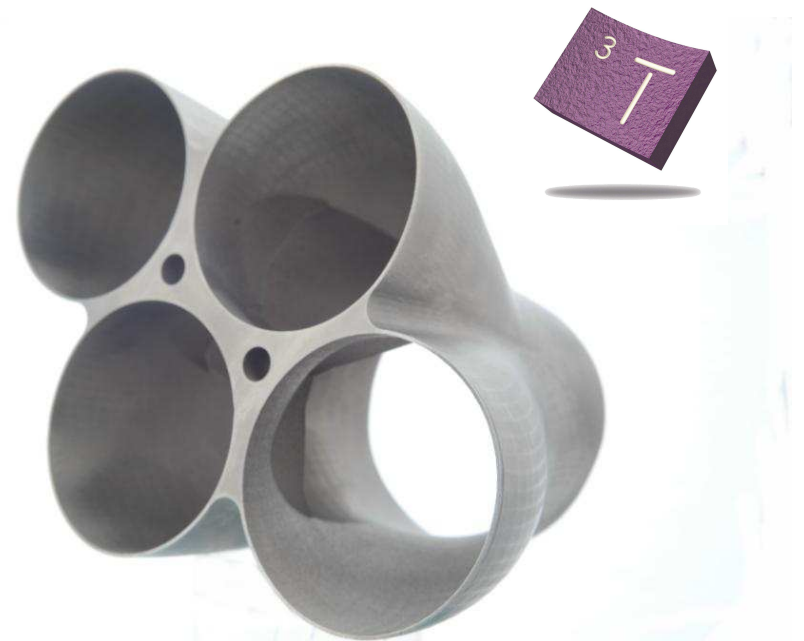
Turbine wheel for a small gas turbine in EOS NickelAlloy IN718 built on EOSINT M 270.

Project: R. Sturzkopf, München

Selected case studies

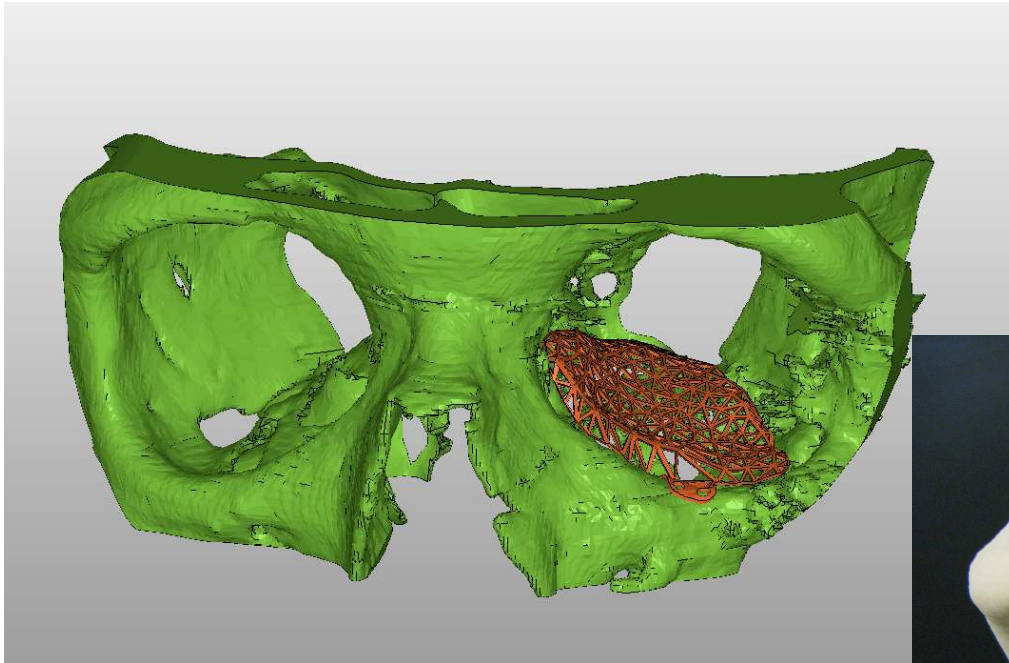
Motor racing applications (F1 and other)

- Difficult to manufacture parts
 - Thin walled
 - Complex
- Dimensions: dia 160mm x H 160mm, thickness 0.75mm
- Build time: 50h



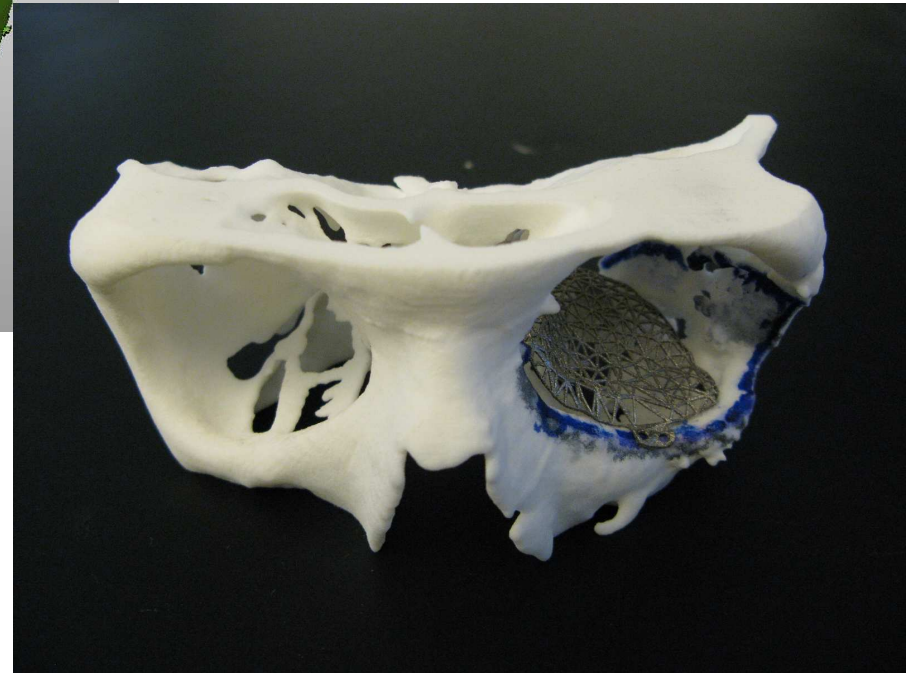
Thin walled part built in EOS NickelAlloy IN718
Wall thickness 0.75 mm

