INTERNSHIP REPORT

Use the laser engraving machines to achieve laser cleaning, laser post-melting and roughness control of the anilox rolls.

Report of a three month internship at Apex Europe B.V. in Hapert, the Netherlands (20 EC).

Han Jin s1530208

SET, CTW

Time duration:
01/09/2015 to 30/11/2015

UNIVERSITEIT TWENTE.

Title: Internship report

Subtitle: Use the laser engraving machines to achieve laser cleaning, laser post-melting and roughness control of the anilox rolls. Report of a three month internship at Apex Europe B.V. in Hapert, the Netherlands, as part of the master program Sustainable Energy Technology (20 EC).

Name: Han Jin

Student number: s1530208

Period: 01/09/2015 - 01/12/2015

Supervisor APEX: Toon van Steensel

Supervisor University of Twente: Gert-Willem Römer

Host Institution:

Apex Europe B.V.

Metaalweg 8

5527 AK Hapert

The Netherlands

Tel. + 31 (0) 497 36 11 11

Fax. + 31 (0) 497 36 11 22

E-mail: info@apex-europe.com

Home institution:

University of Twente

Faculty of Engineering Technology

Chair of Applied Laser Technology

PO Box 217

7500 AE Enschede, the Netherlands

Preface

I was very lucky to have this internship chance in Apex. First of all, all the colleagues, especially Toon and the laser room group companions, they were all very kind to me and gave me a lot of help during the whole three months. The company is very generous, making me comfortable both in the working and also living circumstances.

These three months gave me the precious experience of working in a dutch company. And in the meantime, I learned a lot of knowledge about flexo-printing, anilox roll engraving and the operation of the laser treatment machines. Thank you Apex!

My internship timeline:

9-1 to 9-10: Keep learning a lot of new knowledge, feel a fulfilling life, learning practical operations with nice people in the laser room.

9-10 to 9-20: Research preparation, find problems.

9-20 to 10-1: Experiments for laser cleaning, Hard time, not the same with the matlab simulation tool and the theory. Slowly explore, try to find the solution by looking up articles on the internet, asking my professor and the R&D staff in the company.

10-1 to 10-20: More experiments, more than 100 test burns, 5 rolls. Understand the effect of each parameter and do trial and error. Finally found a proper set of parameters for laser cleaning. Finishing the report of the laser cleaning part.

10-20 to 11-1: Theoretical learning of ceramic melting.

11-1 to 11-11: Experiments on post-melting of the ceramic, to clean the engraving dust and make the surface smooth.

11-11 to 11-20: Write the post-melting part of the report.

11-20 to 11-30: Experiments on the roughness tests, finishing the last part of the report.

Summary

This report includes five parts:

The first chapter, introduction, introduces the general information about Apex and the process of flexographic printing. In this part, different types of anilox rolls are described, including the representing parameters. At last, there is a description of the three projects I did during the internship.

Second chapter is the preparation. Here I introduced the laser sources in Apex, and a simulation tool called "Matlab Laser Toolbox" developed by professors in University of Twente, which could be used to simulate the temperature profile of the material surface during laser treatment. For this tool, I also introduced the thermal properties and light absorbance of the ceramic and inks. Unfortunately, this tool was proved not suitable for the projects in Apex and was not used and shown in the final experiments and report. I also developed an excel calculator to calculate the focus diameter of the laser beam. This excel file would be attached in the final report package.

Chapter 3 is the design and results of the experiments for laser cleaning. The purpose of this project is to use laser to clean the inks on the used anilox rolls, without damaging the ceramic surface and cell structures. In this part, parameters of the laser treatment system – ES, BD, SA, SCL, DC, etc. – were tested out and determined step by step, resulting in a final set of parameters that is suitable for laser cleaning. At the end some improvements and prospects were proposed.

Chapter 4 is the design and results of the experiments for laser post-melting. The plan is to implement laser post-melting just after the laser engraving, to replace finishing process. Same trial and error tests were made to select out the most suitable laser treatment parameters. The results showed that with the post-melting, the dust adhering to the ceramic surface would be blasted away by the laser beam, achieving the same effect of the liquid cleaning. However, with the melting and re-solidification, even though the top of the wall of the cells would be reshaped, the smoothness improvement was not obvious. Therefore, using laser post-melting to replace the polishing process really would depend on the requests of the customers.

Chapter 5 is about the project of the roughness change by laser treatment. The roughness measurement device was introduced together with the measurement parameters. A series of comparison tests were made to investigate the relation between the laser treatment and the roughness. Results showed that most of the laser treatment could increase the surface roughness. With lower laser beam power intensity, it is less possible that it would influence the roughness. And the different SCL (overlap of the beam spots) has no obvious regulation to follow on influencing the change of the roughness. In addition, the roughness of surface would increase obviously with the increase of melting level.

Experiments data, including the excel file "beam diameter calculator", "Roughness test" data, all the pictures and micro-images in the first two projects, would be arranged into a data package.

Table of contents

Introduction

APEX international is a manufacturer of precision coating- and ink-transfer technology products. Apex supplies anilox/metering rolls and sleeves for label, flexible packaging, corrugated, offset and industrial coating applications. Apex has production sites in the Netherlands, Italy, North America, South America, and India. With manufacturing and sales operations on six continents in more than 80 countries, Apex provides added value by supplying our customers with end-to-end anilox or GTT solutions (see later) including measurement devices, cleaning and maintenance products, and educational/use-and-care seminars. My internship place is at the home company Apex Europe B.V. in Hapert, the Netherlands.

Most of the products now in Apex are the anilox rolls and sleeves with ceramic coating on it. These products are mostly used in flexographic printing.

1.1 Flexographic printing

Nowadays there are four commonly used printing technologies: Gravure printing, Flexographic printing, Offset printing and Inkjet printing. Flexography (often abbreviated to flexo) is a form of printing process which utilizes a flexible relief plate. It is essentially a modern version of letterpress which can be used for printing on almost any type of substrate, including plastic, metallic films, cellophane, and paper. It is widely used for printing on the non-porous substrates required for various types of food packaging (it is also well suited for printing large areas of solid colour).

The greatest advances in flexographic printing have been in the area of photopolymer printing plates, including improvements to the plate material and the method of plate creation. Digital direct to plate systems have been a good improvement in the industry recently. Companies like Asahi Photoproducts, AV Flexologic, Dupont, MacDermid, Kodak and Esko have pioneered the latest technologies, with advances in fast washout and the latest screening technology.

Laser-etched ceramic anilox rolls play an important part in the improvement of print quality. By adjusting the temperature of the anilox roll, the ink's viscosity and therewith the amount of transferred ink is controlled. Below is the working principle of the flexographic printing.

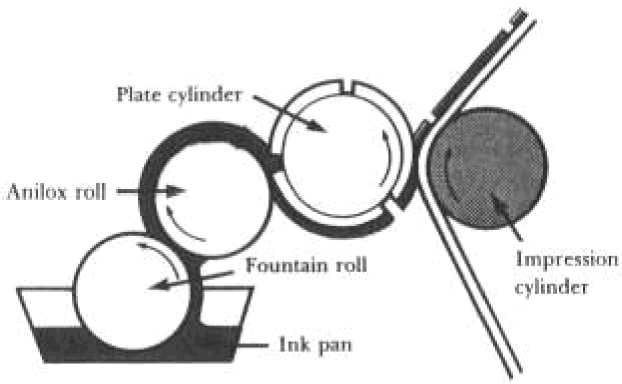

Figure 1.1 Structure of the elements in flexographic printing.

- **Fountain roller**

The fountain roller transfers the ink that is located in the ink pan to the second roller, which is the anilox roller. In Modern Flexo printing this is called a Meter or "metering" roller.

- **Anilox roller**

This is what makes flexography unique. The anilox roller meters the predetermined ink that is transferred for uniform thickness. It has engraved cells that carry a certain capacity of inks that can only be seen with a microscope. These rollers are responsible to transfer the inks to the flexible-plates that are already mounted on the Plate Cylinders.

- **Doctor Blade (optional)**

The doctor blade scrapes the anilox roll to ensure that the predetermined ink amount delivered is only what is contained within the engraved cells. Doctor blades have predominantly been made of steel but advanced doctor blades are now made of polymer materials, with several different types of beveled edges.

- **Plate cylinder**

The plate cylinder holds the printing plate, which is soft flexible rubber-like material. Tape, magnets, tension straps and/or ratchets hold the printing plate against the cylinder.

- **Impression Cylinder**

The impression cylinder applies pressure to the plate cylinder, where the image is transferred to the substrate. This impression cylinder or "print Anvil" is required to apply pressure to the Plate Cylinder.

A flexographic print is made by creating a positive mirrored master of the required image as a 3D relief in a rubber or polymer material. Flexographic plates can be created with analog and digital platemaking processes. The image areas are raised above the non-image areas on the rubber or polymer plate. As Figure 1 shows, the ink is transferred from the ink roll which is partially immersed in the ink tank. Then it transfers to the anilox or ceramic roll (or meter roll) whose texture holds a specific amount of ink since it is covered with thousands of small wells or cups that enable it to meter ink to the printing plate in a uniform thickness evenly and quickly (the number of cells per linear inch can vary according to the type of print job and the quality required) [1]. To avoid getting a final product with a smudgy or lumpy look, it must be ensured that the amount of ink on the printing plate is not excessive. This is achieved by using a scraper, called a doctor blade. The doctor blade removes excess ink from the anilox roller before inking the printing plate. The substrate is finally sandwiched between the plate and the impression cylinder to transfer the image [2]. The sheet is then fed through a dryer, which allows the inks to dry before the surface is touched again. If a UV-curing ink is used, the sheet does not have to be dried, but the ink is cured by UV rays instead.

1.2 Anilox rolls

An anilox roll is a hard cylinder, usually constructed of a steel or aluminum core which is coated by an industrial ceramic whose surface contains millions of very fine dimples, known as cells. Depending on the design of the printing press, the anilox roll is either semi-submerged in the ink fountain, or comes into contact with a so-called metering roller, which is semi-submerged in the ink fountain. In either instance, a thick layer of typically viscous ink is deposited on the roll. A doctor blade is used to scrape excess ink from the surface leaving just the measured amount of ink in the cells. The roll then rotates to contact with the flexographic printing plate which receives the ink from the cells for transfer to the printed material.

