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DELIVERABLE REPORT

FINAL PUBLISHABLE TIFAN PROJECT REPORT AND DISSEMINATION/EXPLOITATION PLAN

Document code: **D1.3**

Deliverable ☒**Technical report** ☐**Other**☐

Project title: **Manufacturing by SLM of Titanium FAN wheel. Comparison with a conventional manufacturing process**			
Project acronym:	**TIFAN**		
Grant Agreement number:	**CS-GA-2013-620093**		
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Abstract (for dissemination)		**Summary of the achievements obtained during the project and dissemination and exploitation plan**	
Keywords		**Technology transfer, dissemination activities, conclusions**	
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1 INTRODUCTION AND OBJECTIVES

This deliverable describes the main activities carried out during the whole project and the most important achievements. In addition, a plan for disseminating and exploiting the obtained results is presented.

First of all, the purpose and objectives of the project are mentioned followed by the participants involved in it.

Afterwards,the results achieved are detailed taking into account the whole duration of the project.

Finally, a dissemination and exploitation plan is defined consisting of the actions for technology transfer in order to disseminate the project activities and results to the European public, both general and specialised.

2 EXECUTIVE PUBLISHABLE SUMMARY

2.1 Purpose and objectives

The aim of TIFAN project is to develop an alternative green manufacturing process based on Selective Laser Melting (SLM) for a titanium TA6V fan wheel of an air cooling unit, that is currently made of stainless steel. Furthermore, the project addresses the comparison between optimized SLM and conventional manufacturing process (bar machining) in terms of mechanical, fatigue and corrosion performance as well as environmental impact and manufacturing cost.

The optimization of SLM process comprises the definition of the required manufacturing route including surface finishing and thermal treatments, process parameters, machine and powder characteristics. Additionally, methodologies for taking full advantage of SLM process based on the improvement of surface quality, powder usage efficiency and wheel design are validated.

Nevertheless, the objective of TIFAN project is not only to achieve the aimed goals (manufacturing of TA6V fan wheel demonstrators and comparative study with conventional bar machining manufacturing process), but to identify the critical factors that could give rise to a further manufacturing cost reduction, weight reduction and mechanical performance improvement, so as to meet with overall requirements of Eco-Design ITD program.

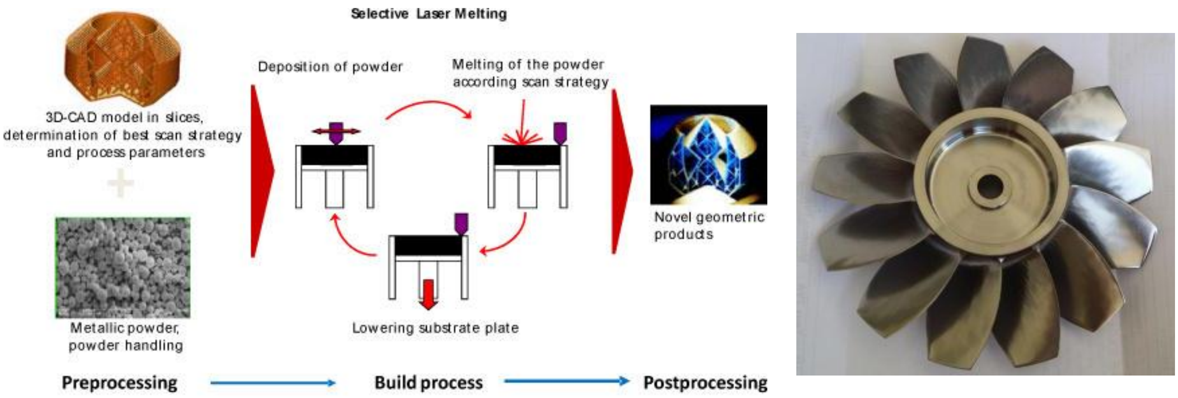


Figure 1. Selective Laser Melting process and image of fan wheel demonstrator

The specific objectives related to full life cycle of component (design and production, use and maintenance and withdrawal) are listed below:

- Reduction of component's weight. A 50% weight reduction target in comparison with current fan wheels (made of stainless steel) and 10% in comparison with Titanium fan wheels manufactured by bar machining due to new SLM design possibilities.
- Improved corrosion resistance compared to conventional manufactured parts. Reduction of 10% of weight loss after exposure to corrosion conditions according to reference standards.
- Improved mechanical properties, both static and dynamic (fatigue). Mechanical properties will be at least equivalent to conventionally manufactured parts.
- Improved material usage efficiency by reducing buy-to-fly ratios (target value 1.25:1).
- Reduction of material wastage by applying SLM technology and optimizing powder recycling methodology: saving of raw material and reduction of scrap rates. A reduction of waste of raw material of at least 40% in comparison with bar machining will be achieved.
- Optimization of SLM manufacturing costs. Definition and validation of different cost reduction strategies including optimization of powder usage efficiency, study of alternative SLM processing routes (with and without surface finishing).

