Deliverable 1.1: End-user application specifications

Dissemination Level: Confidential (CO)

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Context

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Work Package:	WP1
Task:	T1.1 Collection of end-user application specifications

Document Status

Version:	0.6
Last modified:	13.06.2016
Status:	Final
Approved by:	Marwan Abdou Ahmed
Date Approved:	23.06.2016

Declaration: Any work or result described therein is genuinely a result of the Hiperdias project. Any other source will be properly referenced where and when relevant

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1 Version History

Version	Summary of Change	Written By	Approver	Date
0.1	First draft	S. Karg	Michalowski	01.04.2016
0.2	Revised draft – Bosch input only	Ametowobla	Michalowski	13.05.2016
0.3	Revised document – Bosch & C4L	N. Dury	N. Dury	18.05.2016
0.4	Revised draft – Bosch, C4L and E6 inputs	William Scalbert	Michael King	19.05.2016
0.5	Revision	Michalowski	Michalowski	24.05.2016
0.6	Correction	William Scalbert	Michalowski	25.05.2016
0.7	Correction	William Scalbert	Michalowski	05.06.2016
0.8	Correction	Noémie Dury	Michalowski	08.06.2016
0.9	Minor Corrections	Michalowski	Michalowski	13.06.2016
1.0	Corrections	Abdou Ahmed	Abdou Ahmed	22.06.2016
1.1.	Correction	Noémie Dury	Abdou Ahmed	23.06.2016

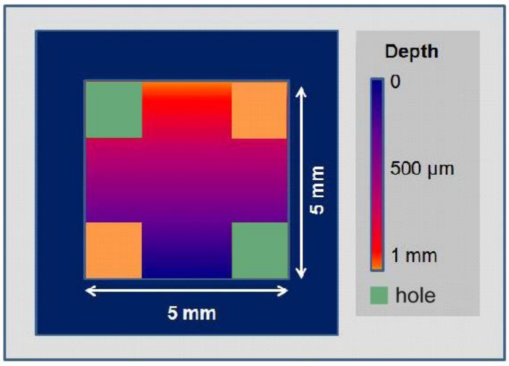
2 Scope

This document should provide an overview about the prerequisites of the end users Element six (E6), Class 4 Laser (C4L) and Robert Bosch GmbH (Bosch) concerning the laser process itself, as well as laser source and systems technology, which will be worked out in the various work packages of HIPERDIAS.

3 Bosch

3.1 Definition of target application

A model geometry for benchmarking the ablation process has been defined. The geometry covers a broad range of geometry features and machining challenges, such as a high total ablation volume, inclined planes, through holes, etc. with a high requirement of accuracy. The inclined plane especially requires minimum shape deviation with respect to the inclination angle, symmetry (left / right) and edge-steepness. The through holes mainly require high ablation rates, in order to remove the material until complete penetration of the wafer. The purpose designed cross shape in addition allows for evaluating the quality of the beam deflection system, since a high number of corners / edges is required to be implemented with a high geometrical accuracy. This in turn requires highly precise positioning and fast switching of the laser beam. Table 1 shows a summary of target geometry and process key performance indicators required for productive industrial mass production and meeting end-user-quality requirements of the Bosch demonstrator applications. Final target values for the thickness of surface damage or surface defects are currently being coordinated with the relevant Business Units at Bosch.

Model Geometry for Benchmarking	Key Performance Indicator	Unit	Target Value
	average ablation rate	mm³/s	≥1
	peak ablation rate	mm³/s	≥3
	shape deviation	µm	≤10 (waviness)
	surface roughness	µm	≤1
	thickness of surface damage	µm	tbd
	Surface defects (e.g. pores, holes > 1 µm diam.)	1/mm²	none
	min. achievable edge radius	µm	as small as possible
	max. edge-steepness	degree	≥ 70

3.2 Systems technology specification

The high targeted ablation rates with high surface quality and accuracy requirements at the same time lead to ambitious specifications for systems technology and laser source development.

Laser source development

Previous studies determined an ablation energy efficiency for silicon during ultrafast laser ablation in the range of 1 – 3 mm³/kJ of input laser energy. Thus, in the final stage, the targeted laser power of 1000W is fully required in order to be able to reach the targeted ablation rates of > 1 mm²/s.

As scanner technology is a limiting factor for high pulse repetition rates, requiring fast scanning velocities, the maximum laser power should be available at pulse repetition frequencies of ≤1000 kHz. Thus, high maximum pulse energies of ≥ 200 µJ are required.

