Development of an industrial femtosecondlaser micro-machining System

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ABSTRACT

Within the research project FEMTO[1], supported by the European Commission, a compact diode-pumped titanium:sapphire laser has been developed which matches the requirements of industrial systems, like compact dimensions and stable laser operation. To achieve this, the laser has been specially designed to be integrated directly into the machining system. For best process speed combined with optimal cutting quality, focus has been laid upon high repetition rates at moderate pulse energies. Typical average output powers are around 1.5 W and repetition rates of up to 5 kHz. Accompanying to the laser development, a micro-machining system has been designed to meet the requirements of femtosecond laser micro-machining.

In parallel to the machine development, machining processes have been investigated and optimised for different applications. The machining of delicate medical implants has been demonstrated as well as the machining of components for electro-optical devices like acceleration grids and cathodes. The potential of the machining system for general micro-machining of sensitive and delicate materials has been proven. Therefore, the developed machine offers the potential to boost the use of femtosecond lasers in industrial operation.

Keywords: Precision micro-machining, femtosecond lasers, industrial operation, laser machining

1. INTRODUCTION

The competitiveness of modern industry strongly relies on the development and introduction of highly innovative products and technologies of many kinds. Obviously, the required innovation cannot be achieved only by evolutionary development of well established processes but also requires completely new manufacturing processes and techniques. One of those technologies might be found in femtosecond [1 fs = 10^{-15} s] laser machining. In contrast to conventional, well established laser-based machining technologies which have the drawback of being limited in precision due to thermal effects and its consequences, it has been demonstrated that fs laser micro-machining can overcome such limitations and meet sophisticated machining requirements[2-7].

Femtosecond laser sources have been mainly scientific laser systems so far, requiring laboratory environments for stable operation. They have been designed to allow adjustment of many parameters like pulse duration, band-width or central wavelength to enable well-trained users to control the laser's characteristics for their own needs. Although very useful for many experiments, such versatility is often at the expense of high reliability, easy handling and low operation

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costs, parameters which are of interest for industrial applications. This lack of robustness and ease-of-use is one of the reasons why femtosecond lasers have failed to be taken up extensively in industry.

A successful introduction into industry calls for the laser system, to be optimized for easy handling, stable operation and long maintenance intervals. It also needs to be integrated into an appropriate machining system, thus providing laser safety and efficient parts handling. Furthermore, a machining process for the specific application has to be developed. Considering the costs of fs laser micro-machining it is obvious that the only products will can be produced economically are those which have a high added value or which cannot be machined with conventional lasers. Within the project FEMTO, an industrial femtosecond micro-machining system has been developed for the machining of sophisticated applications: manufacturing of electro-optical parts for image intensifiers and the machining of cardiovascular implants. The electro-optical parts for intensifiers are used for electron generation and acceleration. Since the electrons are accelerated by an electric field, the device has to be transparent for electrons, be electrically conducting and to provide a homogeneous magnetic field. Such devices can be designed as metallic meshes with structural sizes of a few microns. Thermal influences in the manufacture of these devices can introduce thermal stresses which can cause major deformation of the mesh and therefore the generated electric field.

Cardiovascular implants (stents) are used as an alternative to avoid bypass operations for surgical treatment of arteriosclerosis in coronary vessels. For this, the stent is placed at the location to be treated and is expanded by a balloon catheter. Currently, stents are left in the vessel to ensure a sufficient blood flow. These stents are mostly machined from stainless steel (316L), which has to be post-processed in order to meet the medical requirements such as x-ray opacity, clean and burr-free edges etc. Unfortunately, the risk of post-operative narrowing (restenosis) is fairly high when the implant remains within the vessel. The implant is being incorporated within the wall of the vessel by extensive cell growth which makes an explantation not feasible. To avoid those effects, the stents have to be biodegradable, which then demands new machining requirements to guarantee the material properties remain unchanged even after machining. Ultrashort pulse techniques can meet these processing requirements for biodegradable materials like biopolymers.

2. METHODOLOGY

The implementation of fs technology into industrial manufacturing can be economically realized in applications, which require specifications which are hard to achieve using existing technology. Therefore, in the work of the FEMTO project reported here, the applications have been defined by the industrial end users Photek Ltd, St (UK) and Biotronik GmbH (GER) with distinct specifications as research goals. The laser manufacturer Thales (F) and laser developer CELIA (F) defined, together with the machine manufacturer Exitech (UK), the industrial requirements of the ultrashort-pulse lasers and machining system respectively.