Other collateral objectives of TIFAN project aligned with Eco-Design ITD and coming from the implementation of SLM include:

- Minimal production of dangerous wastes (lubricants, waste oil, polluted scrap, contaminated rags and absorbents, etc.).
- Being SLM a green technology, reduction of CO_2 emissions related to the energy consumption required for part manufacturing by at least 10% compared to conventional manufacturing processes.
- Energy consumption reduction in the air cooling system due to the design optimization.
- Reduction of noise output of manufacturing process. New manufacturing process will completely eliminate the noises related to current bar machining process of Titanium alloys.

Many of these specific goals will be accomplished by changing base material from stainless steel (density 8.0 g/cm^3) to TA6V alloy (density 4.5 g/cm^3) and taking full advantage of lightweight design possibilities and maximum material savings of SLM technology. It must be mentioned that SLM is considered as an environmental friendly technology in which the scraps can be reduced to the minimum and 95-98% of the remaining material (powder that has not melted) may be recycled.

2.2 TIFAN contractors

The list of participants is detailed in Table 1.

Table 1. List of participants

Participant no	Participant organisation name	Participant short name	Country
1 RTD (Coordinator)	IK4-LORTEK	LOR	Spain
2 RTD	Fundación Centro Tecnológico de Miranda de Ebro	CTME	Spain

2.3 Achievements

This section specifies the main tasks carried out during the whole project as well as the results achieved.

2.3.1 *Characterization and verification of powders*

Two different batches of Ti6Al4V powder from two different providers (TLS and LPW) were analysed in order to verify their characteristics and suitability for SLM. Both powders comply with morphological, physical and chemical characteristics required for SLM process.

2.3.2 *Use of recycled powder - powder usage efficiency analysis*

The quality of recycled powder (sieved and dried) used in up to ten consecutive batches was determined following the same procedure as with fresh powder. In addition, oxygen content was measured.

Recycled powder can be used up to ten times without any relevant oxidation.

2.3.3 *Selection of process parameters-manufacturing of simple samples*

The SLM process parameters were optimized in order to obtain parts with optimal surface condition, roughness and relative density. For that a series of cubes of 10x10x10 mm were built being the starting point the material data master. The pursued procedure is shown in Figure 2.

The manufacturing of simple samples in the first stage and control samples, first prototypes and demonstrators afterwards was carried out in SLM Realizer 250 machine, supplied by MTT Group (MCP Group before). This machine is fitted with an IPG fibre laser (Ytterbium laser in solid state) with a wavelength between 1085 and

1090 µm, with a maximum power of 200 W. Some other interesting characteristics can be seen in Table 2.

Table 2. Main characteristics of the SLM Realizer 250 machine

MACHINE	
Weight	~800 kg
Chamber dimensions	2000x1400x2100
Power supply	400 V/3 phase/50/60 Hz
TYPE OF ENERGY	
Fiber Laser	Output power 200W
	Wavelenth 1,095 µm
	Spot size 80-250 µm
PROCESS	
Layer thickness range	20-100 µm
Process rate	5-20 cm^3/h
Atmosphere	Ar with 0,2 % of O_2
Gas requirements	2 l/min
Preheating	200 ºC
Maximum volume of piece	250(X)x250(Y)x220(Z) mm

Nevertheless, the final fan wheel demonstrators were manufacture in machine SLM 280HL from SLM Solutions. One of the differences with respect to the machine from Realizer it does not require two movements (go and come back) for powder spreading. In this sense, some studies show a reduction in time of 30 % with respect to spreading the powder in only one travel and savings in costs of 20 %. The main characteristics of SLM 280HL machine are described in Table 3.

Table 3. Main characteristics of the SLM 280HL machine

System parameters	
Build chamber en mm (x/y/z)	280 x 280 x 350
Laser Power	400, YLR-Faser-Laser
Build speed	20 cm/h / 35 cm/h
Layer thickness	20 µm - 75 µm / 100 µm
Min. Wall thickness	150 / 1000 µm
Operational Beam Focus	70 - 120 µm / 700 µm
Scan speed	15 m/s
Inert gas consumption in operation	Ar/N_2, 2,5 l/min
Inert gas consumption venting	Ar/N_2, 1700 l @ 100 l/min
Compressed air requirement	ISO 8573-1, 18 l/min @ 1,5 bar
Dimensions in mm	1800 x 1900 (2400) x 1000
Weight	1000 kg

Figure 2.SLM optimization flow diagram using simple control samples (cubes)

The optimized manufacturing parameters are specified in Table 4. Both contour and boundaries were optimized in terms of relative density.

