COMSOL Assisted Simulation of Laser Engraving

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Abstract: Laser engraving is becoming an appealing option for those applications where previously Electrical Discharge Machining (EDM) was the only choice because of its advantages with practicability, time and cost. Laser engraving technology removes material in a layer-by-layer fashion and the thickness of layers is usually in the range of a few microns and it is depending on several parameters such as the specimen material, laser power, Transverse Electromagnetic Mode (TEM), and beam traverse speed. The crucial first step in the setup process is to find out the depth of material which will be removed in each layer and is traditionally done off-line by trial-and-error technique. This is a lengthy process in which the operator must alter the laser parameters such as power and traverse speed gradually and use a microscope to examine the quality and measure the depth of removed material. For new materials, which may be very expensive, this process could take weeks and become very costly.

The main purpose of this research project was to develop a proof of concept software that could simulate the geometry of engraved surface and estimate the depth and width of an engraved groove and its associated laser parameters.

For simulation purposes, COMSOL was used to simulate the moving laser beam as a source of heat over physical domain made of different materials. Through interaction modeling of selected materials with the laser beam in TEM01 mode, the temperature distribution was determined. The temperature is the key parameter to determining the geometry of an engraved groove. As the laser heated the material and the temperature passed the vaporization point at high power intensity, the density of the material would switch to the density of air to form the groove. The simulation results were validated by several experiments.

The simulation software can be improved to include more parameters and become a basis for a powerful laser engraving simulation package. The benefits of such a package would be big saving in setup time and material costs for customers who are testing laser engraving on the new and expensive materials. The software would also be an effective tool for the development and evaluation of new engraving techniques with an eye towards reducing wear-and-tear on the actual laser engraving machine and the elimination of a destructive testing procedure.

Keywords: Laser engraving, Laser parameters, COMSOL modeling, material removal.

1. Introduction

As industrial laser applications continue to grow with the development of new laser technologies, laser engraving has become one of the most attractive areas among these technological advancements. The advantage of laser engraving is apparent over some conventional machining methods such as EDM as it is more efficient and economical. As laser engraving is a process of removing layers from objects through vaporization, one of the most important parameters of the process is in determining the thickness of the layers. The common technique for obtaining the proper thickness and its associated laser parameters is an iterative-based process in which the laser parameters are changed individually and the resulting engraving is examined to determine accurate depth and width. To achieve the best engraving results, this trial-and-error process can take from several days to several weeks.

In laser engraving, the process inputs fall into two groups, fixed and variable (controllable). Some of the fixed inputs include laser optics, wavelength, beam profile, ambient temperature, and specimen material and dimension. Some of the controllable inputs include laser power, pulse frequency, and traverse speed. Obviously, the desired process output is good quality engraving characteristics such as smooth edges, good surface finishing, and creating clear and fine details.

The objectives of this research were:

- To generate a computer simulation of laser engraving for a simple line
- To take a fundamental step towards simulating a complete layer and subsequently laser engraving of a 3D object

Some benefits of a computer simulation such as this are as follows:
- The software can be used to fine-tune the laser parameters such as speed, power, and pulse frequency to ensure quality engraving. The depth of engraving will be predicted and as a result the thickness of layers will be determined.
- Identifying more effective parameters involved in the process of laser engraving.
- A tool for evaluation of new engraving techniques without wasting actual machine time. These new techniques may enable good quality engraving on curves surfaces, eliminate side effect of segmentation for engraving over large areas, and improve the continuity of engraving when using Q-switched lasers by tuning repetition rate.
- To assess laser engraving impacts on new materials (e.g., thermal stress generated during laser engraving can lead to microcracking which in turn affects mechanical properties and may induce corrosion in metals).

In this research, COMSOL[1] Multiphysics is used for simulation purposes to mathematically model appropriate heat transfer physics. COMSOL is a Finite Element Analysis (FEA) software package that allows the user to develop 3D models with associated boundary conditions. The material properties and equations can be defined within the program to yield an accurate representation of the problem. Using post-processing function of COMSOL, the data can be returned for visual representations which help to assess the results.

2. Physics

The design of laser material processing requires an understanding of laser theory and heat transfer such as conduction and convection. This understanding can be obtained through a reliable simulation. As stated in the objectives list, the simulation will determine the temperature distributions through a physical domain while it is exposed to a moving laser beam with known parameters. This will increase understanding of laser heat flow in material processing which in turn will help in prediction and process improvement.