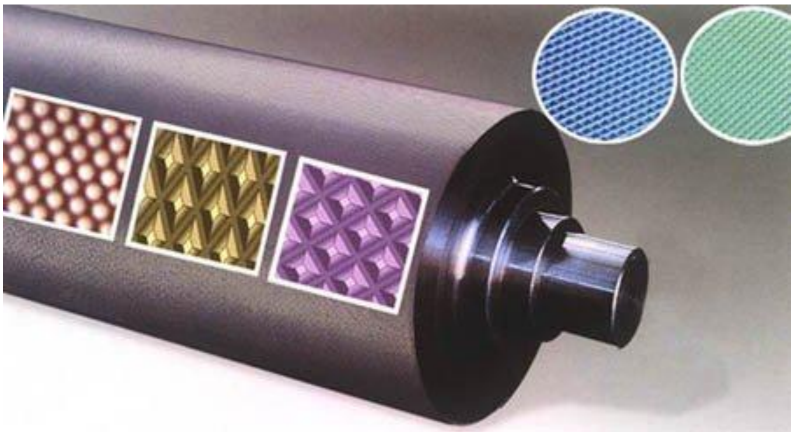

Figure 1.2 An example of the anilox rolls

The characteristics of an anilox roll determine the amount of ink that will be transferred to the plate: angle of the cells, cell volume, and line screen. Lower volume makes for less ink. Low line numbers will allow for a heavy layer of ink to be printed, whereas high line numbers will permit finer detail in printing. Both cell volume and line screen are closely correlated. It is essential for all flexo printers that the anilox gives the correct ink density from the first print and stays consistent throughout the whole run regardless of which cell structure or shape is used.

Line screen indicates the number of cells per linear inch on an anilox roll, and is a major component when specifying an anilox roll.

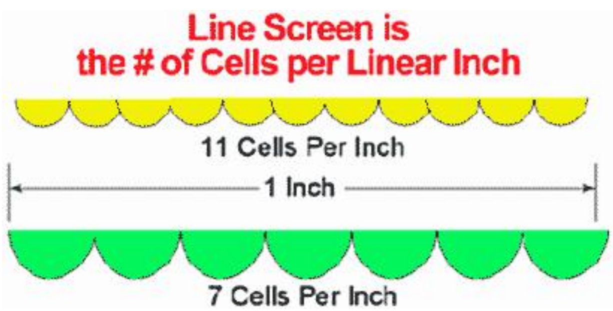

Figure 1.3 Explanation of the line screen on an anilox roll [2]

Line screen is chosen in direct correlation to anilox volume. For example, an anilox volume of 3.2 BCMs (billions of cubic microns), requires a line screen of approximately 500. If an anilox volume of 3.2 BCM was engraved at 1000 line screen, cells would be much too deep. In correlation, a 3.2 BCM anilox at 120 line screen anilox would result in cells being much too shallow. With increased ink strength and lower anilox volumes, higher line screen anilox rolls can now be used. These higher line screen rolls give printers the opportunity to reach for higher graphics with finer vignettes, line and type, and process work. Following, is a rough outline of printing applications matched with appropriate line screens and cell volumes:

Application	Appropriate Anilox Line Screen	Appropriate Anilox Volume
Heavy line and solids	180 - 330	9 - 4 BCMs
Line and type	200 - 400	8 - 3 BCMs
Vignettes	360 - 500	3.6 - 2.8 BCMs
Process	500 - 1200	2.8 - 0.9 BCMs

Table 1.1 Outline of printing applications matched with appropriate line screens and cell volumes

Depending on the detail of the images to be printed, the press operator will select an anilox roll with a higher or lower line screen. Low line screen rolls are used where a heavy layer of ink is desired, such as in heavy block lettering. Higher line screens produce finer details and are used in four-color process work such as reproducing photographs.

Different shapes of the engraving:

Laser engraving is the major method to engrave the microstructures on the anilox rolls. Different types of the shapes are developed to meet the variant requirements and industrial standards already built up. For example, by setting different parameters during the laser engraving, e.g. laser pulse frequency, duty cycle, engraving speed, etc. the microstructures can be shaped into different types and angles like Figure 1.4 and 1.5 shows.

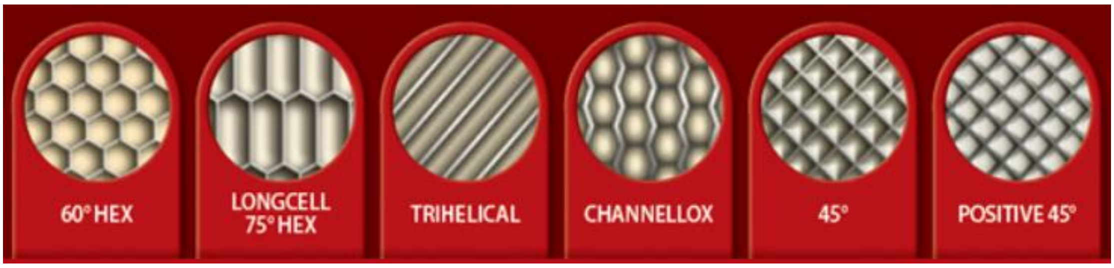

Figure 1.4 Different shapes of the microstructure on the anilox roll from APEX[3]

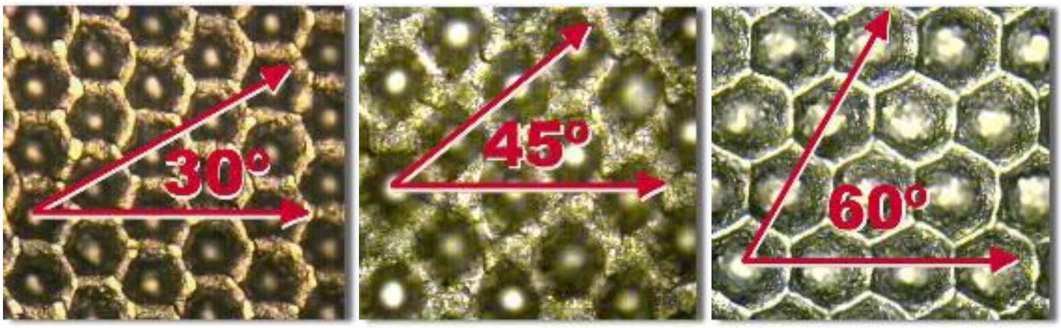

Figure 1.5 Different angles of the microstructure on the anilox roll [4]

Besides, one of the inventions from Apex is the GTT structure as Figure 1.6 shows. The GTT metering rollers feature laser-cut slalom structured channels as opposed to the tradition hexagonal cells. According to the Apex Group of Companies, this type of engraving is smoother as the laser is working as a constant beam rather than through quick short bursts used to create the hexagonal cells. It can also make shallower cells, which again helps the ink transfer to the plate.

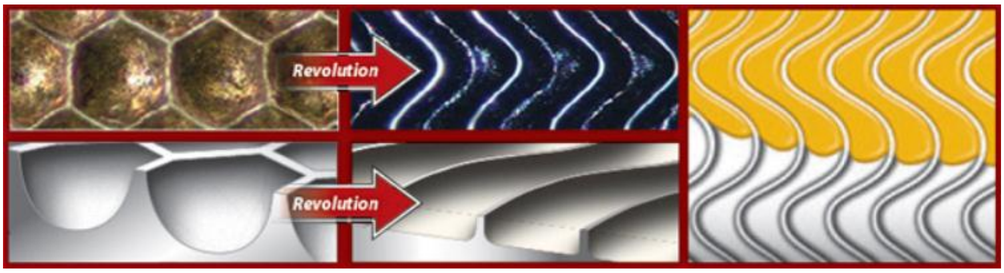

Figure 1.6 GTT structure on the anilox roll from APEX

1.3 Description of the projects

There are a lot of possibilities on improving the production process related with laser. Different improvements would be achieved by changing the laser power, processing velocity, pulse frequency, shape of the laser beam, etc.

Laser cleaning of the anilox roll

Cleaning the anilox roll is an important part of the maintenance service from some production companies. If the cells of the laser engraved ceramic anilox rolls become clogged with dirt, dried ink, or coatings, print quality is affected. In normal use, the rolls must be cleaned as soon as possible after the completion of a press run to remove residual ink/coatings.

Various cleaning methods can be applied, including chemical wash, Ultrasonic cleaning, media blast, and laser cleaning, etc. [5] Through all these methods, laser cleaning as a relative new technology, can evaporate foreign material on the ceramic surface but with no damage to the engraving. Meanwhile, it is environment friendly.

The principle of technology is in the formation of a blast wave and it breaks the adhesion of any ink to the surface of anilox rolls, as Figure 1.7 shows. High efficiency is due to the fact that the laser beam, focused to a spot, warms the layer of pollutant completely and the dried ink is completely removed from the cells. None of the modern ways of deep cleaning can get the ink out of the bottoms of the cells of rolls.