Table 4. Optimized parameters

Manufacturing parameters	ZONE					
	Hatch		Boundary		Contour	
Layer thickness (µm)	**30**	**50**	**30**	**50**	**30**	**50**
Exposure time (µs)	**90**	**110**	**110**	**90**	**110**	**90**
Lens position	**60**	**60**	**30**	**20**	**30**	**20**
Spot size (µm)	**200**	**200**	**-**	**-**	**-**	**-**
Laser scan speed (mm/s)	**1111**	**910**	**910**	**1111**	**910**	**1111**
Power (W)	**200**					
Point distance (µm)	**100**					
Hatch spacing (µm)	**120**					

With these optimized manufacturing conditions cubes with the following properties are obtained:

- Relative densities of 99.98 % are achieved.
- The microstructure of as-built samples is α' martensite as expected.
- Roughness value (Ra) of 9.0 µm signifying a reduction of 20% comparing to non-optimized parts.

SLM process parameters for manufacturing almost fully dense parts produced with a surface roughness lower than 10 µm were achieved.

2.3.4 *Manufacturing of stairs*

The first study of supporting strategy was made by means of manufacturing stairs with the objective of implementing the obtained results in first prototypes (pizza slices) and fan wheels. Supporting strategy should ensure dimensional stability (avoid collapse) and final dimensions (avoid distortions) while using the minimum number of supports. In addition, supporting structures must be easily removed.

After manufacturing stairs with different angle support it was concluded that supports are only necessary for overhang angles around 10°. Above 20° are not required for dimensional and process stability. In addition, the roughness is comparable to the measured in cubes, 9-10 µm. Some influence of overhang angle is observed for the lowest angles.

2.3.5 *Manufacturing of control (testing samples)-thermal and post-processing operations*

Different control or testing samples were manufactured using optimised SLM parameters. Control samples included tensile, fatigue and corrosion testing samples. Figure 3 shows control samples manufactured in z direction.

Figure 3. General view of the control samples manufactured with optimised parameters

In Figure 4 dimensions of these samples are detailed as well as reference standards considered for the definition of the control sample geometries.

(a) ASTM E 8M (b) FFRC16 (c) G31-72

Figure 4. a)Tensile; b) fatigue and c) corrosion samples

The achievements are explained within each sub-tasks.

Tensile samples

The manufactured SLM tensile samples were subjected to different thermal treatments, including conventional thermal treatment and HIP at different temperatures, i.e. 850 and 920 ºC. Tensile properties, microhardness and microstructure were analysed in order to study the mechanical behaviour of the samples and their correlation. The main results and conclusions of these tests are the following:

- The ductility of as-built samples is very low, it is absolutely necessary to subject the samples to a thermal treatment in order to change the microstructure and release residual stresses generated in the selective laser melting process. An increase of 47% in ductility is observed in thermally treated samples comparing to as-built state.
- Conventionally treated samples exhibit lower strength but improved ductility due to the transformation of α’ to α + β phases.
- A coarser microstructure was obtained after HIPping at 920 ºC in comparison with 850 ºC. This coarsening affects directly to the hardness and strength.
- The lower elongation and strength in tensile tests of samples HIPped at 920ºC was related to the presence of an external oxide layer, named alpha case. If this layer is removed, both elongation and strength increase.

Corrosion samples

Corrosion samples were also heat treated, particularly a conventional thermal treatment and a HIP cycle were applied, at 850 and 920 °C, respectively. Afterwards, two different surface treatments were applied both to thermally treated samples and to samples in as-built state. The surface treatments selected were the traditional shot peening and an abrasive flow polishing processes called Micro Machining Process (MMP) from BinC. These surface treatments gave rise to different surface roughness between 3.59 and 0.17 microns. The main conclusion was that smoother surfaces have better corrosion behaviour. Lower roughness postpones the beginning of corrosion.

Fatigue samples

In the first stage, the manufactured fatigue samples were subjected to the same thermal treatments performed in corrosion pieces (conventional thermal treatment at 850 °C and HIP at 920 °C. Then different surface treatments were applied. The surface treatments selected are the traditional shot peening and two abrasive flow polishing processes. The first one is called Micro Machining Process (MMP) from BinC and the second one was developed at Kennametal Extrude Hone (EH). Different roughness values were obtained to study its effect in fatigue performance, but the first poor fatigue results forced to machine the samples (Figure 5). Although remaining pores from the manufacturing with SLM were reduced significantly after the HIP treatment with respect to conventional thermal treatment, was not sufficient to obtain adequate fatigue behaviour. Discretization effect and resulting facet size of SLM process had a higher influence on fatigue than the apparent surface roughness.