The heat conduction principle is considered and solved as the main physics for this problem. The speed of conduction depends on the material density, specific heat capacity and thermal conductivity, the difference in temperatures, and the shape of the conductor.

$$\frac{\Delta Q}{\Delta t} = -kA\left(\frac{\Delta T}{\Delta x}\right)\rho C_P \frac{\partial T}{\partial t} + \nabla.(-k\nabla T) = Q$$

(1)

where:
Q is heat
t is time
k is thermal conductivity
ρ is density
C_p is specific heat capacity
A is the cross section of the material
T is the temperature in difference
x is the distance between the heat sources

Equation (1) is considered to be solved for its transient response under these conditions:
- Moving laser beam at 50 mm/s along a 40mm-long straight line
- 100-micron laser spot considered as a moving heat flux boundary condition with Q=0
- TEM01 considered for heat flux distribution over the laser spot
- Heat flux will be the multiplication of laser intensity by material absorptivity coefficient as *Pxy*Absorptivity*
- Absorptivity will be a function of temperature that yields a new value as the material melts

Heat flux will switch ON and OFF at given frequency (a true q-switching model needs the understanding of the relationship between the duty cycle and pulse peak power)

3. Problem Statement

The problem was defined to estimate the maximum depth and width of engraving. The parameters for this problem are as follows:

- Hermit-Gaussian laser beam working at TEM01 mode
- Beam diameter = 0.1mm
- laser power = 73W
- laser beam velocity = 50mm/s
- Substrate materials are Steel Din 1.2767, Aluminum, Copper, and Brass
- Ambient temperature of 300K

4. Material Properties[2]

In Table 1, the most important properties of the materials for our test purposes are listed, including melting and vaporizing temperatures, and absorptivity percentages in the solid and liquid (melting) states. Notice the high absorptivity for steel and aluminum and low absorptivity for copper: a tremendous increase in absorptivity percentages takes place when temperature passes the melting point.

Table 1. Materials Absorptivity at 1064 nm

Mat.	ρ- kg/m^3	Tm (K)	Tv (K)	Abso-Solid	Abso-Mel.
Steel	7850	1808	3003	0.36	0.9
Al.	2700	933	2333	0.2	0.8
Cop.	8700	1356	2903	0.1	0.35

When the laser beam strikes the material only a portion of laser energy is absorbed and the rest is diffusely reflected. The absorbed portion is converted to heat and melts the material. If the laser power intensity is high enough it can eventually evaporate the material. Therefore, the absorbed part is playing a major role in laser material processing. Absorptivity percentage for metals and transparent materials are defined as:

- For metals: reflectivity=1-absorptivity
- For transparent materials: reflectivity =1- (transmissivity+ absorptivity)

And it is a function of several factors as listed below[3]:

- Wavelength (roughly, the shorter the wavelength the higher absorptivity)

- Temperature (much higher absorptivity at melting state)
- Surface oxidation thickness (acting as anti-reflection coating)
- Angle of incidence
- Material and surface roughness (roughness increases diffuse reflection)

5. COMSOL Modeling

The heat transfer module of COMSOL is used to solve Equation (1) for its transient response. The 3D model of the physical domain can be developed in COMSOL and then the boundary conditions need to be defined carefully. The position of laser path which defines the trajectory of moving heat source must be given to the software. For our case this path is a straight line. The next step in COMSOL modeling is to mesh the physical domain and specify finer mesh size wherever a higher accuracy is required. Solving and post processing are the last two steps.

In laser material processing we are dealing with a multiphysics environment which COMSOL is capable of creating. The complete problem involves the physics of optics, electromagnetic wave (RF), heat transfer, and electro-thermal interaction. For this round of modeling, the laser beam is simulated as a moving heat source over the physical domain which can be defined by Equation (1) if the right hand side of the equation is set to zero and the moving heat flux is considered as the boundary condition along the defined path. For further modeling, physic optics can be brought into the simulation and we can examine some laser optics effects such as beam aperture size, bean expansion factor, q-switching, and spot overlap.

The technique used to find the geometry of an engraved groove is primarily based on the temperature. As a laser heats up the material and the temperature passes the vaporization point for high power intensity, the density of the material will switch to the density of air. COMSOL offers an alternative technique using its moving mesh mode in which the meshes are deformed and moved according to temperature gradient or any other user defined function.

