Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 42 (2016) 475 – 480

www.elsevier.com/locate/procedia

[S1]18th CIRP Conference on Electro Physical and Chemical Machining (ISEM XVIII)

Removal of the Heat Affect Zone created by EDM with pico-second LASER Machining

Georg Wälder* , Jacques Richard *

hepia Geneva, member of HES-SO University of Applied Sciences and Arts
Western Switzerland

* Corresponding author. Tel+41 22-546 2647; fax: +41-22-546 2410. *E-mail address:* georg.walder@hesge.ch

---

Abstract

Metallurgical modifications of machined metal surfaces are created by nearly all machining processes based on thermal and or mechanical processes. The EDM – electro-discharge machining –creates a so called “white layer” or “heat affected zone” (HAZ) having a thickness ranging from a few hundred micro-meters (for roughing operation) down to a few micrometers (for finishing). This remaining HAZ is a problem for many industrial applications: the presence of micro-cracks and metallurgic inhomogeneity inherent to thermal stresses reduces part lifetime of tools, etc. due to fatigue stress.

The study presents a method to remove the HAZ created by Die-sinking EDM on warm working steel (W300) by cold ablation with a pico-second LASER. Technologies & strategies for Laser machining have been developed. The laser machined samples have been metallurgical analysed to prove the removal of the white layer and assure that no heat impact due the LASER machining was created, eg. only cold ablation took place. Fatigue test samples have been prepared by EDM machining and either EDM finished or finished by pico-second LASER in order to compare the lifetime both kind of samples

Peer-review under responsibility of the organizing committee of 18th CIRP Conference on Electro Physical and Chemical Machining (ISEM XVIII)

Keywords: EDM; Laser machining; heat affected zone; fatigue life-time

---

1. Introduction

Most modern micro- manufacturing technologies for material processing focus on geometrical precision as well as on surface integrity. Conventional technologies as well as electro-discharge machining (EDM) are approaching physical limits as there are contact based processes and / or creation of thermal impact. Laser based manufacturing has particular benefits with high accuracy, repeatability and flexibility. Most materials can be processes by Laser without need of any tool. Depending on the Laser pulse width, the physical material removal process will change. Having long LASER pulses (eg. >0.1 nano second) a melting process similar to EDM takes place and a heat affect zone will be created.

Using ultra-short LASER pulses allow to have a cold ablation process where material is directly evaporated, without passing through a liquid - melted phase. Here heat impact is supposed to be negligible, eg. No heat affected zone on the surface of the machine material will be created.

This effect is known [1] when using pulse with a duration below 100 fs where we can access new ablation process like multi-photon ionization. Due to the short interaction time, only the electrons within the material are heated during the pulse duration. Especially for low fluences, where thermal diffusion length is smaller than the optical penetration depth, heat diffusion can be strongly suppressed.

Interaction of the laser light with material depends on material properties, as well as surface quality (roughness, reflectivity) of the sample to be machined. The ratio of the actual laser fluence to the ablation threshold is a measure of the material excitation. As the fluence of the pulse with fixed energy depends on the size of the beam spot, it can be easily controlled by variation working distance relative to the focal plane.

Peer-review under responsibility of the organizing committee of 18th CIRP Conference on Electro Physical and Chemical Machining (ISEM XVIII)
doi:10.1016/j.procir.2016.02.235

According [2] the ablation efficiency can be geometrical optimized for fluence close the ablation threshold, when no plasma is present. At high energy densities, laser radiation ignites plasma and energy coupling might be affected by the ablation products itself. Typical time this process is a few pico-second, thus critical for pico-second laser machining. The reflectivity of the exposed material influences this threshold. As the reflectivity of metals depends on their chemical composition, an adjustment of the applied fluency is necessary.

The typical method of machining with ultra-short laser pulses is realized by raster scanning, or the machining of sequentially overlapping linear trenches. Material removal rate might be increased with the mean laser power and / or pulse repetition rate [3]. Nevertheless, overall material removal rate remain small compared to conventional machining process or roughing operation by EDM. Therefore, high accuracy of processing can be achieved.