Further, the tight specifications on geometry accuracy will presumably require synchronization of laser pulse energy and / or pulse repetition frequency with the local scanner velocity, in order to avoid the formation of trenches during acceleration and deceleration of the scanning mirrors, leading. Thus, fast and flexible triggering (ideal: pulse on demand) and fast power variation are necessary.

The laser wavelength is assumed to be in the 1030 nm regime. However, as also frequency doubled and tripled radiation will be examined during the process development phase, the realization of frequency conversion should at least be considered.

Beam delivery, scanning and control

The optical path of the laser machining station naturally is required to handle the very high laser power without damage to optical elements and without influence of laser power variations on the phase front distribution (e.g. beam quality and distortions of intensity distribution) and focus position (e.g. due to thermal lensing). Thus, low absorption coatings and lenses / mirrors need to be implemented. All components have to be suitable for pulse durations down to 400 fs at a pulse energy of 1 mJ regarding the damage threshold and dispersion. According to experience this means the necessity to use high quality fused silica as the material for all transmitting optical elements (e.g. lenses, protective glass) and high quality coatings for all transmitting and reflecting optical elements (e.g. polarization optics, mirrors).

The beam deflection system (most probably galvanometer scanner) is required to provide very high dynamics and a high positioning accuracy, at least delivering state-of-the-art performance, such as the Scanlab ExcelliScan series. To handle the high average power the beam should be in larger diameter (e.g. >10 mm). All apertures must be larger than twice the beam passing the aperture to avoid diffraction. It can be beneficial to use a large focal length of the focusing device (e.g. 500 mm) to achieve highest dynamics of scanning by using large incoming beam sizes.

As stated in the laser source section, the laser and scanner control systems is required to provide features like pulse-on-demand triggering and / or velocity synchronized laser power control, in order to achieve the desired demonstrator specifications.

Safety

In order to handle the high ablated volumes at maximum laser power, a sufficiently powerful laser fume extraction system is required to avoid detrimental effects from fumes and residues (process quality, damage to optics, health and safety). Further, care has to be taken regarding possible hazards due to the explosive nature of silicon dust.

It is known that material processing with high power ultrafast lasers produces soft X-ray radiation. Thus, proper protection has to be taken into account. Further definition of laser safety and x-ray shielding requirements should be done when optimum processing parameters e.g. laser spot size have been determined.

Sample fixation and movement

In order to allow for the processing of typical substrates, a sample fixation should be designed which is capable of handling 200 mm silicon wafers. There should be the possibility of secure clamping of the work piece. In order to be able to easily access different positions on the work piece and to allow for a quick adjustment of the focal position, a xyz axis system with a state-of-the-art NC control should be incorporated into the laser process machine.

Further requirements

In order to enable efficient process development, the laser process machine should be equipped with an in-situ camera system to position and inspect the laser processed area. A further increase of efficiency and user friendliness will be achieved by providing a quick manual movement control (e.g. a "hand-wheel" for axis movement). The HMI of the machine should allow both for quick manual set up of laser programs (e.g. by using a comfortable and easy user interface – example: LaserDesk by Scanlab), as well as batch programming for larger parameter variations, including the movement of the axis system (e.g. set up of automatic focus search). Furthermore the machine should fulfill the common requirements on laser safety, electrical safety and so on. These details are discussed within the scope of WP6.

4 Element Six

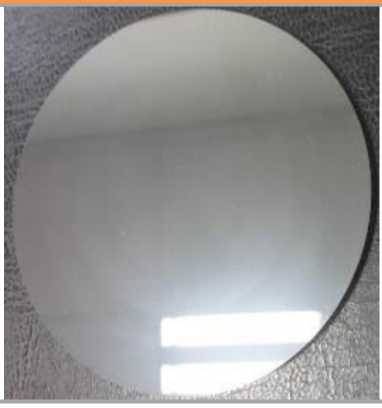
4.1 Definition of target application

The role of the machine is to ablate various PCD products manufactured by Element Six. At the end of the ablation process, the PCD surface must present a mirror surface finish; a polished quality is required as final quality of the PCD surface with a surface roughness Ra value below 0.01 µm.

Panel of PCD products to be processed by the machine:
PCD Syndites (discs), PCD Syndrills (cylindres), PCD segments

The achieved material removal rate from laser ablation must match the material removal rate achieved with mechanical processing at least. Another objective is to ablate the surface with a non-planar form with a height of maximum 30 µm, so waviness defects due to Laser ablation have to remain inferior to a few microns.