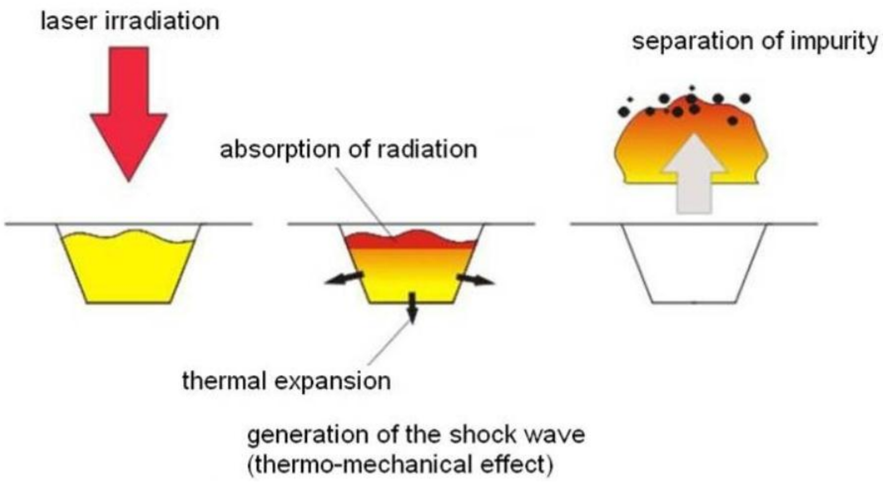

Figure 1.7 The principle of laser cleaning on the anilox cell

The purpose of this assignment is to use the laser source and operating system at Apex now, to achieve a best and efficient result of laser cleaning. Our goal is to drive as much ink out as possible from the roll and do not damage the roll in the meantime. This means, the temperature of the ceramic surface should better < 500 °C but higher than 350 °C [6]. To control the temperature, we can do temperature profile simulation by laser toolbox in Matlab (see chapter 2). The difficulties of this assignment are:

- The Matlab simulation is based on a CW laser, while in Apex the laser for experiment is a CO_2 pulsed laser. Although we can put average laser power into the program, but the practical results could be very different with the simulation results.
- There is no tool to know the diameter of the focused laser beam. To know it I need to measure the machine and calculate.
- The operating system of the laser and the roll is specifically designed for engraving cells, e.g. hexagonal cells, so it is difficult to control the parameters as I want. Because for example if I change the engraving speed, spontaneously the duty cycle and the pulse frequency will change.

Besides the temperature control, what we want is to have the good cleaning function with the shortest time. Also the convenience for the operators needs to be considered. So in the first trial, we shall operate on existed system and not change the optic devices also.

Laser post-melting of the anilox roll after engraving

The usual process after laser engraving is to move the roll to another machine and implement the finishing process, which includes liquid cleaning and polishing. In the liquid washing and polishing process, the dust produced by the engraving process, which is adhere to the surface of the anilox cells, will be washed away by the liquid cleaner. In the meantime, with the friction between the roll surface and the polishing brush, the surface would become smoother, e.g. optical reflective on the surface, and also the volume would become smaller to meet the requirement of the customers.

The problem of Apex now is the shortage of the finishing machines. This means the production chain would be stuck at the finishing process. Rolls are always waiting at this step and would drag down the whole production. Therefore, an idea about skipping the process of finishing could be tested.

The plan is to implement laser post-melting just after the laser engraving, without finishing process. This could be fulfilled by installing another laser source on the laser engraving system. During the engraving, the other laser source also starts the laser post-melting at a same beam speed. With the treatment of the post-melting, the dust adhering to the ceramic surface would be blasted away by the laser beam, achieving the same effect of the liquid cleaning. In addition, with the melting and re-solidification, the top of the wall of the cells would be reshaped. The height of top would be lowered and the thickness of it would be enlarged. This kind of change maybe will make the surface smoother and then replace the process of polishing.

Another concern is the volume change before and after the post-melting. In normal cases, the volume of the cells would be engraved to be about 1-3 BCMs larger than the requirement of the customer, and then finished to be the required volume by the liquid cleaning and polishing system. If the finishing step would be skipped, the relationship of the volumes before and after the post-melting needs to be found.

Surface tension and roughness changes after laser treatment

Laser heat treatment is always a good way to change the properties of the surface materials. Properties that really matters in the anilox rolls are the surface tension and roughness, which are also related with each other.

The plan is to use several kinds of laser beam to process the anilox roll, and compare the roughness and surface tension changes, to see the effects of the beam properties. Because of the limit of the internship time and equipment, the roughness would first be measured and compared.

Chapter 2: Preparation

2.1 Simulation tool: Matlab Laser Toolbox

Matlab® is high-level interpreted language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation, developed by MathWorks Inc. Add-on toolboxes, which are collections of special-purpose Matlab functions and scripts, extend the Matlab environment to solve particular classes of problems.

The Matlab Laser Toolbox [7] provides several functions and scripts for analysis and visualization of laser beam properties, as well as, functions to calculate the interaction (e.g. induced temperature by absorbed laser energy in a solid) in a material.

The function *tsurfsrc* (Temperature of a SURFace heat SouRCe), of the Matlab Laser Toolbox allows the calculation/simulation of the temperature field T(x,y,z,t) in a solid, due to absorbed laser energy at the surface of a material (with semi-infinite dimensions), of a laser beam with a power density profile I(x,y), moving at v [m/s]. As such it can be used as a simulation tool for the surface temperature of the laser processing ceramic (neglecting an impact of ink and a roll microrelief due to their shallow thickness and to a low contribution to energy consumption at multipulse processing accordingly).

2.2 Laser sources in Apex

There are two types of laser sources in Apex.

The first type is IPG's YLR-LP Series. These 10W to 500W CW single mode linearly polarized Yb fiber laser systems are coordinated with highly precise machines used for engraving the anilox rolls. It has 1060 to 1080nm wavelength range and TEM_{00} (M^2<1.1) beam quality.

The second type is a liquid-cooled, RF-excited OEM Industrial CO_2 Laser, Diamond E-150 from Coherent. The properties of this laser source are listed below at Table 2.2.

Specifications	Values
Wavelength (μm)	10.2 to 10.8
Pulse Frequency (kHz)	Single-shot to 100
Maximum Duty Cycle (%)	70
Output power range (W)	20 to 150
Peak Effective Power (W)	375
Pulse Energy Range (mJ)	5 to 315
Pulse Rise/Fall Time (μsec) (at 1 KHz and 35% duty cycle)	50 typical
Mode Quality (M^2)	≤ 1.2
Polarization (Parellel to baseplate)	Linear >100:1
Beam Waist Diameter ($1/e^2$) (mm)	2.2 typical
Beam Divergence (Full-angle) (mrad)	6.6 typical
Beam Divergence Ellipticity	1:1.2

Table 2.1 System specifications of the CO2 laser source, DIAMOND™ E-150, Coherent

This laser is connected with a much older engraving machine, which is less precise in engraving, and also used for post melting or roll cleaning experiments. During the internship, I will mostly use this laser source and engraving machine to do the experiments.

2.3 Properties of the ceramic coating

Chromium oxide Cr_2O_3 thin films have wide variety of technological applications. This oxide exhibit high hardness and high wear with corrosion resistance which is important properties for protective coating applications [8]. Cr_2O_3 adopts the corundum structure, consisting of a hexagonal close packed array of oxide anions with 2/3 of the octahedral holes occupied by chromium. Similar to corundum, Cr_2O_3 is a hard, brittle material (Mohs hardness 8-8.5). It is not readily attacked by acids or bases, although molten alkali gives chromates. It turns brown when heated, but reverts to its dark green color when cooled. It is also hygroscopic [9].

The coating layer of the anilox roll from Apex is all consisted of 99.7% pure Cr_2O_3. The coating method is thermal sprayed plasma coating. The width of the ceramic layer depends on the screen of the structure, most of which are between 0.1-0.4mm, with 90% 0.1-0.15 mm.

Thermal properties of the ceramic

In the laser toolbox program, the thermal properties of the operating surface needs to be filled in. Cr_2O_3 physical and mechanical properties represented in Table 2.2 were taken from the technical reference handbook of manufacturing company of plasma coatings.

k, W/m K	10
χ, m^2/s	2.23×10^{-6}
ρ, kg/m^3 (for chromium)	5.21×10^3
C_p, J/kg K	0.86×10^3
Operating temperature of Cr_2O_3, °C	< 500

Table 2.2 Cr_2O_3 physical and mechanical properties [10].

From Table 1, we can know when the operating temperature of Cr_2O_3 is under 500 °C: Density: ρ = 5210 kg/m^3; Thermal heat capacity: Cp =860 [J/(kg*K)]; Thermal diffusivity: $\kappa = 2.23 * 10^{-6}$ [m^2/s]; Thermal conductivity: k = 10 [W/(m*K)]. Besides: Melting temperature: 2,708 K / 2435 °C; Refractive index: n = 2.551.

However, the properties of the ceramic will change when the temperature grows. When the project is going to melt the ceramic, the properties would be different.

The absorbance and reflectance of the ceramic:

Undoped and Iodine (I)–doped chrome oxide (Cr_2O_3) thin films have been prepared by chemical spray pyrolysis technique at substrate temperatures (773K) on glass substrate [11]. The reflectance of the pure Cr_2O_3 at different wavelengths is shown in the figure below.

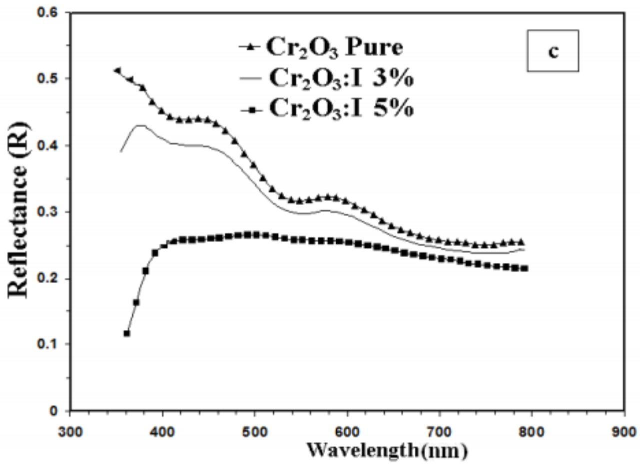

Figure 2.1 Reflectance spectra against wavelength of the undoped and I–doped (Cr_2O_3) thin films.

Usually, by detecting a thin film of a material, there are Absorbance (A), Reflectance (R) and Transmittance (T). In our case, because the substrate is not transparent, plus the power may be not strong enough to penetrate the whole ceramic layer, therefore (A+T) = (1-R), which means (1-R) is the absorbance of the ceramic layer.

According to another reference [11], the light reflectance of the Cr_2O_3 thin film based on stainless steel is shown below.