EDM is a well-established process in micro-machining, despite its thermal impact created on machined material surfaces. Latest EDM generators, able to machine polished surfaces, reduce the heat affected surface zone (HAZ) to a thickness down to a few micro-meters but in a time consuming manner. Thus mechanical polishing is often applied to remove the HAZ after EDM. Both manual and robot- controlled polishing cannot guaranty geometrical accuracy, rounding of sharp edges will appear as well as removed layer thickness may variate or is simply not possible to access**.** The ultra-short LASER machining using femto second pulses at high frequency is known to not create a HAZ, and whereas nano seconds will create HAZ. The frontier between both is supposed to be at a few pico seconds. In this study we investigate to use of pico-second Laser pulse to remove the HAZ created by EDM, which is also has the advantage to guaranty geometrical accuracy due to small removal rates.

In the present study we first created samples by EDM die-sinking having a HAZ on typical tool steels, like warm working steel (W300). Technologies & strategies for Laser using ps-pulses have been developed to remove the EDM created HAZ by Laser. These samples have been metallurgical analysed and we proved that this HAZ could be removed by LASER cold ablation, eg. without creation of a secondary HAZ. In order to investigate the potential gain in lifetime of real parts manufactured by such a combination of EDM and LASER machining, samples for fatigue bending test had been prepared by EDM machining and either EDM finished or finished by pico-second LASER. In the same way inserts for plastic injection molds have been machined by EDM and finished by LASER. For both cases we compared lifetime tests.

2. Experimental work

2.1. Equipment

A commercially available laser, Ekspla Atlantic series, emitting 1064 nm, frequency doubled ,e.g. 532 nm radiation, was used in experiments. This Laser was generating 10 ps-long pulses at repetition rates of 100 kHz. The maximum output power was up to 8 W @ 532 nm

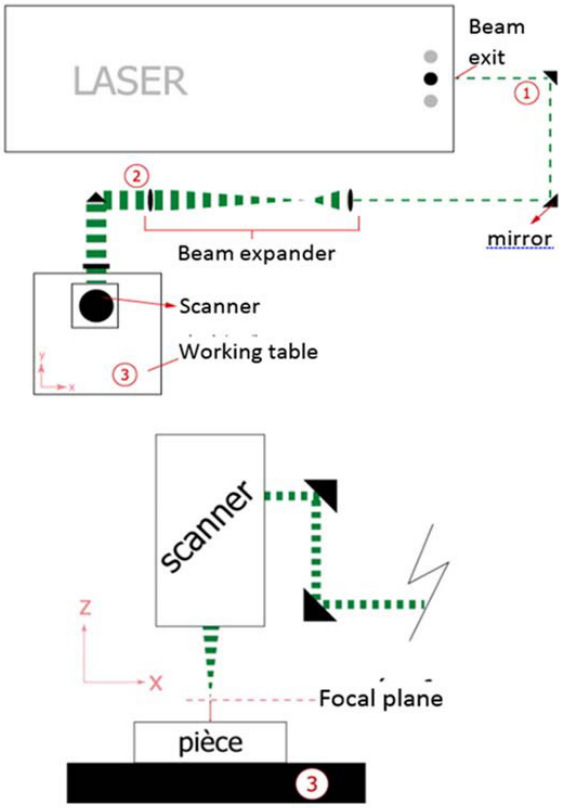

Figure 1 view of Laser system a) top view b) side view

The laser beam was expanded to the diameter of 10 mm and directed to the galvoscanner intelliScan 14 (ScanLab). Laser radiation was focused on the sample by telecentric lens with the focal length of 100 mm. The spot size was 10 µm. The scanner was controlled using SAM Light software (Scaps). All elements e.g., Laser, optical elements and Scanner had been installed an a granite table. See Fig. 1

Workpieces can be moved in X-Y direction as they are placed on a manual movable screw table .For vertical z movement this xy-table is fixed on a motorized ball screw translation stage (Altechna 8MT167) having a repeatability of 1.5 um. Thus working distance in z could be variated via computer control.

Laser power was measured at the machining table after the f-theta-lenses of the scanner , (as well as directly at Laser exit using a Ophir PA12 power meter having a power range from 2 mW up to 12 W and accuracy of +/- 3 %.