In the following sections, the beam profile, P_{xy}, are defined first. Then the effect of mesh

sizes will be discussed before presenting of the simulation results.

5.1 Hermite-Gaussian Mode (TEM01)

Figure 1 shows an image of beam profile for LP100. In this figure the colors indicate the intensity of laser across the spot when working at 3 KHz. This pattern is similar to TEM 01 or Hermite-Gaussian mode, HG01. TEM01 can existed in two configurations as shown in Figure 2 part (b) and (c), vertical and horizontal.

As the experiment indicated in Figure 1, the LP100 can be represented by vertical configuration of TEM01, part (b) of Figure 2. The 3D surface which can represent this mode is shown in Figure 3.
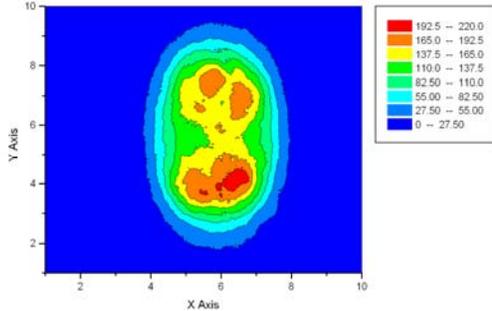
Figure 1. Beam profile for LP100 at 3 KHz
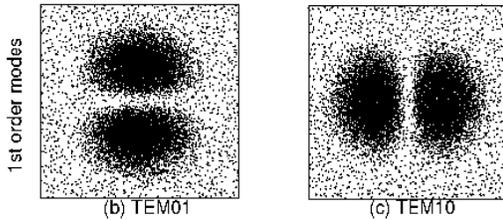
Figure 2. Two configurations of TEM01
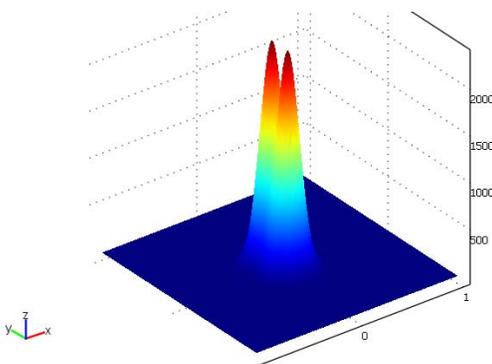

Figure 3. 3D surface to represent TEM01
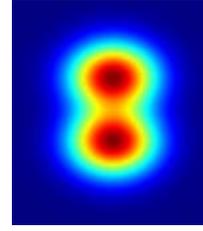
Figure 4. Width of model can be adjusted by β

Using Hermite polynomials, we are able to define the mathematical model for this mode as follows:

$$Pxy = \frac{K\,P}{r_b^2 \pi} \exp\left(\frac{-x^2}{\beta r_b^2}\right)\left(\frac{y^2}{\alpha^2+1}+4\alpha^2 r_b^2\right)$$
$$\exp\left(\frac{-y^2}{4r_b^2(\alpha+1)}\right)$$

(2)

where
P_{xy} is the intensity
P is power of the laser
r_b is beam radius
β, α, and K are the beam size correction factors

In Equation (2), tuning β will adjust the width of the beam in x or horizontal-direction as seen in Figure 4. Tuning α between zero to one can result in the maximum and minimum changes of the beam profile in yz-plane according to Figure 5. In this figure, α is 0.2, 0.5, and 0.8 for the red, green, and blue profiles, respectively. Finally K acts like a gain to adjust the maximum intensity of the beam for being equal to $\frac{P}{r_b^2 \pi}$.
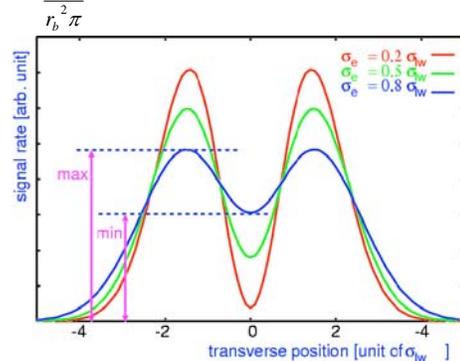

Figure 5. Changing α can result in changing of the max and min of the beam profile

For this problem, the beam diameter is measured 0.1mm (100 μm) and for laser power of 73W, the size correction factors are as follows:

α=0.66, β=8, *K*=6.5e6

Once the Hermite-Gaussian TEM01 formula was designed to model the beam mode it could be used for defining the distribution of laser intensity over the beam spot.