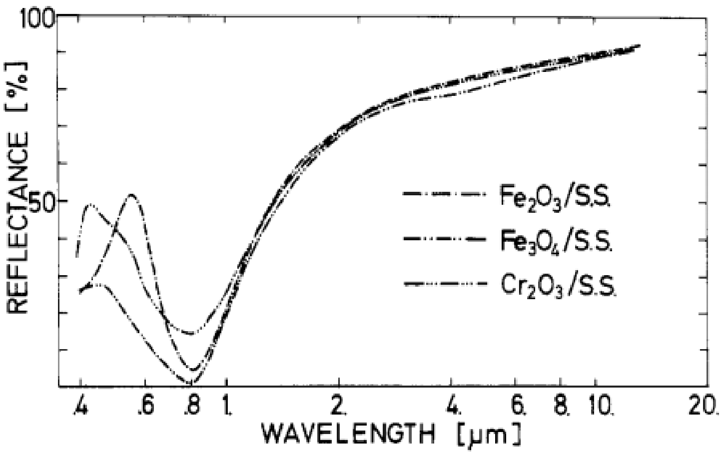

Figure 2.2 Reflectance curves for iron and chromium oxides on stainless steel. The oxide thicknesses chosen were: Fe_2O_3: 58 nm, Fe_3O_4: 70nm and Cr_2O_3: 80 nm.

As shown, the reflectance curve is analogical as the curve according to Figure 2.1. The data is based on the experiment that for the thin film of Cr_2O_3 (less than or around 1 μm), which is not the same with our case (usually the ceramic layer on the roll is mostly 0.1-0.15 mm deep, and it is sprayed on a Nickel layer by thermal sprayed plasma coating). But because of the same material, we can assume the same reflectance could be applied on the Cr_2O_3 of the anilox roll. Another reason could be the color of Cr_2O_3 is dark green, if comparing with Fig (), in the spectrum of visible light (about 390 to 700 nm), the maximum reflected wavelength is 400 to 500 nm, in which the spectrum of dark green is from.

2.4 Properties of the inks

Usually there are three kinds of common used inks: UV ink, Water-based ink and Solvent ink.

Over 90 percent of inks are printing inks, in which colour is imparted by pigments rather than the dyes used in writing inks. Pigments are insoluble, whereas dyes are soluble, though sometimes these terms are used interchangeably in commercial literature. Ink pigments are both inorganic and organic. For example the well-known blue pigment copper phthalocyanine blue is PB 15. Others could be yellow (azo pigment), magenta (lithol pigment), cyan (copper phthalocyanine), etc. Most white inks contain titanium dioxide as the pigment, as rutile and anatase in tetragonal crystalline form.

The boiling point is the most crucial property when choosing suitable solvents. For printing inks, the following boiling point ranges are common:

flexo and gravure	80…140 °C
screen printing	130…210 °C
heat-set web-offset	240…280 °C
cold-set web-offset, letterpress	280…320 °C

Figure 2.3 Boiling points of the printing inks

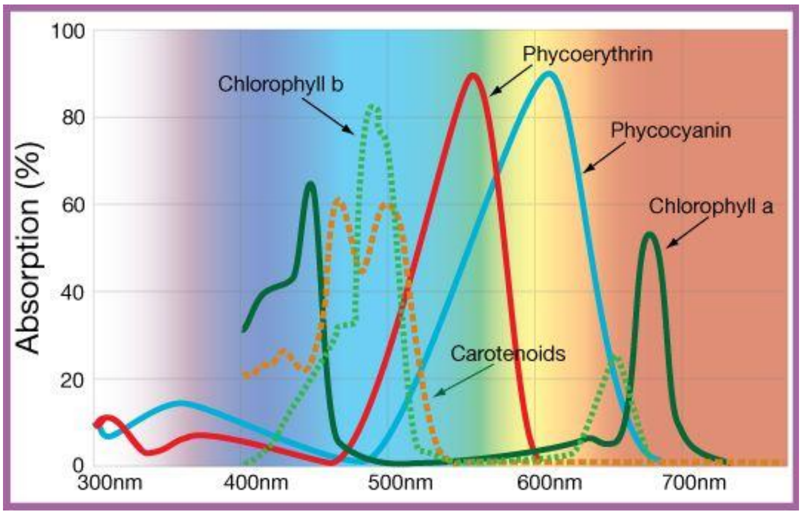

Figure 2.4 Absorbance curves for different pigments against wavelength

Figure 2.4 shows the absorbance curves for some pigments at different wavelengths. In general, Nd YAG lasers at the fundamental 1.064 μm wavelength (So as the Yb fiber lasers in Apex, *IPG's YLR-LP Series*) are best suited for marking metals while the CO_2 laser is more suited for plastics, painted or organic marking. According to reference [12], YAG laser does not work well on organic materials, including some organic pigments, while even a low powered CO_2 laser is very effective at removing paint from most metal surfaces, which means in some level, the pigments of the ink could absorb more energy from CO_2 laser than YAG laser because of the wavelength differences. Also according to Figure 2.2, the reflectance of the ceramic at 10.6 μm is much larger than at 1.06 μm. Therefore, to remove the ink without damaging the ceramic, CO_2 laser at wavelength 10.6 μm is a better choice than the Yb fiber laser at wavelength 1.06 μm.

In my experiments, five kinds of inks were used for experiments: water-based white ink, water-based red ink, solvent white ink, solvent red ink, and water-based blue ink. As shown in figure 2.5, the inks were averagely covered on a roll for test.

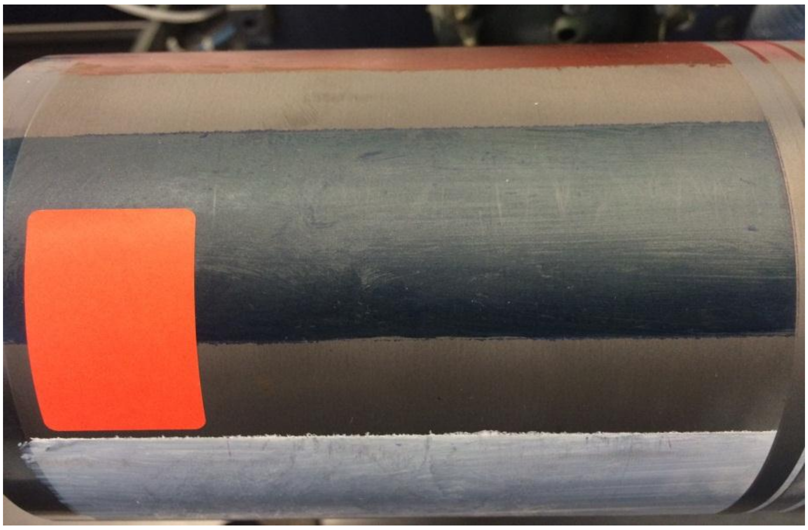

Figure 2.5 Inks on the roll for preparation of the laser cleaning tests

2.5 Calculate the focus diameter of the laser beam

Lens specification: SLZS2-19-50.8PCO2

Diameter: 19.05 mm

Focal length: 50.8 mm / 2 inches

Back focal length: 49.0 mm (The distance from the final optic within a system to the rear image point of the system)

According to the lecture notes by G.R.B.E. Romer, after the focus of the beam,

$$\mathrm{d}_1 = \frac{4}{\pi}\frac{\lambda f}{D}$$

Where d_1 is the diameter of the focus, λ is the wavelength of the laser, D is the diameter of the beam before focus, f is the focal length of the lens.

The diameter of the focused laser beam along the optical axis can be described as

$$\mathrm{d(z)}^2 = d_f^2 + \theta_f^2 (z - z_{0f})^2$$

where d_f [m] is the diameter of the focus, θ_f [rad] is the full far field divergence angle of the focused beam, and z_{0f} [m] the location of the focus relative to a reference location. And

$$\theta_f = tan^{-1}\left(\frac{D}{f}\right) \approx \frac{D}{f} \quad \text{if } D \ll f$$

The way to measure the D is to put a plastic plate, which is specific for this measuring purpose, in front of the laser beam for a while, and measure the melted area. As Figure 2.6 shows, D is measured to be 9 mm. After knowing this, an excel form for calculation was made as shown below.

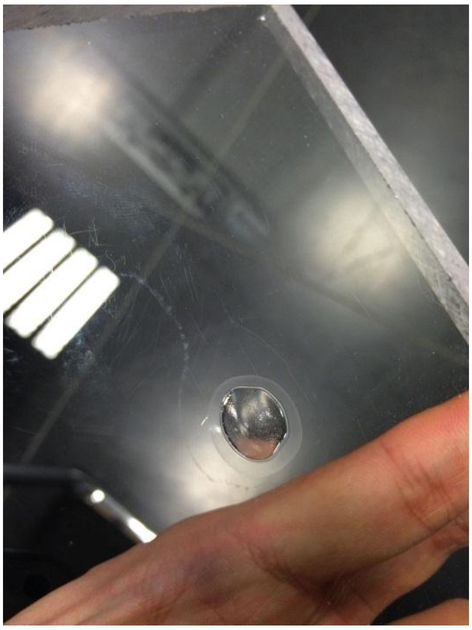

Figure 2.6 Melted plastic plate for measuring the beam diameter before focus

parameter	value	unit	remark
D	9	mm	Beam diameter before focal lens
f	50.8	mm	Focal length of the lens
θ_f	0.175345902	rad	Full far field divergence angle of the focused beam
d(f)	86	um	Diameter at the focus
d(z)	600	um	Diameter of the beam on the ceramic surface
Δz	3.386475959	mm	Radial distance between the beam at d(f) and d(z)
y1	5.296475959	mm	Number of distance that should be set on the clock if use an adjusting shim that has a thickness of 15mm (1.91mm + Δz)

y2	0.296475959	mm	Number of distance that should be set on the clock if use an adjusting shim that has a thickness of 10mm (1.91mm + Δz - 5mm)

Table 2.3 Laser beam properties calculation

For the special setup in Apex, when installing the lens, if you use an adjusting shim that has a thickness of 15mm, the beam focus would be achieved at a radial distance of 1.91mm on the clock in the specific CO_2 laser system "Zedco". That means, for example, if you want to get a beam diameter of d(z) = 600 μm, and the thickness of the adjusting shim is 15mm, then the number of the radical distance on the clock should be set to be y1 = 1.91 + Δz = 5.296 mm, as shown in table 2.3. In addition, if the the thickness of the adjusting shim is 10mm, then the number of the radical distance on the clock should be set to be y2 = 1.91 + Δz – 5mm = 0.296 mm. The rest can be done in the same manner.