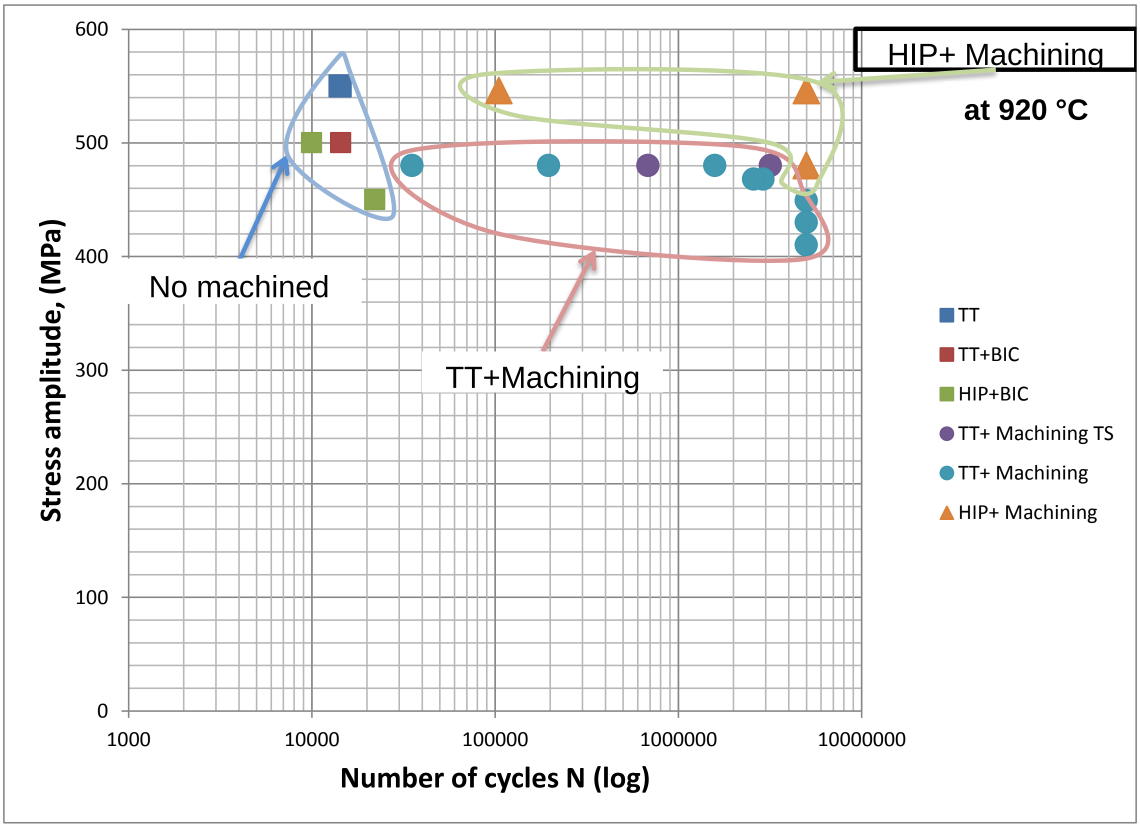


Figure 5. S-N curve with results of completed fatigue tests

The most relevant conclusions acquired from these tests are:

- With the selected surface treatments different roughness values have been achieved in fatigue testing samples. These were used for the study of the roughness in fatigue performance. Two surface treatments gave rise to Ra values below required threshold value (between 0.2 and 0.37 µm).
- Facet size is a critical factor for ensuring good fatigue performance. This is even more critical than apparent roughness (measured parallel to facets). This effect cannot be masked or removed with surface treatment, only by machining.
- If the effect of facet size is removed, it can be concluded that HIPing at 920 ºC is required in order to ensure good fatigue performance. This is linked to the capability of removing porosity and other internal defects (lack of fusion). These defects have been identified as fracture triggering points. Subsurface defects are particular critical defects that affect fatigue performance. Nevertheless, conventionally treated samples with the effect of facet size removed, present promising mechanical properties (fatigue life close to 480 MPa which is higher than the obtained for bar machined samples, 326 MPa).

2.3.6 *Manufacturing of first prototypes (pizza-slice)*

Before starting with fan wheel demonstrator, first prototypes were manufactured with similar shape as the final fan wheel. These parts consist of a quarter of a fan wheel named as pizza-slice. The objective of this task was to manufacture pizza-slices which complied with dimensional specifications. That required the optimisation of supporting strategy. It must be mentioned that the supporting strategy must ensure dimensional stability (avoid collapse) and final dimensions (avoid distortions) while using the minimum number of supports. In addition, supporting structure must be easily removed.

In addition, regarding the efficiency of metal powder usage, the need of supporting structures reduces this efficiency because powder required to build the supports cannot be recycled. Therefore, an optimization of the supports structure and volume was performed in order to reduce the volume of supporting structures.