After definition of all technological requirements, scientific fs laser systems have been used to initially determine optimum process parameters for the chosen applications by Laser Zentrum Hannover e. V (GER). Parameters from these tests have been used to update the key parameters for the novel design of the industrial femtosecond laser source as well as the machine design. In iterative steps of laser processing and prototype testing, the machining process has been established and optimized in close collaboration between process developer and end user.

3. SPECIFICATION OF REQUIREMENTS

The mesh structures for intensifiers are usually produced by lithographic-based methods or by electro-forming and this can produce dimensions of 10-20 µm. The ratio between the spaces between the struts and the sizes of the stuts in the meshes defines the open area ratio (OAR), which determines the electron transmission and is therefore needs to be as high as possible. Although meshes can be produced with the above well-established processes, it is not possible to generate a three-dimensional shape of the struts. As the shape of the struts strongly influences the electron generation, this is an important parameter in obtaining small light intensifiers with good resolution and high gain. The required specifications are therefore high OAR, small dimensional size and defined shape of the metallic grid structures.

Biodegradable materials were invented in the 1960s and have attracted big interest for applications in the medical field for the last ten years[8-11]. In form of biodegradable polymers they are now used within medicine for osteosythesis implants or surgical seam material. Such material has not yet been used for cardiovascular implants, as the manufacturing of such implants has not been realized without affecting the material properties. Structural sizes of biodegradable stents are of the order of 100 µm. Therefore, structural dimension is not a limitation in the laser cutting process, but in order not to alter the properties of the biodegradable material, thermal influence of the machining process has to be avoided as far as possible. As conventional laser techniques do not to meet this requirement, attention is being laid on the reduction of laser-influenced zones during the development of a fs laser based cutting technique. As there is no post-processing available for such materials, cutting quality has to be very high. Any kind of burr causes post-operative complications like thrombosis. etc. and this has to be avoided. Furthermore, evaluation has been carried out on the design of the stents for maximum exploitation of the mechanical properties of the materials.

4. LASER AND MACHINE DEVELOPMENT

4.1 Diode-pumped Ti:sapphire-based femtosecond laser

The principal goal of the laser development has been the realisation of a reliable femtosecond laser which is suitable for the machining of the named applications. In both cases, the influence of the laser machining on the remaining material has to be minimised which, in simple terms, calls for the shortest feasible pulse. This is of special significance for biodegradable materials, as will be shown later. Femtosecond laser pulses with a duration of only few fs have been already generated, but those systems do not yet match the general requirements for industrial laser systems. Therefore, a compromise has to be made on pulse duration and industrial needs. Machining trials have demonstrated that a pulse duration of less than 150 fs is short enough for acceptable results but the lasers from which these pulses are generated are still sufficiently stable and reliable. The required pulse energy is a few hundreds of µJ per pulse, which is realisable with conventional oscillator/amplifier designs using CPA[12] (Chirped Pulse Amplification). It is our view that for the applications in question, it is preferable to have high repetition rates and modest (hundreds of µJs) pulse energies.

The laser performance targets and achieved performance are given in table 1:

Table 1: Targeted laser performance

Laser Performance		planned		realized	
Repetition Rate	kHz	3	5	3	5
Average Power	W	1.5	1.5	1.5	0.8
Pulse Energy	µJ	500	300	500	160
Pulse duration	fs	< 150		135	
Stability	% rms	1		0.8	
Contrast		> 200:1		> 200:1	
Beam Quality		< 2		< 1.2	
Intensity Profile		Gaussian, circular beam		Gaussian, circular beam	

Stability in operation is a further important aspect regarding operation in industrial environments. Temperature shifts often occur, which requires a temperature tolerant system. Two approaches have been taken to reduce the temperature sensitivity of the laser: (i) the oscillator is chosen to be a commercial system with a compact diode-pumped fiber-based set-up, and (ii) the oscillator is incorporated into the laser system, which results in uniform thermal load on all components Which therefore reduces thermal affects. The laser system is designed as a two step amplifier with both a regenerative amplifier and a multipass amplifier, which are configured to maximum stability.