Material of fatigue testing samples was a typical warm-working steel, W300 from Böhler, being hardened to around 55 =HRC. W300 is also known as X38CrMoV5-1, or EN/DIN 1.2343. Injection mold samples had been made of K107 cold working steel, also known as X2CrW12, or EN/DIN 1.2436. The metallurgical compositions are listed in table 1

Table 1 metallurgical composition of samples

Material	C	Si	Mn	Cr	other
W300	0.38 %	1.10	0.40	5.0	1.3 % Mo
K107	2.1	0.25 %	0.40	11.50	0.70% W

2.2. Analysis Equipment

A Mahr Perimeter was used for roughness measurement of machined samples. Due to the typical only a few micrometer thickness of the LASER removed material layer, this device was also be used to determine the depth (eg. volume) of the material removed by Laser ablation. In addition we used a WERTH 3D measuring machine equipped with video check UA and Foucault LASER for detail depth measurements of removed layers as well as to measure width of Laser machined lines. For selected detailed inspections of micro geometries, a KLA Tecnor Stylus was used.

A spectrometer from Ocean Optics, serie USB2000+ was used for the measurement of the optical reflectivity of the steals used (K107 & W300) in the visible range

2.3. Design of the fatigue test samples

The fatigue test samples had been designed to allow mechanical constrain between 0 and 1000 MPa –compatible with the used testing machines.

Unlike conventional flat specimens flexural fatigue, in which the maximum stress zone is reduced to a single line, we wanted to define a large area in which the stress is constant: having a high stress zone (red) in the center of the sample with reduced width, see Fig.2. This will solicit greater number of cracks and therefore achieve a more meaningful test against real cases. The blue end parts are used to fix the sample in the apparatus shown Fig 3. These tests are tougher than those published in the literature. Simulations have shown in the case of conventional test shapes, with a semicircular shrinkage, that the maximum stress region is not located at least bending, but closer to the fixed heel.

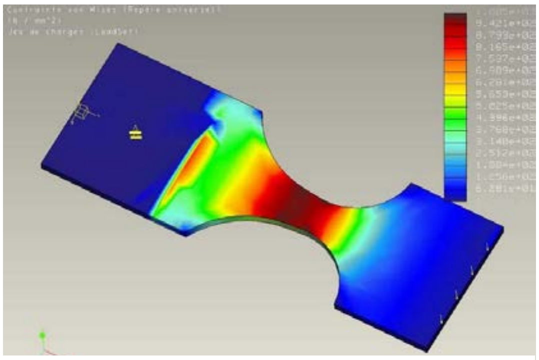

Figure 2 FEM simulation of fatigue test samples

Figure 3 Fatigue test apparatus

2.4. Manufacturing of test samples

All fatigue test samples first had been cut by wire EDM out of the same block of hardened W300 steel. Then the central zone of these samples had been machined using a “Charmilles Roboform 350” die-sinking machine on both side down to a sample thickness of about 2.0 mm. A standard, sequences of EDM parameter technology (recommended by machine manufacturer) was applied to achieve a final roughness of typical Ra = 2.0 µm for the samples to be LASER machined, and Ra= 0.2 µm with EDM- polishing for same samples for comparative tests without any LASER treatment. In a previous project, same kind of sample had be manufacture and in addition samples had been finished by die-sinking EDM using a powder suspended die- electric liquid instead of LASER treatment. There the samples had been fixed on a special designed reservoir containing standard dielectric oil (flux ELF II) with 2 g/l of graphite powder additive and EDM machining was performed down to a polished surface of Ra = 0.2 µm roughness.

Due to limitation of remaining qualified material (where more the 50 fatigue test samples had been tested under standard conditions, only 4 samples for Laser, 4 EDM polished and 2 EDM standard samples could be manufactured. Thickness of each sample was measured by micrometer to adjust the bending distance in order to expose them to the desired bending stress (650 / 750 MPa).

2.5. Preparation of samples

2.5.1. Optimization of laser beam focusing

In order to align the position of the work piece surface in z-direction to given focal distance f (defined by the f-theta lenses) we machined lines at different z-distances of the workpiece and measured the width of the lines. The z-position smallest line width was defined as the optimum focal distance.eg. zero working distance. At this distance we could achieve the smallest possible spot size, e.g line width. The line with was measure at 10 different positions using the Werth video microscope (see Fig 4.) The smallest mean line width was found to be 10.8 +/-1 um. This result was cross-checked by KLA-Tecnor Stylus Profiler (fig 5.). The experimental value found was 10.8 µm for the spot diameter which fits well with theory $d = 1.27 * f * \lambda * M^2 * 1/D \approx 10$ µm (1) , with D = 10 mm beam diameter at entrance of f-theta lenses and $M^2 = 1.5$.