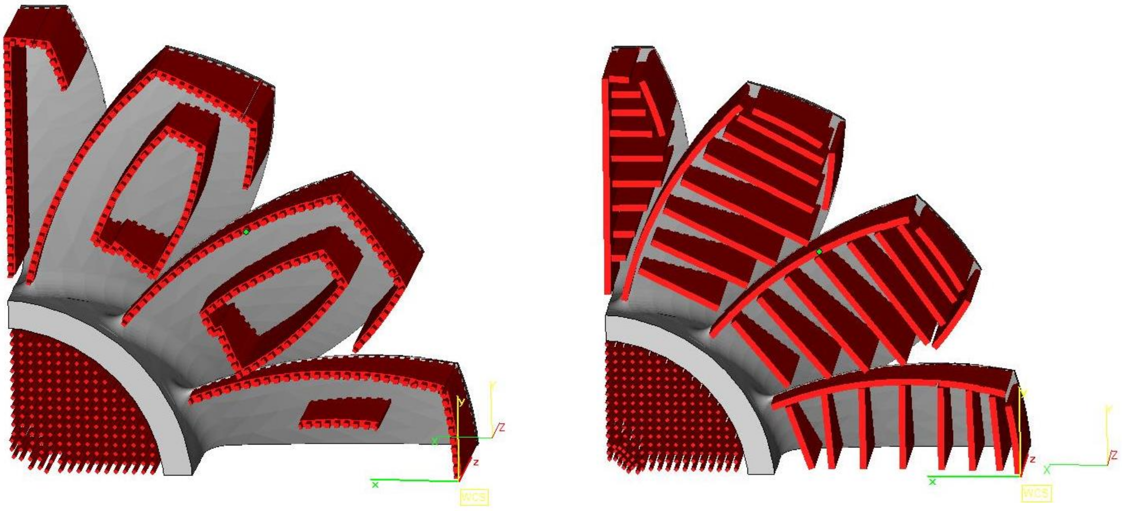
Several pizza-slices with different supporting strategies were manufactured. The main differences between of these prototypes relied on:

- Nature and shape of supports: both solid (conic, cylindrical or wall shape) and non-solid (thin reticular net) supports (Figure 6).
- Location of supports: edge supporting and blade surface supporting.
- Number and density of supports. This was quantified comparing the relative supporting volume vs total sample volume (pizza-slice + supports).
- Relative orientation of pizza slice vs wiper.

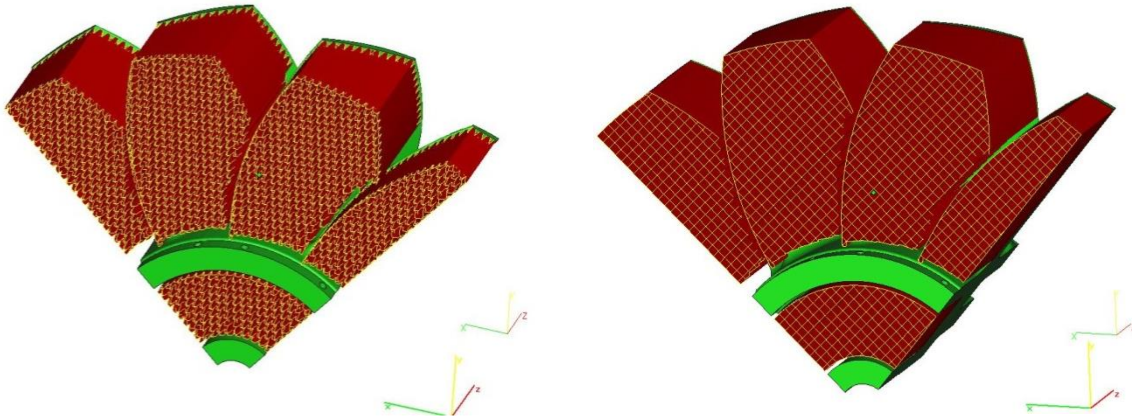
The manufactured pizza-slices were characterised in terms of dimensional accuracy, that is, tridimensional measurements were applied.

In order to meet dimensional specifications, extended support structures (solid or non solid) must be used, reducing powder usage efficiency. In the case of non solid supports, the powder usage efficiency is lower but it is necessary to sacrifice this efficiency in order to ensure the repeatability and the robustness of the manufacturing process. Nevertheless, due to the nature and shape of non solid supports, thin reticular net, were easier to remove, reducing of post-processing time. It must be pointed out that both supporting strategies (solid and non solid) left marks in the rear part of the blades, being necessary to apply a surface treatment to remove them.

Besides, several destructive tests were performed to pizza-slices. The transversal section of blades was analysed measuring the density, studying the defects present in the section and the microstructure, and measuring the microhardness. The destructive tests were realized to pizza-slices in as-built state and after applying a thermal treatment. These characterizations were completed with powder usage efficiency evaluation in each pizza slice.



Solid supports



Non-solid supports

Figure 6. Different types of supporting strategies carried out in the manufacturing of pizza slices: solid and non-solid supports

The most relevant conclusions drawn from the manufacturing of pizza slices are:

- Extended supporting structures are required to avoid SLM process induced distortions of blades.
- Supporting strategies that enable to meet dimensional specifications (control of distortions) have been determined. Supporting structure was optimised obtaining pizza slices and fan wheels within required tolerances. Both solid and non-solid strategies are suitable but they require high supporting volume, 28.4% and 45%, respectively.
- Difficulties in optimizing powder usage efficiency have been detected due to problems finding the equilibrium between low supports quantity and dimensional accuracy and stability. High amount of supports are needed to meet dimensional specification, which reduce powder usage efficiency.
- The surface quality of the bottom of the blade is worse than the top of the blade, due to the manufacturing on powder of the bottom side.
- Samples HIPed (Figure 7) show a very fine microstructure without defects and high hardness together with optimised mechanical properties (tensile tests).