Surface defects must be extremely small and comply with Element Six quality criteria which are listed in E6 quality standards document. The very main surface defects which are critical from Element Six perspective for this process are quoted from this document in the following chart, but they are non-exhaustive. During the whole process development activities there will be a close exchange between Element Six and the corresponding partners of WP2 and WP6 to ensure the compliance to all Element Six quality criteria.

Key Performance Indicator	**Unit**	**Target Value**
Benchmarking product: • PCD Syndite		
Surface roughness	µm	≤ 0.01
Average ablation rate	mm³/s	≥ 0.15

Shape deviation	µm	≤ 2 (waviness)
Edge Chip		Must not encroach on the usable area (defined per disc). A maximum of three chips allowed as long as they are separated by the length of the chip. No more than 45° of the periphery can be affected by chipping. Chip-out cannot extend the thickness of the disc.
Pits	µm	A hole, cavity or small indentation in the PCD polished surface. Pitting is one or more small shallow craters on the surface. It has a definite depth. Typically can be large discrete pits or a scatter of pits smaller than 0.05mm diameter. See table 2 for diameter specifications Pits with a significant* depth are not allowed.
Surface Scratches		A scratch with a significant depth* is not acceptable. Requires case-by-case review.
Black spot (Binder components leakage)		Follow pitting specifications Requires case-by-case review.

Table 1

**a significant depth is detected by running a sharp edge over the scratch or pit*

Max pit diameter	Number of pits allowed	Minimum distance between pits
µm	*Quantity*	*cm*
>200 (XL)	0	0
200-100 (XL)	0	0
100-50 (XS)	Approximately 12 pits per disc. 0.25pits/cm^2	1
50-25 (XS)	Visual judgement	
<25	Not measured in production use polish surface guidelines	

Table 2

4.2 Systems technology specification

A high targeted ablation rate combined to high surface quality and accuracy requirements at the same time lead to ambitious specifications for laser source development and systems technology.

To achieve both goals, process will be divided into two steps:

- a first phase with a high ablation rate removing most of the material and smoothing the surface
- and a second phase with a slower ablation rate giving a final polished finish

Laser source development

The diamond polishing step will take place in several step. As for mechanical machining one can expect rougher steps with high energy at the beginning and several finishing layers in order to reach the expected mirror surface.

In both operations, a high ablation rate is required to reach the expected processing time, so a high average laser power is necessary to remove most of the material during the first machining step and match the timing requirement. A power of 200 W is estimated to be necessary for high speed machining of a large surface; the requirement for a power of 500 / 1,000 W is not cleared yet. For this the 200W laser system planned in the project shall be sufficient to achieve the goal. However, in case more power is required, E6 can get access to the 500W (initially only planned for the Si-ablation applications).

A mirror surface finish is required as surface quality, so the Laser ablation must induce the less possible thermal damage into the material. Therefore short pulse lengths of an order of a few hundred of femtoseconds are required. The requirement to increase the pulse length to few picoseconds could be of interest for the first machining step to increase removal rate, but it has not been studied yet but this study will be shortly completed for deliverable 1.2. The flexibility of the laser source with tunable pulse duration, frequency and pulse energy is required.

High average laser power is usable for the processing if the repetition rate is adequate to ensure the necessary (small) fluency per pulse at the required spot size for the final machining step. A minimum of 1 MHz is at least expected.

The laser wavelength is assumed to be close to 1030 nm. No requirements for different wavelengths are expected.

Beam delivery, scanning and control

The machine will run for long processing time like over 12 hours in a row without any interruption. All optical systems used to deliver the Laser beam must overcome high power repeatedly and durably without any thermal damage. Low thermal expansion and very low absorptive optical devices are required to ensure no shift of the power delivery of the Laser beam or its location over long processing time. Maintenance of the machine has to be minimal and limited to once a year maximum, no critical damage of the laser beam delivery system should occurs repeatedly.

In order to achieve a surface with the lowest roughness possible, the Laser spot size should eventually match the lateral unevenness of the PCD surface roughness. It is expected to be small considering the nature of the process applied to the surface before the Laser ablation. But surface analyses of PCD surface will have to be carried out to accurately characterize PCD roughness and measure peaks width and set up an accurate target for the laser spot size. However a larger beam spot will be required in a first phase to smoothen surface and efficiently ablate using the high Laser power output. So a modular beam expansion system will be required to adjust spot size accordingly to the processing steps: a large spot size will be used to be then reduced to a size approaching roughness width.