Table 2.4 shows some typical values that the operators could use.

BD (μm)	Thickness of the adjusting shim (mm)	Distance values on the clock (mm)
86 (minimum)	15	1.910
100	15	2.201
200	15	2.940
400	15	4.138
600	15	5.296
800	15	6.450
1000	15	7.592
1000	10	7.592-5 = 2.592
1200	10	3.736
1400	10	4.879
1600	10	6.022
1800	10	7.164
1800	5	7.164-5 = 2.164
2000	5	3.305

Table 2.4 Distance values on the clock according to different BD required (calculated by the excel file)

Chapter 3 Design and results of the experiments for laser cleaning

To design the experiments, first the working principle of the engraving system needs to be understood.

As Figure 3.1 shows, during the engraving, the anilox roll will be fixed and turn around the center shaft at a certain velocity. In the meantime, the laser beam is located as vertical with the center shaft and move along the parallel direction with the center shaft of the anilox roll. With this mechanical system, the cells produced by the laser pulse can be distributed uniformly on the surface of the whole roll.

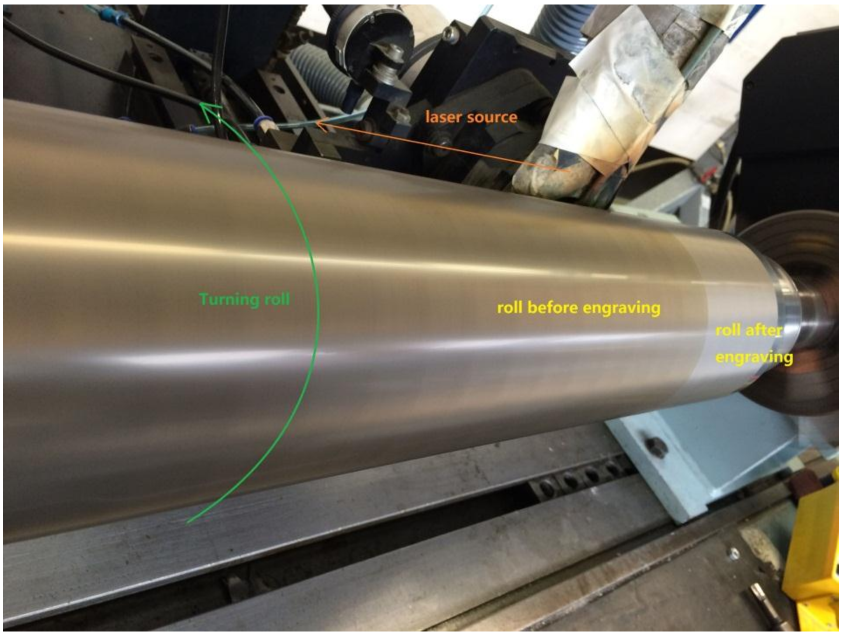

Figure 3.1 CO_2 laser engraving system in Apex

In the ALE engraving processing system, when inputting some parameters, other parameters will change to fulfill the need of engraving a serious of decent cells. First there are explanations about these important parameters:

- **ES (Engraving Speed)**

The ES (Engraving Speed) is the circumferential speed at which the surface of the roller passes the engraving nozzle. This speed is normally specified in cm/second.

- **RD (Roller Diameter)**

The RD (Roller Diameter), is the diameter of the roller, usually specified in millimetres.

- **DC (Duty Cycle)**

The DC (Duty Cycle), is the ratio of 'On' to 'Off' time of the laser pulse expressed as a percentage.

- **PF (Pulse Frequency)**

The pulse frequency of the laser source. Details can be found in Figure 3.2.

- **PL (Pulse Length)**

The PL (Pulse Length), is the length of the laser pulse.

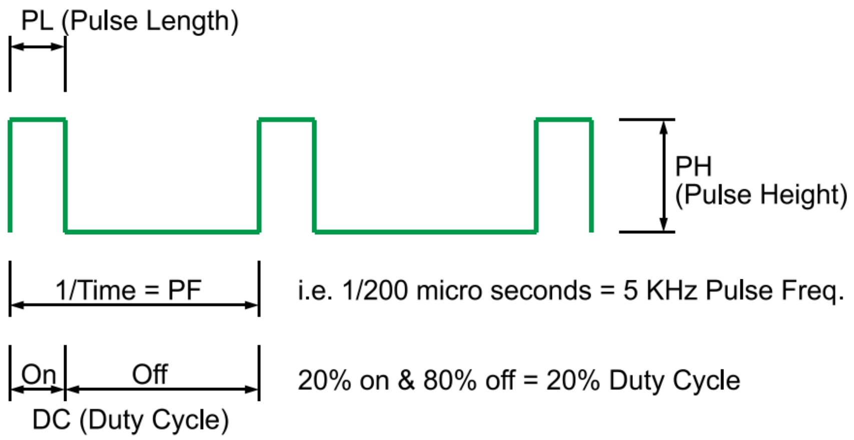

Figure 3.2 Anilox pulse details

- **SA (Screen Angle)**

The SA is the 'Screen Angle' of the anilox cells, measured in degrees. Examples are shown below:

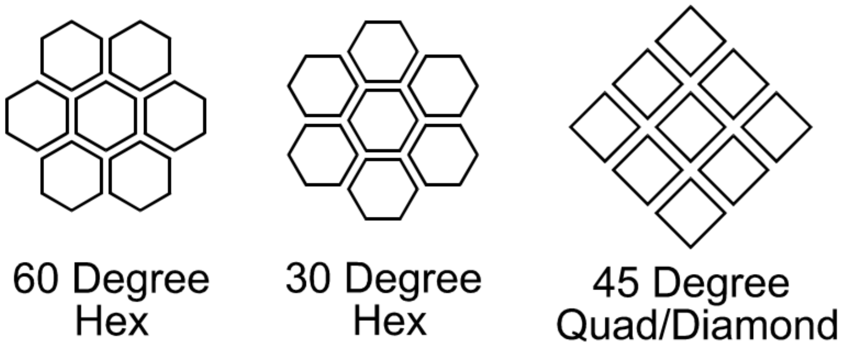

Figure 3.3 Anilox screen angle examples

- **SCL / SCLI (Screen Count Linear)**

The SCL (Screen Count Linear), is the number of cells per centimetre, whilst SCLI is the number of cells per inch.

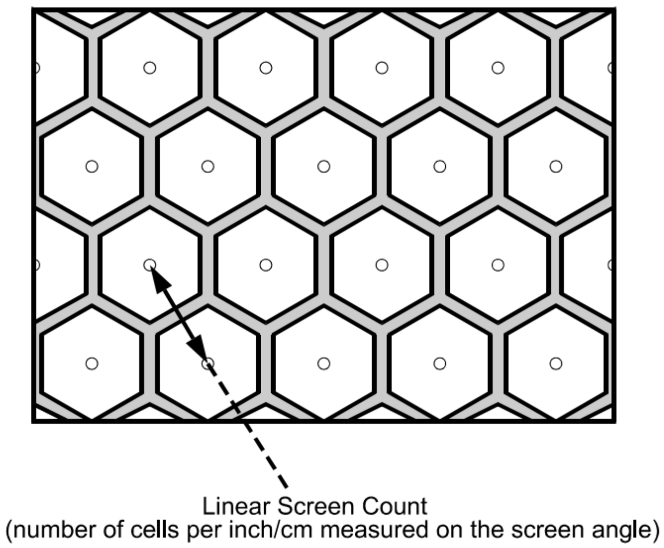

Figure 3.3 Anilox SCL example

For the convenience of the operation and also the safety of the machine and system, using the existed engraving system (while changing some parameters to make it suitable for cleaning) is then the first option. For understanding, below is some data transformation (assume the diameter of the roll is 150mm, the length of the roll is 1000mm.)

ES [m/s]	SCL [l/cm]	SA 60°			SA 10°		
		DC [%]	PF [kHz]	Finish t	DC [%]	PF [kHz]	Finish t
0.05	50	0.5	0.144		12.5	0.720	
	20	0.2	0.058		5	0.288	
	10	0.1	0.029		2.5	0.144	
0.1	50	1.0	0.289	13’6’’	24.9	1.440	6’39’’
	20	0.4	0.116		10	0.576	
	10	0.2	0.058	2’38’’	5	0.288	1’20’’
0.5	50	25	1.444	2’38’’	124.7	7.199	1’20’’
	20	10	0.578		49.9	2.879	
	10	5	0.289	0’32’’	24.9	1.439	0’16’’
1.0	50	50	2.887		249.4	14.397	
	20	20	1.155		99.7	5.758	
	10	10	0.578		49.9	2.879	
2.0	50	100	5.774		498.7	28.794	
	20	40	2.311		199.5	11.516	
	10	20	1.157		99.7	5.757	

Table 3.1 Parameters change in the ALE engraving system

1. At the same SA (Screen Angle, °) and ES (Engraving Speed, m/s), with the increase of SCL, the pulse length PL is the same, which means the energy used to engrave a cell is the same.
2. The SA and SCL determine the cell distance, which will determine the relation between ES and PF. Vertical cell distance = ES * 1/PF.
3. From the finish time, we know the time increases with the increase of the SCL, and also the increase of the SA, and the decrease of speed. To understand this, with the increase of the SCL and SA, the intensity of the cells in the axis direction of the roll increases, i.e. the decrease of the EPR (Engraving Pitch Rate), which means the axis speed of the roll will decrease, resulting the increase of processing time.

4. At certain ES, with the increase of SA, PF decreases, which means the intensity of the cells in one circle of the roll decreases, whist in the meantime the intensity of the cells along the shaft increases. At 45° SA, the cells are most averaged distributed.

For us, to clean the roll, we want the processing cells to be as many as possible to cover and even overlap the area of the ink, which means higher SCL and a proper SA. But in the meantime, the processing time will increase obviously. Therefore, there is always a compromise between the cleaning effects and the processing time.

The plan of the experiment is to do a series of comparison experiments, step by step, to test out the best set of parameters for the practical laser cleaning of the anilox rolls. ES, SA and SCL will determine PF. With DC, PF and DC will then determine the PL. Together with ES and PL, they will determine the energy that is put into cell on the ceramic surface, which is the most important judgment on whether the ceramic would be damaged or not.