This HIP temperature condition was selected for heat treating the final fan wheels.

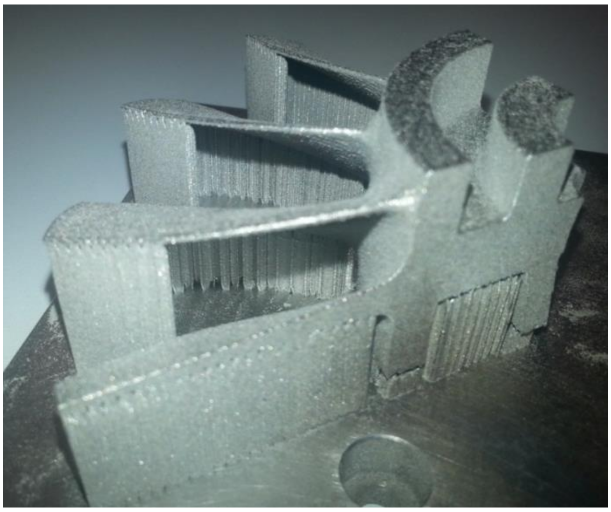


Figure 7. Images of pizza slices after applying a thermal treatment

The best strategy to manufacture the fan wheels was defined by means of optimising the supporting structure. Non solid supports were selected for the manufacturing of final fan wheel demonstrators.

2.3.7 *Manufacturing of fan wheels*

8 fan wheels were manufactured with the supporting strategy which met dimensional specifications and using the optimized manufacturing parameters. In the first approach, one of the fan wheels was subjected to a HIP cycle and dimensional measurements were performed before and after the thermal treatment. Several control points were out of dimensions after the HIP cycle. This indicated the need of subjecting the fan wheels to a stress relieving cycle before HIPing. It is worth noting that in as-built condition this fan wheel was considered valid (only two points were out of dimensions). Thus, as a second approach, another manufactured fan wheel was subjected to a stress relieving treatment. Comparing to the previous fan wheel which was directly HIPed, less control points were out of dimensional specifications. Afterwards, this fan wheel was HIPed at the same conditions.

The rest of the manufactured fan wheels were processed following these two different routes, half of them were stress relieved and the rest were directly HIPed.

Eight fan wheels were manufactured and the best manufacturing routes were determined for them.

2.3.8 *Comparison between optimized SLM and bar machining*

One of the objectives of this project was to compare the properties of SLM samples with properties of samples obtained from conventional manufacturing. Before the project, fan wheels were machined instead of using additive manufacturing technologies. In this section a comparison between both types of samples is performed in terms of microstructure, tensile properties and fatigue properties. The most relevant conclusions are the following:

- The microstructure of SLM sample is α' martensitic transforming to α + β after the applied thermal treatments (conventional or HIP at 850 and 920 ºC). The α phase appears as fine needles. However, the bar machined sample is α equiaxic and lamellar α + β.
- Although having different microstructure, the microhardness of both types of samples is comparable, around 380 HV.
- SLM samples show superior strength but lower ductility even if they are subjected to a HIP cycle. The strength in SLM samples with HIP cycle is 10,2% higher (1080 MPa) but the ductility only reaches 12.5%, where in bar machining is 15%.
- In general, it can be concluded that SLM samples properties are comparable or superior to bar machined samples. Nevertheless, in order to reach the results presented, it is compulsory to apply a thermal treatment and a surface treatment (see previous section about mechanical properties). The thermal treatment needs to be a HIP cycle to close the remaining porosity and thus, to have enhanced tensile and fatigue properties.

2.3.9 *Life Cycle Analysis (LCA)*

Concerning environmental evaluation three different types of fan wheel have been compared: Ti6Al4V fan wheel processed by SLM, Ti6Al4V fan wheel manufactured by machining and machined stainless steel fan wheel

The goal of the comparative LCA was to compare the environmental behaviour of the combination of two manufacturing processes (SLM and bar machining) and two materials used to manufacture a fan wheel (Ti6Al4V and stainless steel), with the aim of identifying which technology/material is better from an environmental point of view. In the case of SLM the titanium alloy was only evaluated whereas in bar machining both materials. The planned application of the results of this study is for internal use in order to implement improvements in the product ecodesign.

Five methodologies, included in the commercial software SimaPro 8.0.4.30, were used to model impacts: CML 2011, ReCiPe (H) endpoint and midpoint, Cumulative Energy Demand, Impact 2002+ and ILCD 2011 Midpoint +.