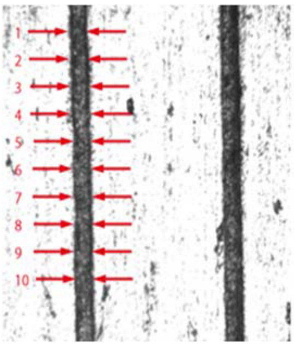

Figure 4 Determination of line width

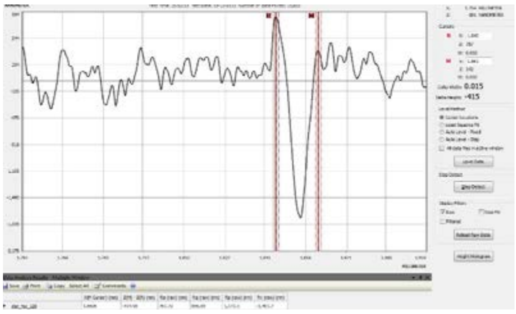

Figure 5 Line profile measured with KLA Tencor

2.5.2. Determination of the working distance

Having defined the z-distance with the thinnest line width as the optimum focus distance, (e.g achieve the smallest possible spot size, we had been looking to optimize the material removal rate. With constant setting our Laser at 100 kHz, 532 nm and a Laser power (typ 8 W at output = 5.6 W at surface) the working distance (wd),was changed, keeping all other parameters (scanning speed, frequency etc.) constant while The depth of the captivities was measured with help of the surface profiler (and cross checked by the Werth 3D machine). A typical profile of the ablated zone is shown in figure 6

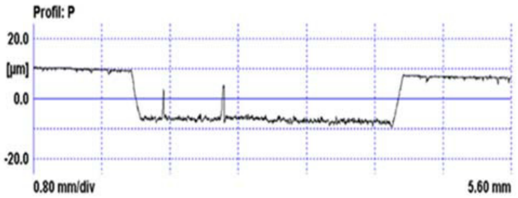

Figure 6 Measurement of removed layer thickness

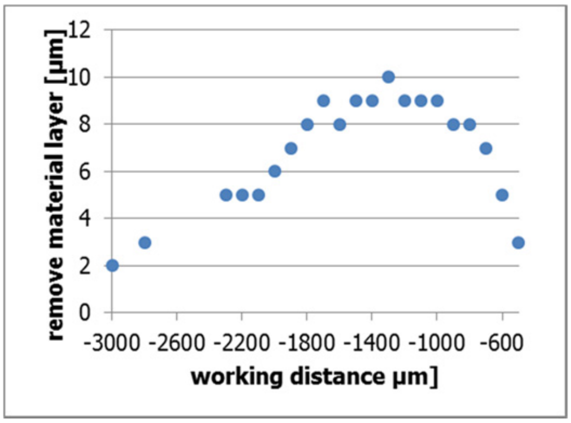

Figure 7 Material removal as function of working distance

The thickness of the removed material layer was found to follow a "Gaussian like shape profile having a maximum removal at a work distance *wd* out of focus of typical 0.5 to 1.5 mm. See figure 7.

No material removal takes place if *wd* exceeds a certain value and removal is reduced when *wd* is getting close to zero. The value of this optimum work distance *wd* depends on used laser power as well as the kind of material machine. Having high power and/ or material with low ablation threshold, the optimum *wd* is far from the focus plane.

2.6. Design of the fatigue test samples

The HAZ of the EDM-samples for fatigue tests (made of hardened steel W300) was removed in the central part of the sample by using 100 kHz 532 nm, 4.2 W (at working zone), a scanning speed of 200 mm/s (hatch line distance of 2 µm eg. identic to the displacement of 2 spots due to scanner movement) and a working distance of 0.6 mm. The thickness of the removed layer was about 20 µm, thus the HAZ was completely removed.

The mould inserts made of K107 consist each of a cavity of 30 * 37 mm^2 and 4.8 mm depth, which was finished by sinking EDM down to a roughness of Ra = 2.0 µm (+/-0.2 µm) . The remaining HAZ was removed using 5 W (80%) of LASER power, 100 kHz at a working distance of 0.6 mm with a scanning speed of 200 mm/s and a line distance /hatch of 2 µm. The removed layer thickness was estimated to about 16 µm.