5.2 The Effect of Mesh Sizes

Before solving of the model, the meshing and mesh sizes need to be defined. These values are very important and can have a huge impact in the precision of the results. Figures 6 and 7 show the low and high number of meshes around the laser path on the center of the top surface of the material block. In these figures the block of 50 by 50 by 11 mm made of Steel 1.2767 are created first. The 40 mm-long laser paths on the center of the top surface are defined next. The meshes are defined with variable sizes as seen in the figures. The mesh sizes are much smaller around the path of the laser for greater accuracy (down to 5 micron in Figure 7). A finer mesh increases the total number of meshes and hence increases the computer simulation time.
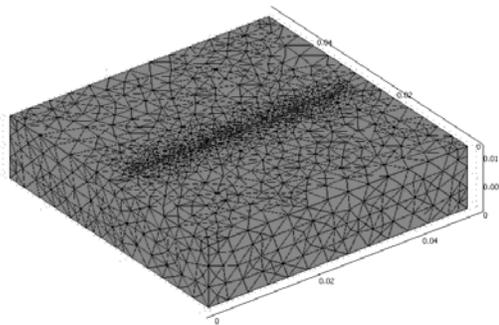

Figure 6. Low number of meshes
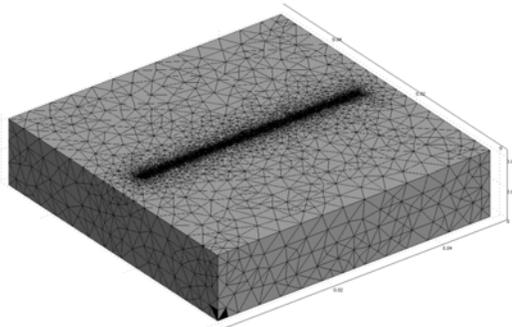
Figure 7. High number of meshes

5.3 Simulation Results

In this section, the inputs and outputs (results) of simulation are presented.

Inputs:
- Material properties such as absorptivity at solid and melting states, melting and vaporizing temperatures, density, heat conductivity, and specific heat capacity
- Material geometry and dimensions
- Ambient temperature
- Beam properties spot size, beam profile, power, speed, and frequency

Outputs:
- Geometry of the groove: depth and width
- Temperature distribution
- Animation of laser engraving

In Figure 8 the physical domain modeled for Steel 1.2767 is shown. The laser beam will move along a straight line on the top surface. In Figure 9, the software produced the heat distribution according to TEM01 beam profile. The vertical temperature penetration can be found in any point along the laser path as shown in Figure 10. More 2D simulations are shown in figures 11 and 12. In 2D simulation fairly fine meshes can be used without facing problems such as memory shortage or lengthy simulation time.
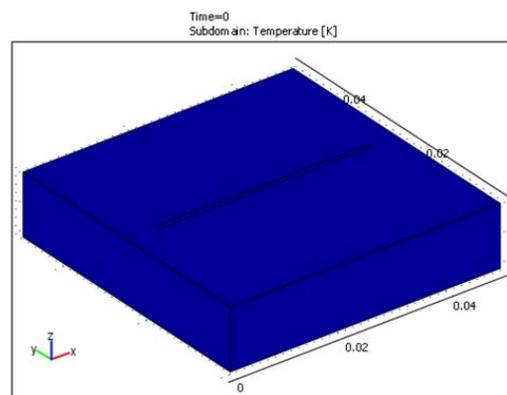

**Figure 8.** The block of Steel 1.2767 modeled along with laser path on the top
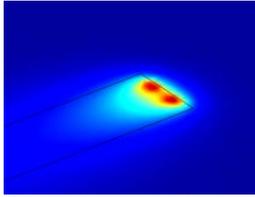
Figure 9. TEM01 formed during the simulation

The heat penetration is shown in Figure 11. The temperature increased to 3400 K when engraved by a 73W laser beam with a 100 micron spot diameter. In Figure 12, the groove was formed by vaporization of the material.
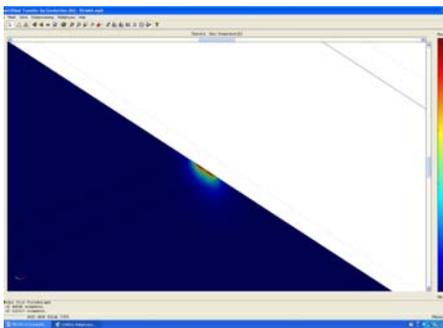

Figure 10. Slice of material which shows vertical heat penetration according to TEM01

The blue area represents empty space in this figure. For this simulation the depth was measured at 20 microns with a width of 120 microns. The red color indicates the material density and the transition yellow-green strip shows the molten material as it turned to gas.