All relevant information and data necessary for the interpretation were available and complete.

When comparing the cradle-to-gate environmental profile of the three fan wheel under study, it was observed that the TA6V SLM fan wheel was the one with the greatest impact, followed by TA6V machining fan wheel; being the stainless steel machining fan wheel the more environmental friendly (Figure 8). However, when considering the entire life cycle, the stainless steel machining fan wheel was the worse one, mainly due to its greater weight, and the relation of the weight with the impact in the use phase (emissions and fuel combustion).

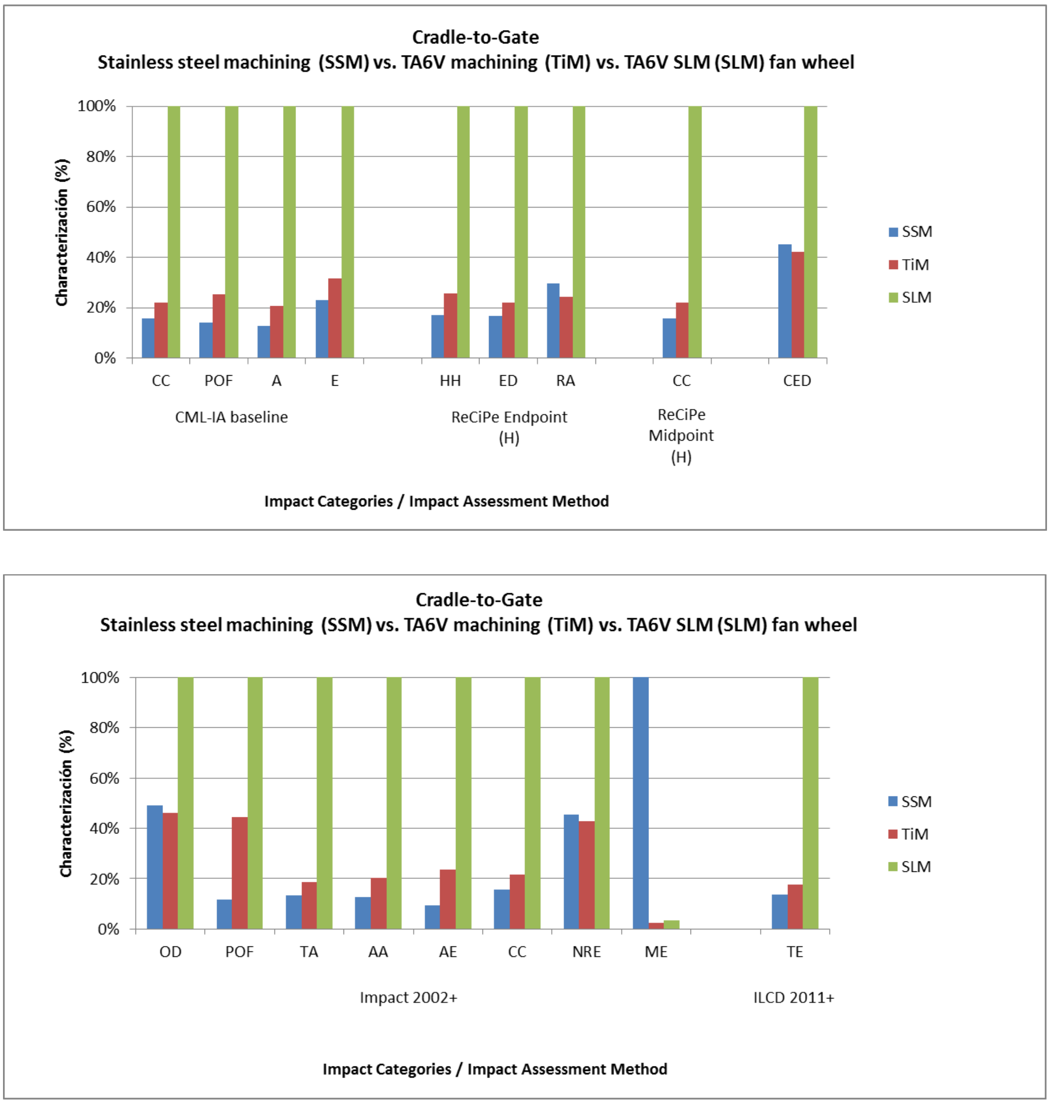


Figure 8. Environmental comparative assessment (cradle-to-gate)

The consumption for raw material production and delivery (by plane from UK), the management of the process wastes and the manufacturing process are the items with greater impact in the three fan wheels. Nevertheless, the difference of impact between the three products is mainly attributable to the impact of post-treatments needed to ensure the right finish of the TA6V SLM fan wheel and to the impact of the transport by air of TA6V powder required for the SLM process.