Safety requirements and long maintenance periods are also crucial for industrial operation. To achieve this goal, the user is not given direct access to the laser, but only certain elements can be adjusted by motorised controls via software. This allows for laser optimisation (e.g. output power and pulse duration) to be performed by non-experts For efficient operation and to minimise maintenance time, the system's amplifiers are diode-pumped. Although quite expensive in procurement, diode pumped lasers reduce operational costs.

The system has been developed and tested. Figure 1 shows the schematic internal set-up (a) and the final appearance of the final Ti:sapphire laser (b)

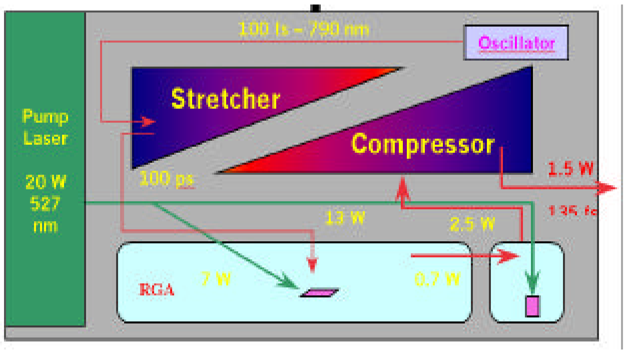


Fig. 1a: Schematic of the set-up of the ti:sapphire amplifier

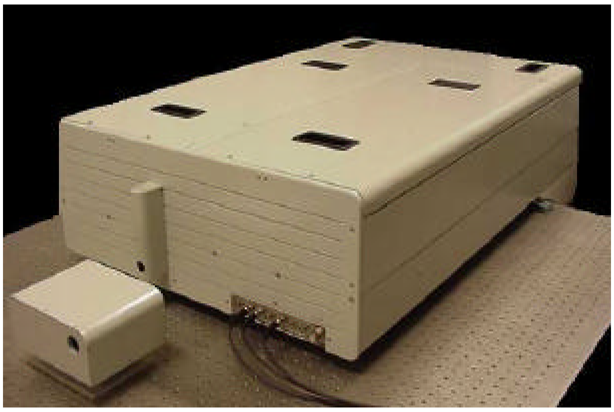


Fig. 1b: Final ti:sapphire laser product

4.2 Directly diode-pumped femtosecond laser

One disadvantage of ti:sapphire is, that it has to be pumped with green light. Presently, frequency-doubled Nd:YAG or Nd:YLF lasers are used for this purpose, with the drawbacks of reduced efficiency and high number of optical components which can fail, resulting in an unnecessarily large laser system. For a optimal system, a directly diode-pumped solution is desirable.

In parallel to the ti:sapphire laser system, a second concept for a direct diode-pumped, solid state femtosecond laser has been developed. The main difficulty of this approach is the fact that direct diode-pumpable gain materials had to be developed, as they were not available at the start of the project. An oscillator as well as an amplifier were subject of the research and development. Due to the required research, the laser specifications had been defined as given in table 2

Table 2: Laser performance of the diode-pumped fs-laser system

Laser Performance		**planned**	**achieved**	**potential**
Repetition rate	kHz	1	3	10
Average Power	W	1	0.6	1
Pulse duration	fs	500	400	250
Pulse energy	µJ	1000	200	100

The key issues for the diode-pumped fs oscillator are to provide the shortest possible pulses (broadest spectrum) in an amplitude-stable pulse train. Additionally, a strong spectral overlap with the gain curve of the regenerative amplifier is required for efficient seeding. Consequently, the most important property of the laser material is a broad effective gain bandwidth. Other material properties, e.g. thermal conductivity, are not as important since the pump power is relatively moderate.

Research has been performed on different gain materials, including Yb:GdCOB, Yb:YAG and Yb:KGW. The shortest pulses have been generated using the broadband material Yb:GdCOB. Using this material 90 fs pulses have been obtained at a central wavelength of 1046nm providing 40 mW of average output power. Due to better thermal stability, Yb:YAG and Yb:KGW have been chosen for the final laser set-up.

It is worth mentioning, that the displayed laboratory laser system delivers 400 fs laser pulses with 100 µJ per pulse at a repetition rate of 3 kHz with a total power consumption of 200 W without the need of water cooling. It is therefore, to our knowledge, the first fully diode-pumped high power laser system in Europe. In its final extension, it will deliver 1W average output power at a repetition rate of 10 kHz. Nevertheless, the system needs to be industrialized before being integrated within a machining system. Figure 2 shows the schematic of the diode-pumped laser system.