The final result of 3D simulation for laser engraving of a groove is presented in Figures 13 and 14. As seen in these figures, the bottom of the groove has a W-shape which represents the reverse shape of beam profile TEM01. Using this simulation the maximum and minimum depth and width of the groove can be measured.
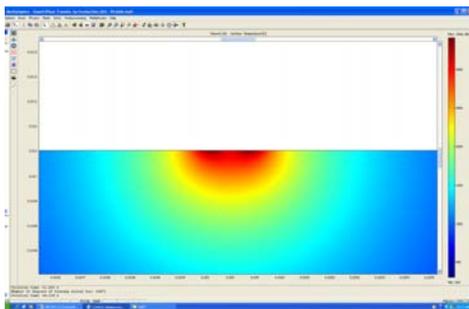

Figure 11. Heat penetration in 2D

6. Experimental Results

The collected experimental data are presented in this section. The conditions for the experiments were:

- Tested materials: Steel 1.2767 (DIN 45NiCrMo16), Aluminum, Copper, Brass
- LP100 Nd:YAG used for engraving of a 40mm straight line at speed of 50mm/s
- 6 tests conducted per each material: low (17.5), medium (39.5), and high (73) powers at constant frequency (15KHz) and then low (5), medium (10), and high (15) frequencies at constant power (73 W)
- Depth and width of the engraving was measured using a microscope at a magnification of 50X
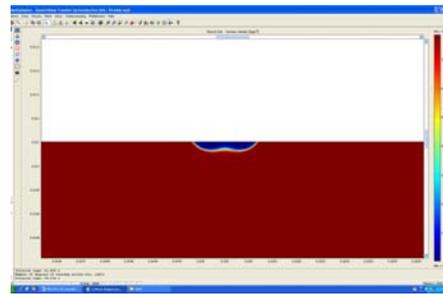

**Figure 1.** Groove geometry produced by engraving using LP100 working at TEM01 mode
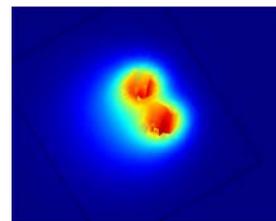
**Figure 2.** 3D engraving model using COMSOL moving mesh mode
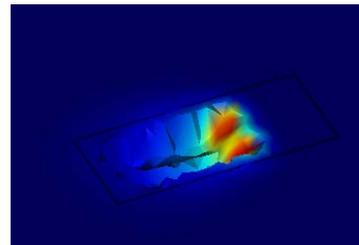
Figure 3. 3D simulation of laser engraving of a groove

Figure 15 depicts LP100 Nd:YAG laser beam striking a block of aluminum. Figure 16 illustrates the optical microscope which was used for measuring the depth and width of the engraved grooves.

Figures 17 through 20, present the resulting grooves of the laser engraving process on the used materials. A consistent observation through all these images reveals a non-flat bottom. The bottom of the grooves is shallower in the center and deeper at the sides. This observation can be explained by TEM01 mode of the beam which concentrates more energy over its two peaks and therefore cut deeper into the sides at the bottom of the grooves.
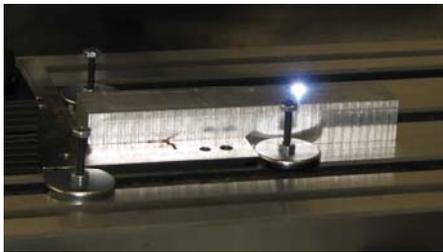