As very high power pulses will be emitted at high repetition rates, they need to be spread onto the PCD surface at a very high speed to minimize thermal damage and reach high material removal rate. So a state of the art scanning system will have to be implemented to direct Laser beam onto the top PCD surface. The next generation of scanner is capable of reaching a speed of 3,000 m/s, the implementation of the new polygon scanning system on the machine is required to ensure high ablation rate and thus a low processing time ensuring success of the project.

Element Six processes a wide panel of PCD grades; the machine will have to capable of processing these various grades. Laser parameters will need to be adjusted accordingly to the properties of these different PCD materials. Flexibility on the Laser parameters is required on the Laser control: pulse length, frequency, power average, pulse divider should be easily tunable.

Safety

As every machine in use on the production floors of Element Six, the Laser machine must respect European safety standards and be CE marked.

Due to the extremely fine ablation of the PCD material during Laser machining, very small particles are expected to be generated. A performing exhaust system is compulsory to ensure total evacuation of these harmful particles and protect health of surrounding operators.

Sample fixation and movement

PCD discs from Element Six have a variable diameter from 75 mm to 76 mm. So the machine must be able to handle various discs sizes. For production efficiency, long process runs are preferable while several discs are machined per run: a minimum of 10 discs per run is required up to 30 discs ideally. The number of discs to be processed has to be tunable on the controlling software. So the ideal fixation system would be to fit only one disc holder underneath the Galvo scanning head with a discs magazine on the side as long as a disc changer replacing discs after the end of the Laser ablation of each disc. The discs magazine and the disc changing/holding system will be design to easily process the various Element Six disc sizes.

A 3 CNC axis system will be mounted to drive the disc holder. This 3 axis will have to move with high accuracy. By only driving one disc holder, the CNC axis can remain quite small which allows keeping an extreme accuracy of the movements more easily. As polygon scanners are one dimensional scanners, the scanned line is only in one direction. The extreme fast scanning system has to be accompanied by a secondary slow superposed linear motion perpendicularly to the line scanned by the polygon scanner, superposed linear motion will be synchronized in speed with the rotating speed of the polygon to generate a 2D scanning of the surface. The Z axis will have to automatically adjust its position to the focal position during the Laser ablating process by using the OCT system feedback which is described in the following paragraph.

Further requirements

A topography measurement system called OCT will be developed to map the topography of the PCD surface up to a high resolution close to a few microns per pixel. The mapping of the topography will result in an image locating the peaks of material present on the PCD surface and their heights. These peaks will be targeted and ablated by the Laser beam to level the surface; each sequence of topography measurement/Laser ablation will smooth the surface, and this sequence of topography measurement/Laser ablation will be iterated until PCD surface is polished.

The resolution of the OCT mapping will directly influence the quality of the ablation. Resolution of the PCD topography image should ideally be matching the Laser beam spot size.

To gain in processing time and develop a viable industrial process, OCT and Laser machine will run simultaneously: topography measurements will run in Laser process control.

5 Class 4 Laser

5.1 Definition of target application

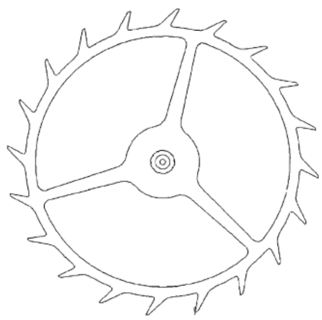
The goal of this application is to use the full advantage of laser technology (flexibility, absence of tooling, no contact process…) while competing with the quality level of traditional machining (milling, etching), and this at an industrial production pace especially on functional parts. This is the only viable way to establish ultrashort pulse laser on a large scale in the watch industry.

The geometries chosen cover a broad range of geometrical features and machining challenges, such as high accuracy, challenging materials, small features, functional surfaces, through holes, a relative high thickness…

This also requires highly precise positioning, high repeatability, a high frequency and energy of the laser as well as a fast switching of the beam.

Table 5.1 shows a summary of target geometry and process key performance indicators required for productive industrial mass production and meeting end-user-quality requirements of the C4L demonstrator applications.