3. Results & Discussion

Figure 8 a & b show the metallurgical cross section of samples of W300 & K107 steel after polishing and chemical attack with Nital. The heat affected zone, also known as "white layer created by the sinking EDM is clearly visible on left half of the section and has a thickness of about 10-12 µm. On both samples the HAZ could be removed – see right half of the section for the K107 and right for W107 - by cold ablation using 10 ps LASER light at 100 kHz.

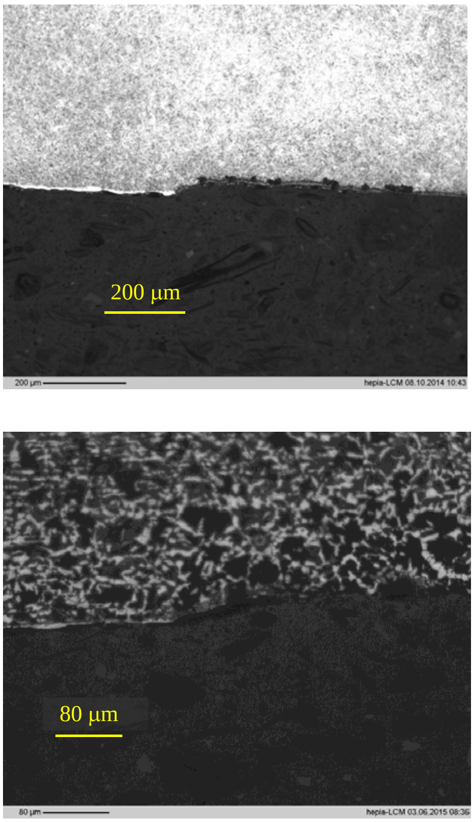

Figure 8 White layer (left parts) and removed HAZ (right half) top for W300, bottom K107

This demonstrates that “cold ablation” of the HAZ is possible by using a 10 ps Laser pulses without creation of a secondary. In most cases, the HAZ is thicker than visible white layer. Thermal stress can introduce micro-cracks, not visible by microscopy, but this cracks might reduce lifetime of parts exposed to bending stress or friction.

Concerning the comparison of the influence of material and surface quality on the material removal rate: Laser ablation of W300 compared to K107 steel using identical conditions gave a 5%- 17 % higher material removal for the W300 steel, both for polished (Ra= 0.3 um) and EDM-surface (Ra= 0.8 um) . Samples prepared by sinking EDM also had a higher material removal than polished samples. See table 2.

To understand this difference of the material removal which clearly depends on kind of material as well as on surface quality, the reflectivity of the samples was measured in the visible spectrum form 400 nm to 800 nm, see Fig.9.

Samples made of K107 have a much higher reflectivity for both machining methods (EDM, polishing) than similar samples made of W300, reaching about 56% at the used Laser wavelength of 532 nm for polished sample compared to about 18 % for W300. This difference in reflectivity might be one of several reasons causing the difference in material removal for the 2 kinds of material. In fact reflected light cannot interact with the material and result in less material removal. It has to be mentioned that both samples had the same roughness before Laser machining using identical fluency and scanning speed, an improvement of surface roughness was not intended in this study.

Table 2 Material removal

Material		**W300**		**K107**	
	# layers removed	Ra	Removed material layer	Ra	Removed material layer
Surface	[-]	[µm]	[µm]	[µm]	[µm]
Polished by Grinding	1	0.44	21	0.46	17.5
	3	0.84	58	0.85	58.3
	5	1.73	100	1.25	91.7
Die-sinking EDM	1	0.96	20	1.31	18.75
	3	1.7	66.7	0.94	62.5
	5	1.85	116.7	1.06	100

For final prove of crack removal, the developed technology was applied on the test samples for fatigue life made of hardened W300. Figure 10 details the S-N curves for samples machined by standard sinking EDM: sinking EDM using a graphite powder suspended die-electric liquid (EDM-G), EDM polished samples and LASER treated samples. A curve for standard sinking EDM from literature was added for comparison [4].