Figure 4. Laser engraving of Aluminium

**Figure 5.** Measuring the depth and width of engraving on the block of Steel 1.2767
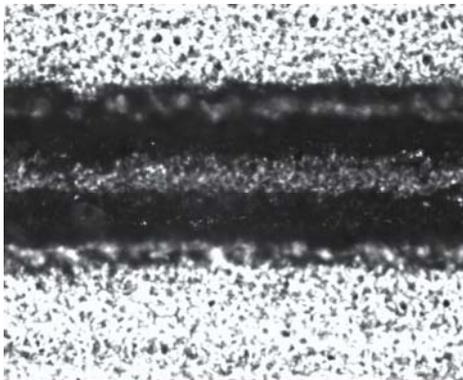
Figure 6. Steel 1.2767 test # 3
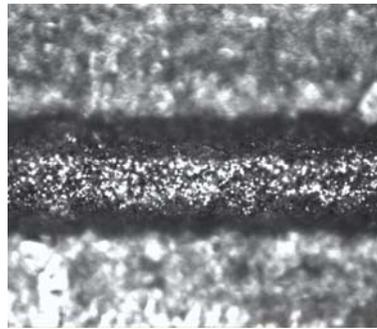
Figure 7. Aluminium test # 4
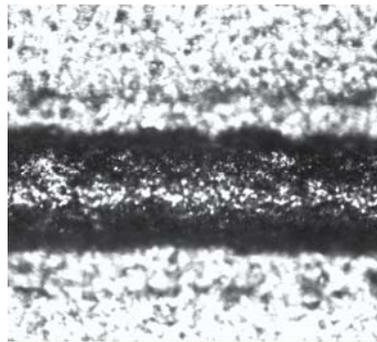
Figure 8. Brass test # 3
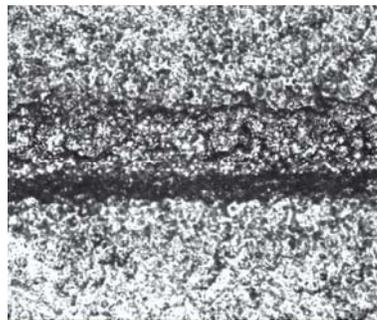
Figure 20. Copper test # 5

The depth and width of engravings for tested materials are listed in Tables 2 to 5. The upper portion of the tables consist of all constants in the test such as; laser head and material specifications, spot size, beam speed, wavelength, ambient temperature, and size of the specimen. The lower portion of the tables shows the measured depth and width of engravings in microns at different powers and frequencies. These results were obtained both before and after sand blasting. In Table 2 the depth of engraving ranges from 12 to 20 at high power for steel 1.2767. The test results for aluminum show deeper and narrower grooves for the same condition compared with the results for steel as

shown in Table 3. Also, the test results for copper demonstrated less depth and more width for the grooves as compared with obtained results for steel in Table 5. This can be justified by the much lower absorptivity of copper at wavelength of Nd:YAG as previously discussed.

7. Discussion and Conclusion

The simulation results of COMSOL indicate a similar geometry change among the materials tested in this experiment. This similarity can be interpreted by the shape of beam profile, TEM01, where there are two side peaks and a middle valley. The valley in the middle means less power intensity and in turn less engraving depth. The curved bottom shape of the grooves can be seen in all the images taken and verified by simulation in Figures 13 and 14.

Table 2. Laser Engraving Results on Steel 1.2767

Constants						
Laser head:	ND:YAG LP100	Wave length:	1060 nm	Spot Diam.: 100 μm	Focal length:	205/163mm 6x beam expander, 1.8 Fθ
Material:	STEEL 1.2767 (P20)	W/P Dimension:	50wX50lX 10.5h	Ambient temp: 24°c	Path:	Straight line 40mm, ±25
Speed:	50mm/s	Beam Mod	TEM01		Date:	April 11, 2008

Engraving Data									
#	First row before Sand blasting and second after	# of paths	Depth (μm)	Width (μm)	#	First row before Sand blasting and second after	# of paths	Depth (μm)	Width (μm)
1	Low Power: 20A/17.8W	1	12		4	Low Freq.: 5 KHz	1	20	
	Freq.: 10 KHz	1	6	108		Power: 30A/73W	1	16	200
2	Mid. Power: 26A/39.5W	1	14		5	Med. Freq.: 10 KHz	1	26	
	Freq.: 10 KHz	1	12	154		Power: 30A/73W	1	24	200
3	High Power: 30A/73W	1	26		6	High Freq.: 15 KHz	1	44	
	Freq.: 10 KHz	1	26	163		Power: 30A/73W	1	38	200

The depth and width of engraving obtained from simulation for steel 1.2767 were 20 and 120 microns, respectively. These values were consistent with the values obtained from experiments for the same material. This is an strong indication that the simulation technique can be used as a tool to accurately predict the geometry of laser engraving.