Final specifications for the demonstrator part are ongoing, but will correspond to the values in the table 5.1

Key Performance Indicator	Unit	Target Value
Benchmarking shape Standardized watch arm Standardized Gear	 	
Parts thickness	mm	0.1 – 0.5
Material covered	Metal, ceramic, sapphire	
General dimensions tolerances	µm	From ± 5 to ± 20
Specific dimensions tolerances	µm	From ± 2 to +-5
Smallest holes	µm	From 50 to 100
Maximal side steepness (taper)	Relative to dimension tolerances	
Average cutting speed (relative to shape and thickness)	mm/min	≥ 300
Shape deviation	µm	+- 2
Surface roughness (non-functional)	µm	0.4 (N5)
Surface roughness (functional)	µm	0.1 (N3)

5.2 Systems technology specification

Beam delivery, scanning and control

The optical system of the laser system naturally is required to handle the very high laser power without damage to optical elements and without influence of laser power variations on the beam quality and focus position (e.g. due to thermal lensing). Thus, low absorption coatings and lenses / mirrors need to be implemented.

Several beam delivery will be tested according to the cutting strategy implemented:

- Rotation optic (also known as trepanning optic – C4L)
- Galvanometer scanner (Intelliscan from Scanlab for instance)
- Direct beam cutting optic (From C4L)

The laser and the system have to enable the use of these 3 beam delivery.

Galvanometer scanner is required to provide very high dynamics and a high positioning accuracy, at least delivering state-of-the-art performance.

The state of the art rotation optics have a rotation speed between 3000 and 40 000 rpm. The development of such optic may conduct to speed up to 200 000 rpm in a near future.

Laser source development

The detailed laser specifications are going to be communicated later within the deliverable D1.2 (M12). Still the following input can already be considered:

The laser should be able to work on an equally base with the 3 different kind of sub-mentioned optics.

As CNC and scanner technology are a limiting factor for high pulse repetition rates, requiring fast scanning velocities, the maximum laser power should be available at pulse repetition frequencies of ≤ 1000 kHz. Thus, high maximum pulse energies of ≥ 0.25 mJ (up to 1mJ) are required.

The Laser should be able to work at low frequency as well (≤ 100 kHz for direct beam cutting). A pulse-on-demand function (pulse picker), enabling frequencies from single pulse to the nominal frequency is an important feature.

Further, the tight specifications on geometry accuracy will presumably require synchronization of laser pulse energy and / or pulse repetition frequency with the local scanner velocity, in order to avoid heating during acceleration and deceleration phases of the scanning mirrors. Thus, fast and flexible triggering (pulse on demand) and fast power variation are necessary. The details of these features are going to be more precisely established within deliverable D1.2

The laser wavelength is assumed to be in the 1030 nm regime. However, a wavelength of 532 and would be appreciated.

From the trials already performs, we can conclude that a tunable pulse duration from x00fs to x0ps would be a much appreciated feature. (More precise value will be provided within the D1.2)

The demonstrator laser should include the state of the art features of industrial laser: pilot laser, safety shutter, tunable power, tunable repetition rate. The details of these features are going to be more precisely established within the D1.2 Deliverable.

Safety

The state of the art industrial laser safety rules should apply, to be able to use this laser in an safe environment. (Safety shutter, interlocks, emergency stop…)

In order to handle the high ablated volumes at maximum laser power, a sufficiently powerful laser fume extraction system is required to avoid detrimental effects from fumes and residues (process quality, damage to optics, health and safety).

It is known that material processing with high power ultrafast lasers produces soft X-ray radiation. Thus, proper protection has to be taken into account. Further definition of laser safety and x-ray shielding requirements should be done when optimum processing parameters e.g. laser spot size have been determined.

Sample fixation and movement

In order to allow for the processing of typical watch parts, a sample fixation should be designed which is capable of handling 150 mm parts, square or circular.

A clamping enabling to maintain the parts over an empty space (for traditional cutting and trepanning cutting) is required. There should be the possibility of secure clamping of the work piece.

In order to be able to easily access different positions on the work piece and to allow for a quick adjustment of the focal position, a xyz axis system with a state-of-the-art NC control should be incorporated into the laser process machine.

Further requirements

In order to enable efficient process development, the laser process machine should be equipped with an in-situ camera system to position and inspect the laser processed area (off axis also possible as long as the axes accuracy allow respecting the parts requirement).

The HMI of the machine should allow both for quick manual set up of laser programs, as well as batch programming for larger parameter variations, including the movement of the axis system (e.g. set up of automatic focus search and part position recognition).