3.1 Determine the ES

In ideal case, to get the best production efficiency, the higher the speed, the shorter the cleaning time would be. However, due to the mechanical limitations of the engraving system, the top ES you can type in the engraving system is 250 cm/s. In addition, in case of safety, it is not allowed to have a very high angular speed of the roll. For rolls that has diameter below 100mm, the engraving speed below 200 cm/s is required.

Because for convenience, an uniform set of parameters is needed. So for safety concern (for rolls that have larger diameters, higher speed is possible), the **engraving speed is chosen to be 150 cm/s**.

3.2 Determine the beam diameter (focus distance)

According to section 2.5, the relation between the beam diameter and the focus distance would be known. So the operators here can adjust the beam diameter to a certain value freely.

According to the principle of laser cleaning stated in section 1.3, the blast wave will break the adhesion of any ink to the surface of anilox rolls, which requires a certain amount of power intensity to provide the enough thermal and mechanical effect. In practical experiments, if the power intensity is not enough, i.e., the beam diameter is not small enough, then the adhesion between the ink and the ceramic would not be broken and the inks would not be totally evaporated and pushed out.

Comparisons between some tests can explain the importance of the laser power intensity. Tests 62, 63 and 64 in Figure 3.1 were using the typical post-melting parameters which were developed by operators in Apex:

62: ES = 170 cm/s, DC = 41.4, PF = 9.617 kHz, SA = 7°, SCL = 57, BD (beam diameter) = 550 μm.

63: ES = 170 cm/s, DC = 41.4, PF = 9.617 kHz, SA = 7°, SCL = 57, BD = 460 μm.

64: ES = 170 cm/s, DC = 41.4, PF = 9.617 kHz, SA = 7°, SCL = 57, BD = 380 μm.

And also, most of the tests in Figure 3.2, BD = 1800 μm. It can be seen that with a big beam diameter (low power intensity), even though the speed was low and all the ink and ceramic were melted, there was still the trace of the ink on the ceramic (black and yellow). This is because the laser intensity was not high enough to create the blast wave to shock the ink away. In addition, once the black and yellow melted substances were produced, even if you use the highest power intensity, you will not remove them, which means these substances are much more difficult to clean than the normal inks.

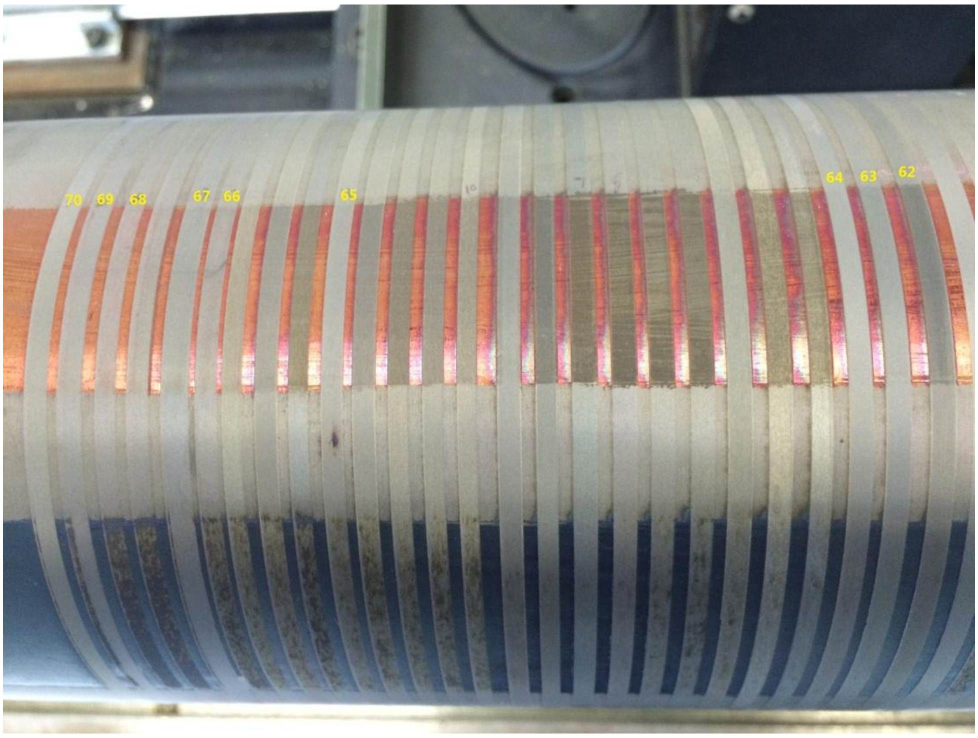

Figure 3.1 Tests on a roll covered by solvent red and blue ink (numbers are experiments marks by which microstructures can be found in the pdf files)

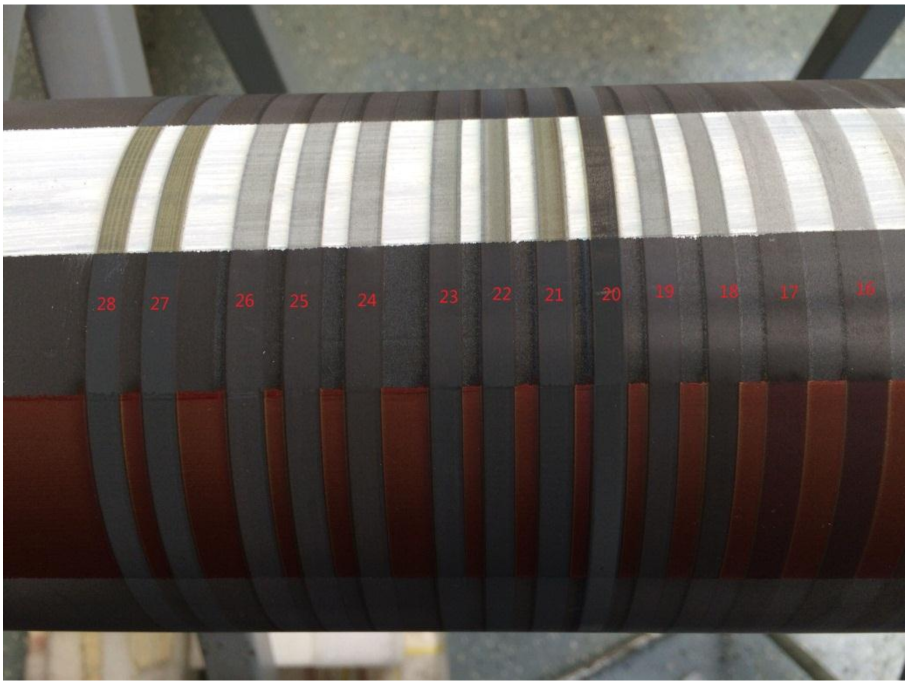

Figure 3.2 Tests on a roll covered by water-based white and red ink (numbers are experiments marks by which microstructures can be found in the pdf files)

65: ES = 100 cm/s, DC = 15, SA = 45° , SCL = 150, BD = 200 μm.

66: ES = 150 cm/s, DC = 12, SA = 45° , SCL = 150, BD = 200 μm. (Ceramic not melted, left red, blue and white ink.)

67: ES = 150 cm/s, DC = 12, SA = 45° , SCL = 150, BD = 200 μm. 3 times repeat. (Ceramic not melted, red and blue ink well cleaned, left white ink.)

68: ES = 150 cm/s, DC = 8, SA = 45° , SCL = 200, BD = 100 μm. (Ceramic not melted, left red, blue and white ink.)

69: ES = 150 cm/s, DC = 8, SA = 45° , SCL = 200, BD = 100 μm. 3 times repeat. (Ceramic not melted, red and blue ink well cleaned, left little white ink.)

70: ES = 150 cm/s, DC = 9, SA = 45° , SCL = 200, BD = 100 μm. 4 times repeat. (Ceramic little melted, red, blue and white ink well cleaned)

As the results shows, there is a range of the BD, in which the laser beam is powerful enough to blast away the dry ink, and while BD is not too small to ablate the ceramic:

- If the **BD is too big**. The advantage would be with a proper SCL, a bigger BD allows the beam to clean the same place of the roll for more than one time, which means less left ink (you can see the left ink on the test 68 in Figure 3.1). The disadvantage would be that the area of the low power intensity laser beam would be relatively large and the resulting melted ink (yellow and black substances sticking to the ceramic as shown in 27, 28 in Figure 3.2) would be very difficult to clean.

- If the **BD is too small**. The advantage would be a very small low power intensity area, dry ink would be easily blasted away and the melted ink would barely stick on the ceramic surface. The disadvantage would be that after cleaning one circle of the roll, a part of the melted ink would be pushed aside and accumulated on the next circle, then one time cleaning is not enough, resulting the left ink (see 66, 68). Also a small BD needs a larger SCL for a fully cover of the cleaning, meaning longer cleaning time.

The smallest BD of the system is 86 μm. According to experiments 53-61 (see pdf), with the control of DC, the minimum BD would not damage the ceramic. In the meantime, after a series of tests in Figure 3.1, the upper BD was found to be 200 μm. The testing way is to see after cleaning, whether the ink would be left with melted yellow and black substances.

Among the three inks of different colors, **the white ink is the most difficult one to be cleaned**, mostly because of its low light absorbance and heavy TiO_2 particles. According to tests 67, when BD=200 μm, even after 3 times cleaning, the cleaning results of the white ink was still not good. See the microstructure of the test 67 after cleaning.

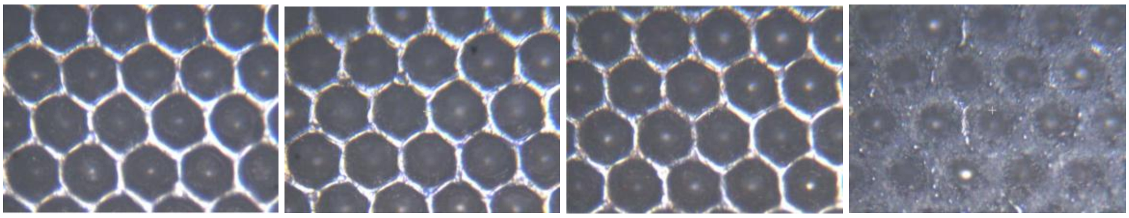

Figure 3.3 Microstructures of test 67 after cleaning. (a) Original area (a little dirty); (b) Blue solvent ink; (c) Red water-based ink; (d) White water-based ink.