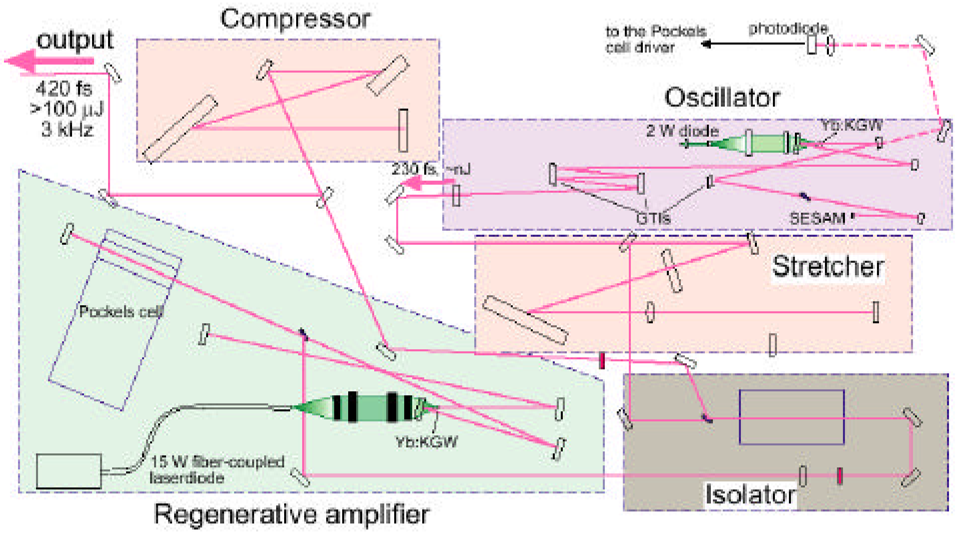


Fig. 2: Set-up of the diode-pumped fs laser system

4.3 Machining system

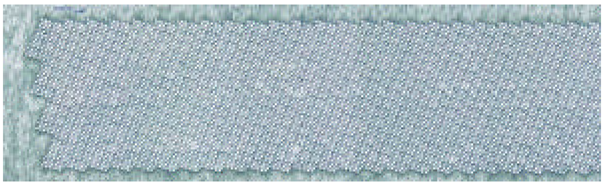
One major aspect on the machine development is the generation of an industrial (compact self-contained) machining system. Besides good vibration isolation and suitable parts handling, it has to provide a class 1 laser safe enclosure. As there are no laser safety glasses which provide full protection against fs radiation, this is achieved using total enclosure of the optical path and using vision systems for part alignment and monitoring. Furthermore, the architecture of the system has been strongly influenced by the experiences of the machining trials. The system is capable of using direct beam focusing or mask-projection techniques for maximum flexibility. A picture of the machining system is shown in Figure 3.

Fig. 3: Completed femtosecond laser system displayed in operation at the LASER 2001 fair in Munich

5. PROCESS DEVELOPMENT

5.1 Metallic meshes

Most photomultipliers use dynodes, which are mostly coated with a material of high secondary emission, e.g. antimony-caesium. Conventionally, dynodes are individually made pressed parts with dimensions on the order of millimetres. Within the latest generation this has been reduced down to a dimension of about 50 µm, which has enabled a reduction of the size of photomultipliers down to 5-10% of their original size. Furthermore, a high number of parallel channels have been introduced within such a conventional sized tube. To reduce this size even further a fs laser machining process has been developed for cutting thin nickel foils. Fig 4 shows different acceleration meshes.



1 mm

Fig. 4a: fs laser machined hexagonal meshes from. 7 µm Ni-foil. Machined by imaging technique in ambient air

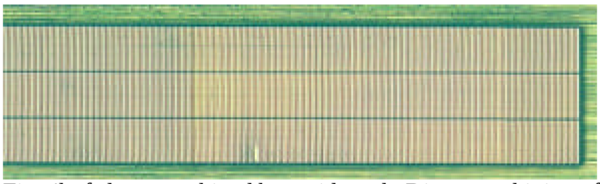


Fig. 4b: fs laser machined bar-grid mesh. Direct machining of 7 µm Ni-foil in ambient air

The main focus was laid upon the generation of metallic meshes with high transmission. By direct machining in ambient air, transmission ratios of 50-60% have been reached (Fig. 4a, b). More complex patterns have also been machined (Fig.3a) in order to reach an even more homogeneous transmission.