Selected case studies



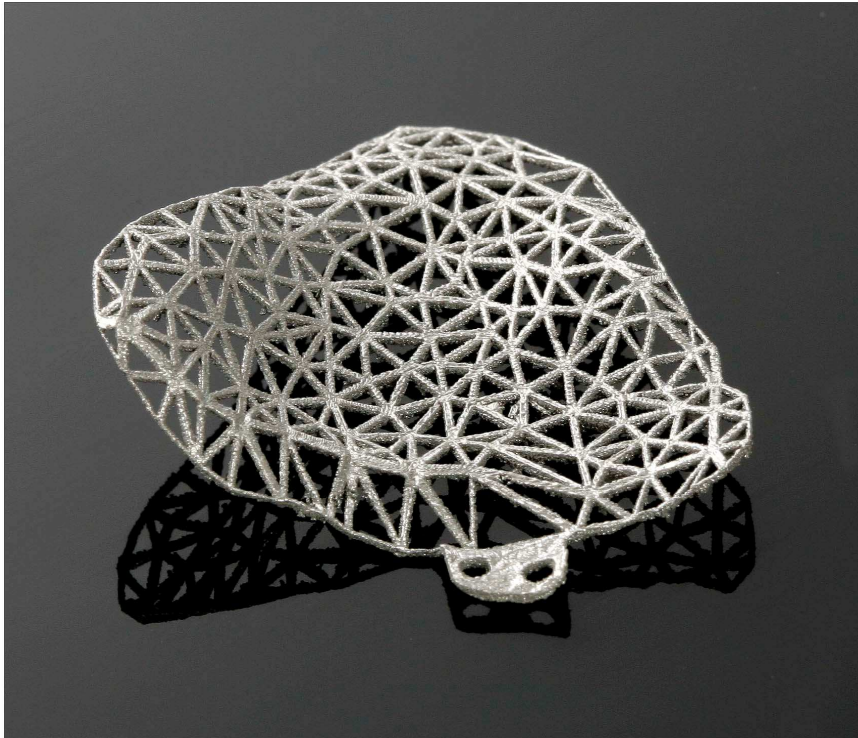
Preoperative model

- Preoperative model using SLS from fine polyamide PA 2200

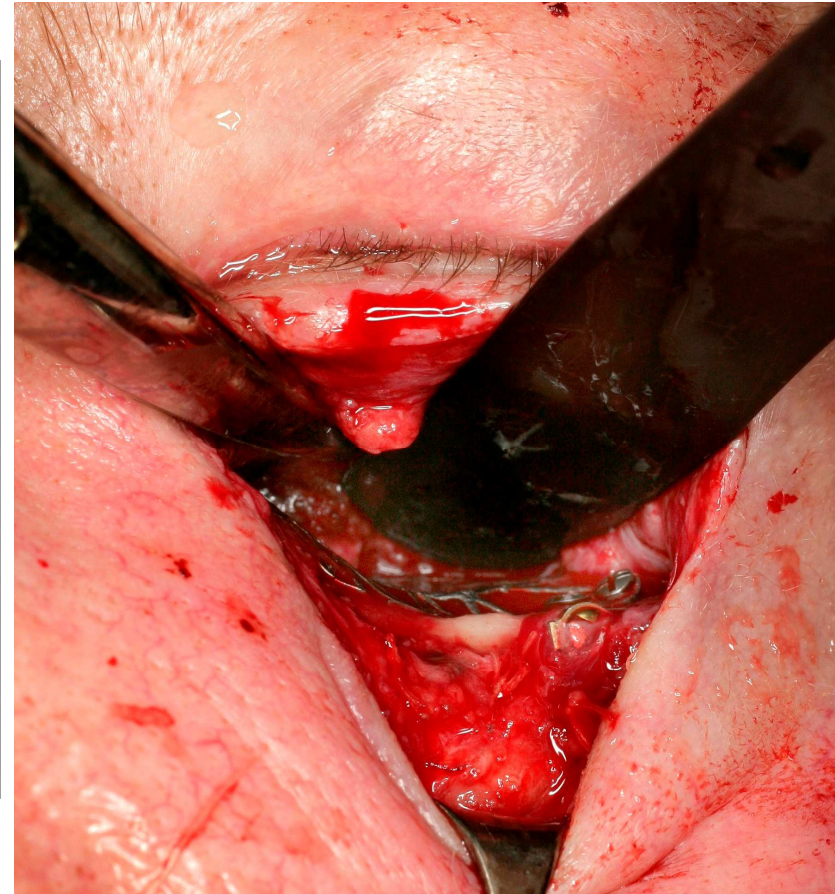


Selected case studies

Surgical operation



- EOS Titanium Ti64ELI
- DMLS EOSINT M270 Ti
- Polished and sterilized



- Surgery February 2009

Conclusions

- DMLS can be used in the manufacture of very complex parts
- DMLS Ti64 material fulfils the main international standards
- DMLS Ti64 is being qualified as manufacturing material in many of the leading companies in industries such as medical and aerospace



Thank you !