Moreover, SLM manufacturing process requires a great amount of raw material, 32 times the weight of the fan wheel vs. about 10 times the weight of the fan wheel in the case of the machined ones. Hence, the raw material impact in the titanium alloy SLM fan wheel is the highest; however, the benefit associated with the recycling of the waste generated during its manufacture is also the highest, which reduces its impact, since the used assessment model gives credits for recycling or re-use.

Finally, a review of the study was recommended, once data related to optimized SLM process and post-treatments applied to the different fan wheels were available. Also, taking into account the impact of product life cycle, eco-design efforts should focus on the use phase, lightening the fan wheel or increasing its energy efficiency.

2.3.10 *Cost analysis and improvement plan*

A cost analysis for manufacturing a fan wheel by SLM was performed and guides for reducing it were given, detailed in the improvement plan. It was concluded that the steps that most affect to the overall cost are the subsequent post-processing such as heat treatments, surface treatments, quality control and support elimination in addition to the manufacturing process. Nevertheless, these all steps are necessary for the right performance of the fan wheel. Figure 9 shows costs breakdown for processing one fan wheel using two different surface treatment, BinC and EH.

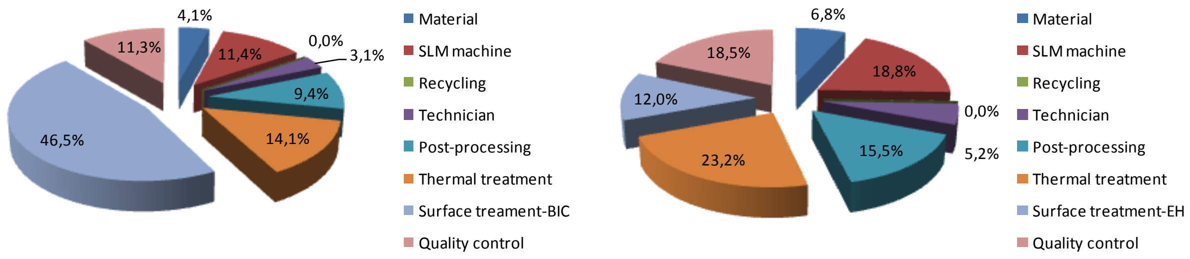


Figure 9. Cost breakdown for the processing of one fan wheel. BinC and EH surface treatments are compared

The cost reduction proposed in the improvement plan are related to increase the number of fan wheels that can be manufactured in one batch as well as increase the scanning speed, by means of SLM machines with bigger build envelope and higher power laser or multilaser, which enhance the productivity. Moreover, more automated machines reduce time, manual work and costs.

Costs also can be reduced introducing monitoring systems in the machines. In this way, defective parts are avoided and less scrap is produced.

According to several studies about costs, where the whole process is taken into account, specifying costs of each manufacturing step, indicate that significant reductions can be obtained if higher scanning speeds and bigger building envelopes are used. Increasing the scanning speed from 6.3 cm^3/h to 20 cm^3/h together with a material cost reduction of 45%, savings of 50% in the manufactured parts can be achieved. Other studies predict that in the future (in 2020) machines with 120 cm^3/h of scanning speeds and building chambers of 2 m^3 will be available in the market. In this case the machine cost will be reduced from 75% to 45%.

Figure 10 shows costs reductions that can be obtained if several parts are manufactured in one batch.

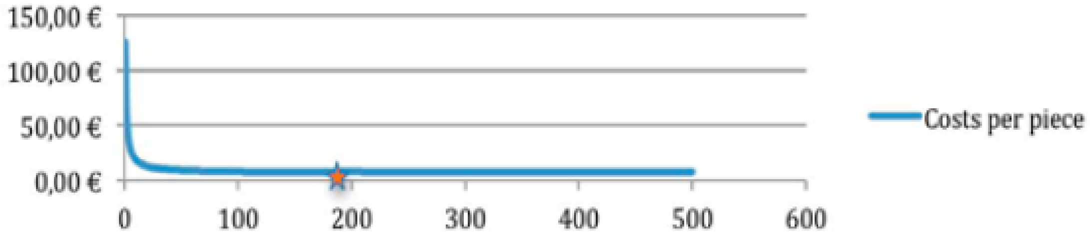


Figure 10. Cost per piece in function with the number of manufactured pieces

2.4 Dissemination and Exploitation

A Plan for use and disseminating of Foreground (PUDF) was elaborated, summarising the dissemination activities of the project and describing the exploitable results based on the research work performed under the scope of TIFAN.

The overall objective of the TIFAN project was not only to manufacture some fan wheel demonstrators, but also to identify the critical factors that could give rise to a further manufacturing cost and weight reduction as well as mechanical performance improvement.

TIFAN has not been until now too active disseminating the results, because it has been carried out in just 18 months and the time has been spent performing research and development activities. Nevertheless, after completion of project some dissemination activities are programmed, presenting the project and the results / developments on various conferences and scientific journals (**one publication in a peer-reviewed journal)** and on well-known fairs such as Paris AirShow and Aerodays, as well as company internally.