The most advantageous effect while laser cutting is the generation of three dimensional structures (Fig. 5a). This enables the machining of dynodes with structural sizes of 10-20µm (Fig. 5b), which can be effectively machined on fairly large diameters. The given example shows a dynode prototype with 12mm diameter (Fig. 5c).

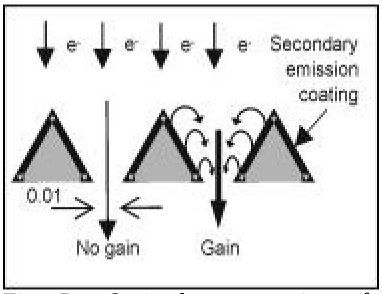


Fig. 5a: Optimal cross-section of the dynode structure

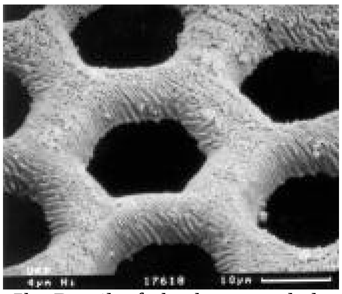


Fig. 5b: Detail of the hexagonal dynode structure, Periodicity of 23µm.

Fig. 5c: Machined Ni-dynode with 12 mm diameter

The overall appearance and general cleanliness of the product is also important as well as the structural integrity of all strut and bars. This is one of the requirements conventional laser techniques usually cannot fulfil. The mesh is held several millimetres from the photocathode at high potential, which creates a field strength of the order of $2 \cdot 10^6$ V/m. Any imperfections or impurities give rise to field emissions and cause serious problems to the finished device. The machined prototype dynodes have been implemented into photomultiplier tubes and have been tested. The dynode gain was measured to be approximately in line with the expectations and will be presented to public in the near future.

5.2 Cardiovascular Implants

Polymers are of great interest for the production of temporary stents (i.e. stents which degrade after a defined time). These polymers can be semi-crystalline thermoplastic polyesters, which have the benefits of being bio-compatible and biodegradable. Due to recent material developments, tubes of polymer blends with very good mechanical properties are now available. However, because this material is very delicate, of the cutting parameters have to be optimised very carefully. Typically, the heat affected areas of the material around the laser cuts reach values up to 60µm if a CO_2 laser cutter is applied. This is too much and a reduction down to 5µm or smaller is required. The comparison between CO_2-laser and fs laser machined stents is given in Fig.6.