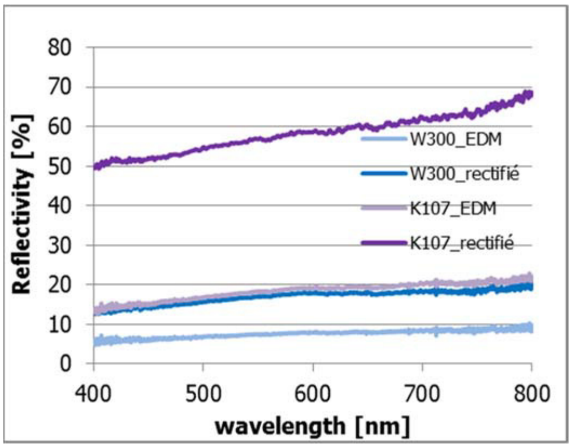

Figure 9 Reflectivity of K107 and W300

The number of bending cycles for all laser treated samples was up to 40 % higher than the number for EDM polished samples at corresponding bending stress. This indicates that Laser treatment not only removes the white layer completely without introduction of secondary thermal defects, but also the not visible micro-cracks had been removed.

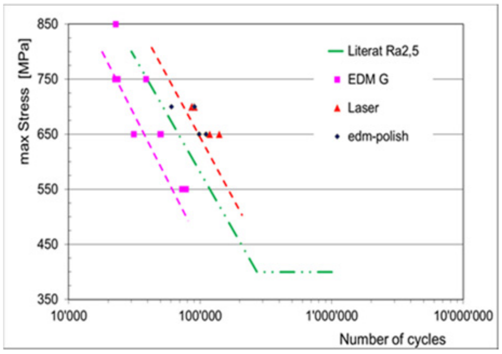

Figure 10 SN-curve : # fatigue bending test cycles

A final conclusion for an exact number of the expected lifetime would require to test much more laser machined samples and compare the result with pure EDM machines ones. Both kinds of sample should be made out of same material block to eliminate intrinsic cracks due to casting and head treatment of the material. As mentioned the remaining block of previous tests comparing EDM with and without powder additive in the die-electric liquid allowed only to manufacture a limited number of pieces

4. Conclusion

Machining of material by EDM introduces a heat affected zone (HAZ) at the machined surface. This HAZ is known to impact the lifetime of parts like injection molds or parts exposed to bending stress. The presented study demonstrate that it is possible to remove the white layer completely by cold ablation using pico-second laser radiation, e.g without introduction of secondary heat effect. First fatigue bending tests also show an improvement in cycle numbers (= lifetime) compared standard or EDM polished samples, thus indicating the absence of micro-crack, eg. HAZ. This Laser machining technology will allow to remove the HAZ locally on selected areas which are exposed to stress impacted and thus increase the lifetime of the treated part. Thus resulting in a big economic potential to increase tool-lifetime in mold & die industry or manufacture stress sensitives parts by EDM. A detailed study having more samples should follow based these very promising results to give precise numbers of lifetime prolongation. The measured difference of optical reflectivity between W300 and K107 give an indication for the difference in material removal by LASER ablation. In surface texturing using nano-pulses of fiber lasers the difficulty to structure high-chromium steel (like the K107) is known, a more detailed study will be necessary to show if the measurement of the reflectivity could be an indicator to adjust Laser machining setting.

Acknowledgements

The presented work was support by the HES-SO, Western-Switzerland, EcoSwissMade Program, under the project “AZAT” and by the as well as on CTI- project “Flew” No 7396.2-EPRP. . We also like thank to J.M Boechat for performing of the injection molding and to A. Chan who performed several of mentioned tests during his Bachelor thesis

References

[1] J.Meijer et al., Laser Machning by short and ultrashort pulses. CIRP Vol 51, 2002, 531-539.

[2] J. Furmanski, A.M. Rubenchik, M.D. Shirk, B.C. Stuart (2007) Deterministic processing of alumina with ultrashort laser pulses, J. Appl. Phys., 102, 073112

[3] G. Raciukaitis, M. Brikas, M. Gedvilas EFFICIENCY ASPECTS IN PROCESSING OF METALS WITH HIGH-REPETITION-RATE ULTRA-SHORT-PULSE LASERS, Eskpla Application notes. Laboratory for Applied Research, Institute of Physics, Savanoriu Ave. 231, LT-02300 Vilnius, Lithuania

[4] R.Perez et al. Advanced Strategeis for improving the Surface Integretiy in EDM, ISEM –XVI ,2010 & CTI-project Flew 7396.-2 final report, confidential