Table 3. Laser Engraving Results on Aluminum

Constants						
Laser head:	ND:YAG LP100	Wave length:	1060 nm	Spot Diam.: 100 μm	Focal length:	205/163mm 6x beam expander, 1.8 Fθ
Material:	Aluminum	W/P Dimension:	30wX150l X20h	Ambient temp: 24°c	Path:	Straight line 40mm, ±25
Speed:	50mm/s	Beam Mod	TEM01		Date:	April 11, 2008

Engraving Data									
#	First row before Sand blasting and second after	# of paths	Depth (μm)	Width (μm)	#	First row before Sand blasting and second after	# of paths	Depth (μm)	Width (μm)
1	Low Power: 20A/17.8W	1	6	112	4	Low Freq.: 5 KHz	1	44	170
	Freq.: 10 KHz	1				Power: 30A/73W	1		
2	Mid. Power: 26A/39.5W	1	54	158	5	Med. Freq.: 10 KHz	1	96	184
	Freq.: 10 KHz	1				Power: 30A/73W	1		
3	High Power: 30A/73W	1	94	164	6	High Freq.: 15 KHz	1	122	232
	Freq.: 10 KHz	1				Power: 30A/73W	1		

Table 4. Laser Engraving Results on Brass

Constants						
Laser head:	ND:YAG LP100	Wave length:	1060 nm	Spot Diam.: 100 μm	Focal length:	205/163mm 6x beam expander, 1.8 Fθ
Material:	Brass	W/P Dimension:	50wX76lX 7h	Ambient temp: 24°c	Path:	Straight line 40mm, ±25
Speed:	50mm/s	Beam Mod	TEM01		Date:	April 11, 2008

Engraving Data									
#	First row before Sand blasting and second after	# of paths	Depth (μm)	Width (μm)	#	First row before Sand blasting and second after	# of paths	Depth (μm)	Width (μm)
1	Low Power: 20A/17.8W	1	10	102	4	Low Freq.: 5 KHz	1	22	200
	Freq.: 10 KHz	1				Power: 30A/73W	1		
2	Mid. Power: 26A/39.5W	1	28	168	5	Med. Freq.: 10 KHz	1	32	200
	Freq.: 10 KHz	1				Power: 30A/73W	1		
3	High Power: 30A/73W	1	34	200	6	High Freq.: 15 KHz	1	30	200
	Freq.: 10 KHz	1				Power: 30A/73W	1		

Further development of the software could extend the simulation to a 3-Dimensional model that includes more parameters and could lead to the creation of a complete laser engraving software package. The benefits of such a package could yield considerable savings in terms of materials, employees, and set-up costs. The software could also be an effective tool for the development and evaluation of new engraving techniques that will reduce destructive

testing of expensive materials and save wear-and-tear of the actual laser engraving machine.

Table 5. Laser Engraving Results on Copper

Constants							
Laser head:	ND:YAG LP100	Wave length:	1060 nm	Spot Diam.: 100 µm	Focal length:	205/163mm 6x beam expander, 1.8 Fθ	
Material:	Copper	W/P Dimension:	74wX106l X2h	Ambient temp: 24°c	Path:	Straight line 40mm, ±25	
Speed:	50mm/s	Beam Mod	TEM01		Date:	April 11, 2008	

	Engraving Data								
#	First row before Sand blasting and second after	# of paths	Depth (µm)	Width (µm)	#	First row before Sand blasting and second after	# of paths	Depth (µm)	Width (µm)
1	Low Power: 20A/17.8W	1	0	145	4	Low Freq.: 5 KHz	1	12	230
	Freq.: 10 KHz	1				Power: 30A/73W	1		
2	Mid. Power: 26A/39.5W	1	4	220	5	Med. Freq.: 10 KHz	1	14	250
	Freq.: 10 KHz	1				Power: 30A/73W	1		
3	High Power: 30A/73W	1	14	220	6	High Freq.: 15 KHz	1	14	245
	Freq.: 10 KHz	1				Power: 30A/73W	1		

8. References

1. Website: http://www.comsol.com/
2. LIA Handbook of Laser Materials Processing, Laser Institute of America, ISBN # 0-912035-15-3
3. W. M. Steen Laser Material Processing, Springer, ISBN # 1-85233-698-6

9. Acknowledgements