At the minimum BD, the white ink could be well cleaned, see test 60 and 61. **Considering the production time, the BD was finally set to be 100 μm**. According to test 69 and 70, with a proper DC, the results were acceptable, see Figure 3.4 and 3.5.

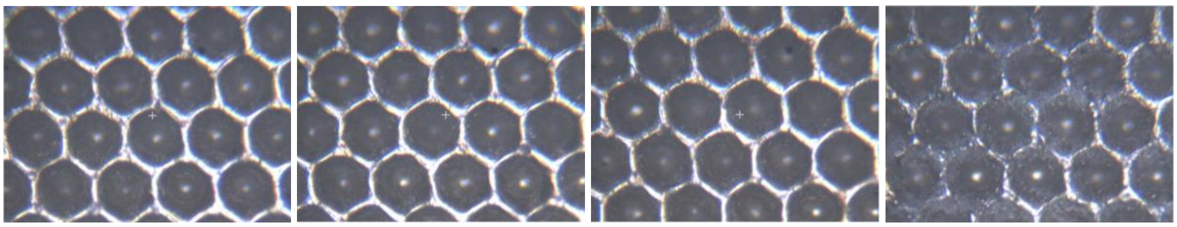

Figure 3.4 Microstructures of test 69 after cleaning. (a) Original area (a little dirty); (b) Blue solvent ink; (c) Red water-based ink; (d) White water-based ink.

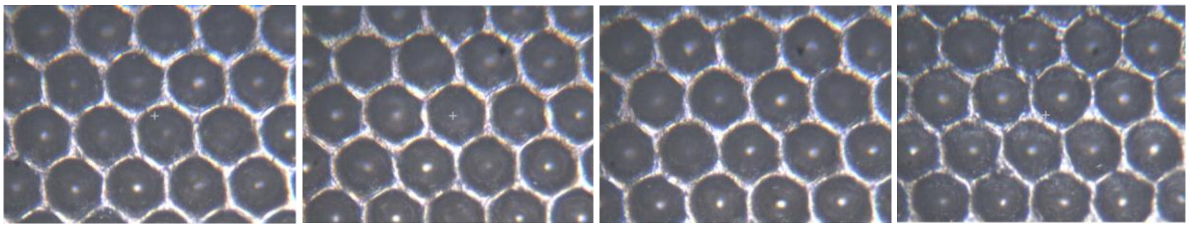

Figure 3.5 Microstructures of test 70 after cleaning. (a) Original area (a little dirty); (b) Blue solvent ink; (c) Red water-based ink; (d) White water-based ink.

For BD = 100μm, the number of the radical distance shown on the clock should be set to be 2.201mm if an adjusting shim of 15mm thickness were used, as table 3.2 shows.

parameter	value	unit	remark
D	9	mm	Beam diameter before focal lens
f	50.8	mm	Focal length of the lens
θ_f	0.175345902	rad	Full far field divergence angle of the focused beam
d(f)	86	um	Diameter at the focus
d(z)	100	um	Diameter of the beam on the ceramic surface
Δz	0.291021362	mm	Radial distance between the beam at d(f) and d(z)
y1	2.201021362	mm	Number of distance that should be set on the clock if use an adjusting shim that has a thickness of 15mm (1.91mm + Δz)

Table 3.2 Laser beam properties calculation when BD = 100μm

3.3 Determine the SA

As stated before, at certain ES, with the increase of SA, the intensity of the cells in one circle of the roll decreases, whilst the intensity of the cells along the shaft increases. **At 45°SA, the cells are most averaged distributed**. For cleaning, we want the laser beam to averagely cover the ink, so 45° is the best choice. However, smaller SA means shorter production time. Compromises could be made in the future to meet the cleaning request while improving the production speed by decrease the SA.

3.4 Determine the SCL

BD, SA, and SCL together will determine the type of the beam cover on the ink. At least, the beam spots should be overlapped in order to cover the whole ceramic surface. First, SCL=200 l/cm was chosen, which means the distance between two cells along the circle is $\frac{10000}{200} * \sqrt{2} = 70.7\mu m$. For BD=100 μm, the ceramic surface can be well covered, see Figure 3.6.

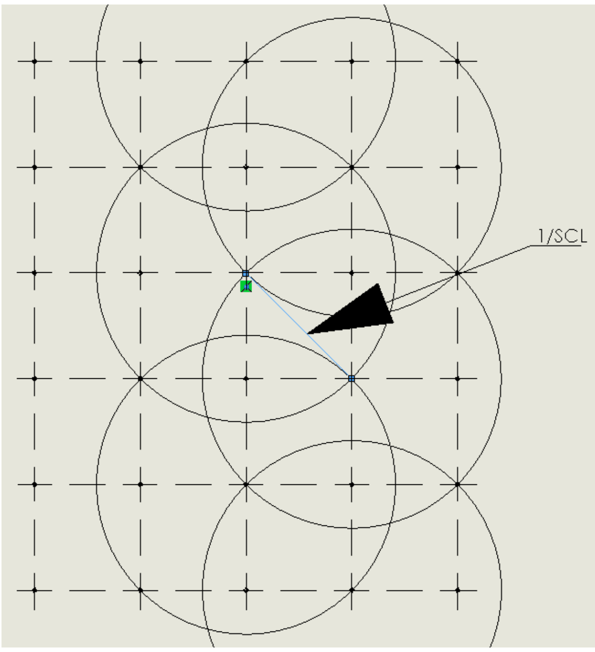

Figure 3.6 Overlap of the laser beam during test if SCL=200 l/cm, BD=100 μm.

Next, a series of comparison tests had been done:

(1) ES = 150 cm/s, DC = 8.5, SA = 45°, SCL = 200, BD = 100 μm. (Ceramic not melted, left red, blue and white ink. After the second cleaning, all the ink could be well cleaned.)

(2) ES = 150 cm/s, DC = 9, SA = 45°, SCL = 250, BD = 100 μm. (Ceramic a little melted, cleaning results worse than (1).)

(3) ES = 150 cm/s, DC = 11, SA = 45°, SCL = 400, BD = 100 μm. (Ceramic a little melted, cleaning results worse than (2).)

(4) ES = 150 cm/s, DC = 11, SA = 45°, SCL = 600, BD = 100 μm. (Ceramic a little melted, cleaning results worse than (3).)

From the tests, we can see the overlap is not the more, the better. **The reason may be that with the higher SCL there would be higher PF, making it more like a CW laser. Too overlapped and a shorter pulse duration would make the ink difficult to be blasted away**. This is why in test (2) (3) (4), even though the ceramic were melted, the cleaning results were still worse than (1). Therefore, **SCL=200 l/cm is a good choice**.

3.5 The function of adjusting DC

ES, SA and SCL determine the PF, then PF and DC determine the PL, which determines the energy that is put into the ceramic per laser pulse. Every different set of parameters has a **critical value of DC** that would just melt the ceramic. That DC would provide the most potential of cleaning the ink while not melting the ceramic. Most of the DC values used in my experiments are this critical value. This DC could be found by doing series of tests or by computer simulation in the future.

For our particular set of parameters: ES = 150 cm/s, SA = 45°, SCL = 200, BD = 100 μm, PF = 21.214 kHz, PL = 4 μs. The best DC would be between around 8.5. Due to different practical cases, the **DC could be between 8.0 – 9.0**.

3.6 Testing trials for the selected set of parameters

The selected set of parameters: **ES = 150 cm/s, SA = 45°, SCL = 200, BD = 100 μm, PF = 21.214 kHz, PL = 4 μs, DC = 8.5.**

In addition, one important step before laser cleaning is to use **liquid cleaner, try to mix the inks and make the ink layer smooth and have average thickness.**

(1) Put some liquid cleaner on the tissue;

(2) Press the tissue on the running roll and go through the roll, hold longer time when you feel unsmooth lumps and try to clean it off.

(3) Repeat the process for one or more times.

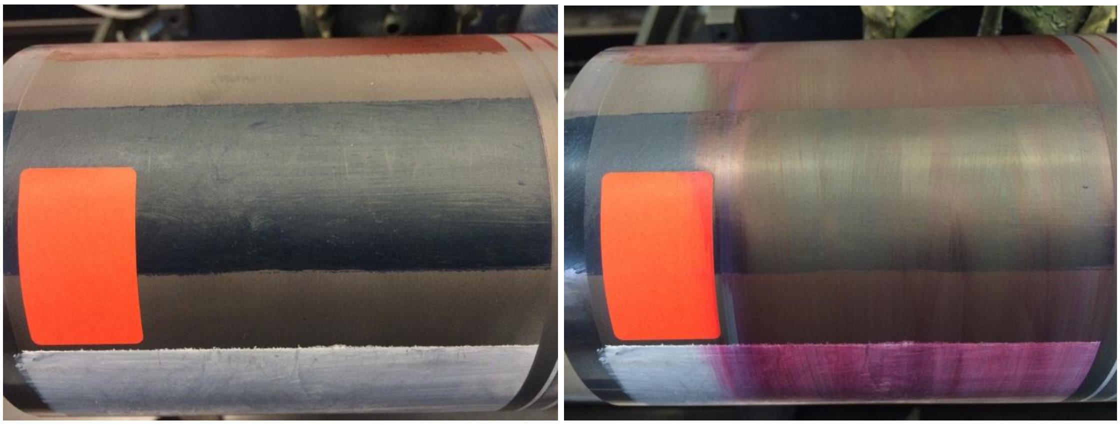

Figure 3.7 A testing roll before and after liquid cleaning.

The process can be seen in Figure 3.7. There are two reasons for doing this. First one is to decrease the possibility of remaining ink lumps. Because if the ink layer is too thick in some places, the laser power would not be enough to clean it just by one or two times. The second reason is that some rolls are covered with different inks, mixing the inks would average the light absorbance of the inks and make the cleaning more efficient.