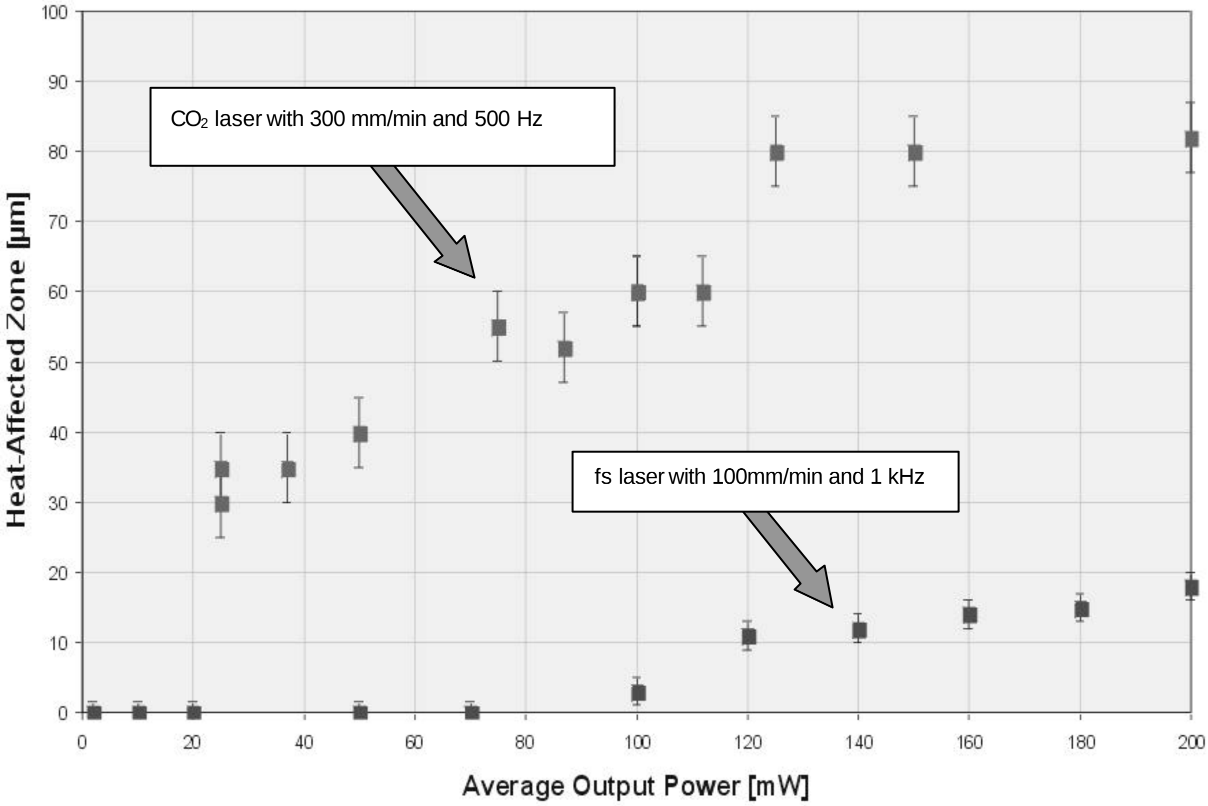


Fig.6: Diagram of heat-affected zones in biodegradable polymers of CO_2 and fs laser machined cuts.

The diagram in Fig.6 demonstrates that heat-affected zones obtained with a ti:sapphire laser at low output powers are not measurable and that at output levels higher that 100mW only a region of about 10 µm is thermally affected. Although the used polymers are transparent to the wavelength of the fs lasers, they can be machined by multi-photon absorption processes. As these effects are highly intensity dependent, it is crucial to use very short pulse duration. Increasing pulse energy is not feasible, as it is followed by thermal effects causing the polymer to melt. Fig. 7a shows the details structure of a bio-degradable polymer stent, and the changes before (Fig. 7b) and after (Fig. 7c) expansion by an balloon catheter.

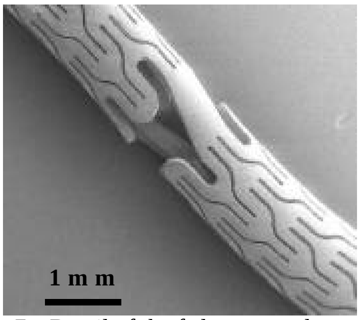


Fig. 7a: Detail of the fs laser cutted stent

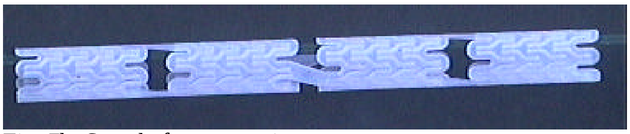


Fig. 7b: Stent before expansion **1mm**

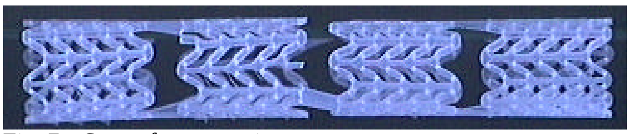


Fig. 7c: Stent after expansion

Besides improvement of the cutting process, investigations on the mechanical behavior during stent expansion have also been tested. The machined prototypes have proven to be very promising with regards to their mechanical integrity.

Nevertheless, further research is still necessary in order to optimize the polymer's mechanical strength further and tobtain better designs for the stent geometries to give minimal recoil.

6. CONCLUSIONS

Considering the processes and systems developed within the FEMTO project, it is clear femtosecond technology offers many crucial advantages in the machining of certain high specification applications. Besides the discussed applications in the medical and electro-optical field, further applications of femtosecond lasers can be found in the automotive sector (drilling of injector nozzles), printing industry (machining of ink reservoirs), electronic industry and medical surgery (dental treatment, eye surgery and cochlear surgery).

The work carried out within the project has demonstrated the potential of femtosecond technology. Further research will be carried out in order to exploit the advantages of femtosecond laser machining. It can be expected that the demonstrated potential of this technology will lead to an introduction of femtosecond laser into industry within the next few years.

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