After the pre-cleaning process, laser cleaning treatment can be used afterwards. Figure 3.8 shows the test result using the selected set of laser cleaning parameters on the roll from Figure 3.7. The inks covered include five kinds of inks: water-based white ink, water-based red ink, solvent white ink, solvent red ink, and water-based blue ink.

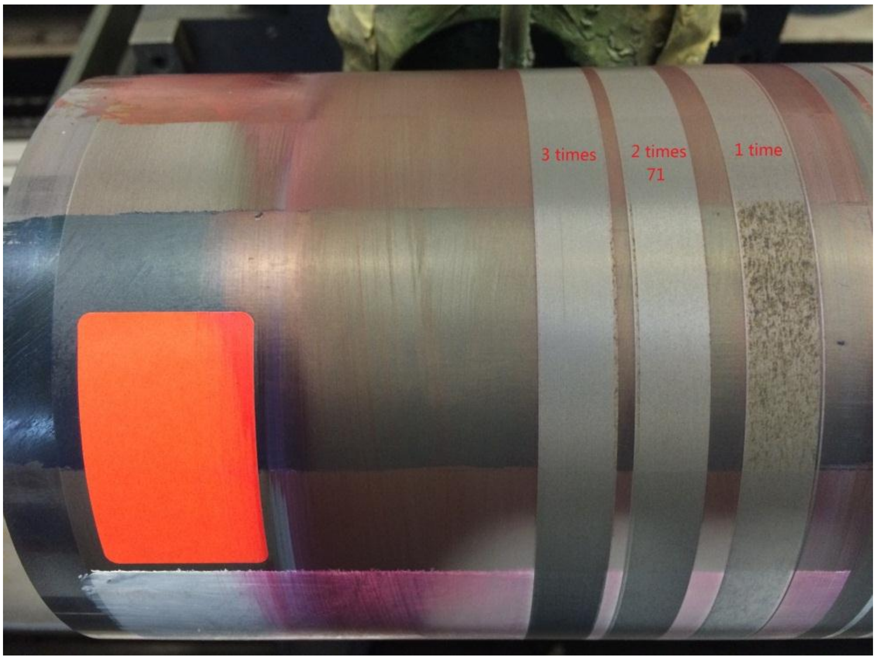

Figure 3.8 Test results using the selected parameters for 1, 2 and 3 times.

As can be seen in Figure 3.8, one time cleaning is not enough for this situation, there are left ink on the roll by three kinds of inks. This is because the ink layer was thick and also as stated before, part of the ink that was blasted away would accumulate on the neighbour and left an **ink lump**.

Therefore, a second even more times are needed for well cleaning. In theory, the more times it goes through, the cleaner it would be. For production efficiency, a third time is not allowed. Figure 3.9 shows the microstructure of the test 71.

71: ES = 150 cm/s, SA = 45°, SCL = 200, BD = 100 μm, PF = 21.214 kHz, PL = 4 μs, DC = 8.5. Twice.

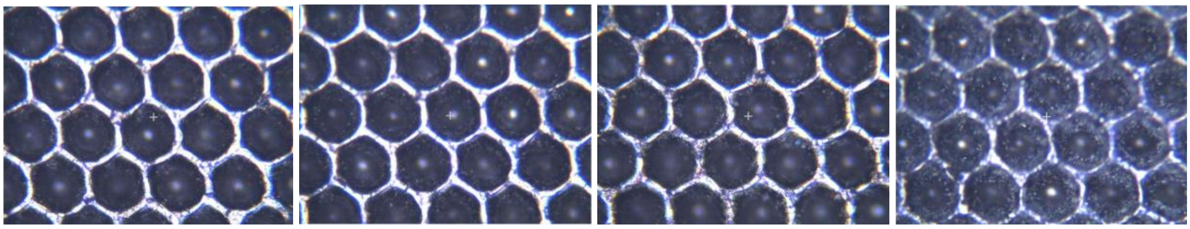

Figure 3.9 Microstructures of test 71 after cleaning. (a) Original area (a little dirty); (b) Blue solvent ink; (c) Red water-based ink; (d) White water-based ink.

As can be seen, by twice cleaning, most of the inks can be well cleaned, except the white ink, still a bit worse than the result in Figure 3.5. To ensure the effectiveness of the two time laser cleaning, volumes of the roll were measured:

Volume before cleaning: 5.46 BCMs;

Volume after cleaning (red ink 1 time): 6.20 BCMs;

Volume after cleaning (red ink 3 time): 6.09 BCMs;

Volume after cleaning (white ink 2 time): 6.03 BCMs;

Volume after cleaning (white ink 3 time): 6.23 BCMs;

After 2 times cleaning, the volume of the cells covered by white ink is already similar with the other clean places on the roll. If the customer were not satisfied, then it needs more times cleaning.

When cleaning the white inks, it is inevitable that there would be left inks and the test in my experiments is an extreme example because the roll was totally covered by big area of pure white ink. Common dirty rolls are covered with different kinds of mixed inks and the layer is relatively thin because the customer would had already used some chemical cleaning methods for reuse, which could be easier to clean and sometimes one time laser cleaning is enough.

Different kinds of dirty rolls in Apex were collected and cleaned by using the selected set of parameters. The microstructures of the rolls include GTT, 60°, 30°, and Helical, etc.; The type of SCL varies; The type of inks also varies . The results show that all the rolls would be relatively clean without damaging the ceramic after 2 times laser cleaning, some of them only need 1 time. Below are some pictures showing the cleaning results.

Figure 3.10 shows a roll with a helical structure that is originally covered with black ink. Different inks were then covered on purpose. After pre-cleaning process and one time laser cleaning, the roll is already pretty clean.

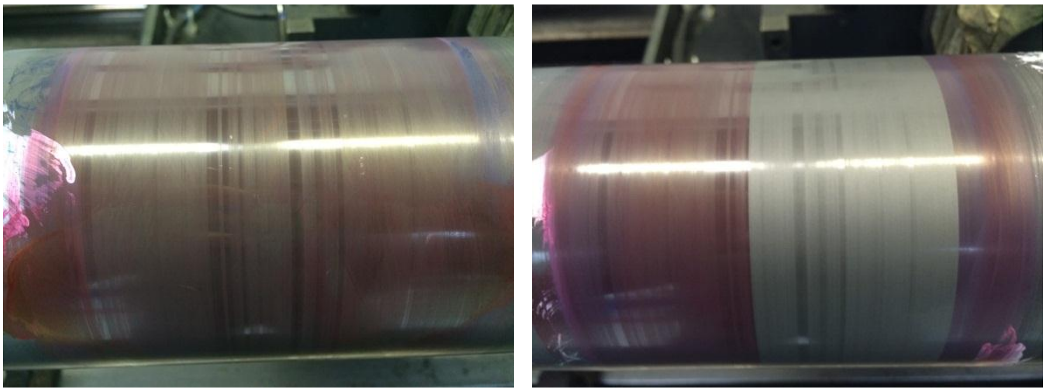

Figure 3.10 Comparison before and after laser cleaning. Helical structure covered with black ink. 1 time.

Figure 3.11 shows a roll with a 60° structure that is originally covered with thick blue ink. Different inks were then covered on purpose. After pre-cleaning process and two times laser cleaning, the roll is already pretty clean. At the first time laser cleaning, because of the thickness of the ink, there were left ink on the roll. The second cleaned all of the inks including the white inks because with the blue inks under, the laser energy would be better absorbed by the ink and it was easier to be cleaned.

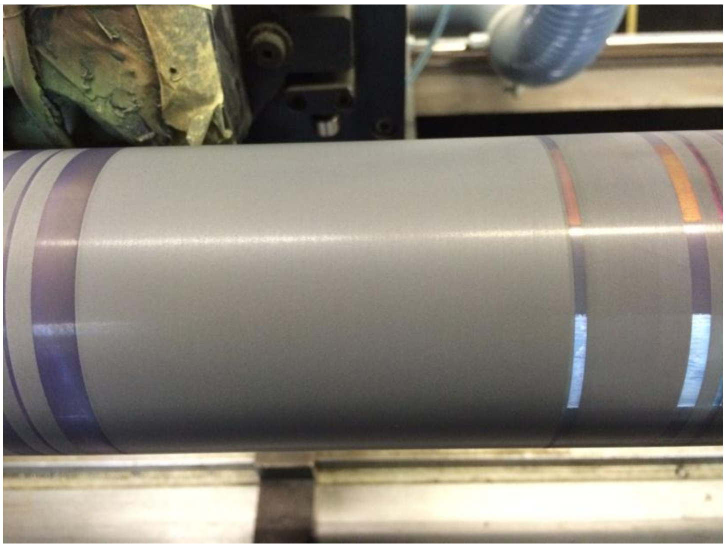

Figure 3.11 Comparison before and after laser cleaning. 60° structure covered with blue ink. 2 times.

3.7 Conclusion and prospects

According to the selection process and trial experiments, a set of parameters was screened out to be used as laser cleaning parameters:

ES = 150 cm/s, SA = 45°, SCL = 200, BD = 100 μm, PF = 21.214 kHz, PL = 4 μs, DC = 8.5. No limit times.

If an **adjusting shim of 15mm thickness** were used, **the number of the radical distance shown on the clock** should be set to be **2.201mm**.

In practical, operators can slightly adjust the **value of DC** to adapt to the real situations, in case the DC would be too large to melt the ceramic.

By simple chemical pre-cleaning, this set of parameters is suitable for cleaning all kinds of rolls which are covered with different inks without damaging the ceramic. Theoretically, the more times the laser cleaning is through, the cleaner the roll would be. Practically, 2 times is enough for usual rolls (depending on the request of the customers).

Improvements and Prospects:

1. The beam profile is Gaussian. If the profile could be changed into top-hat, the laser power intensity would be averagely distributed and there would be less possibility to cause the melted left inks (yellow and black substances, difficult to clean). Then the BD could be enlarged, which means smaller SCL is possible and shorter production time could be achieved.
2. For other colour inks except white ink, smaller laser power intensity is enough and the BD could be larger than 200 μm, which means smaller SCL is possible and shorter production time could be achieved. So one possibility is to set two groups of parameters, one is for white ink, one is for other inks, which can save a lot of cleaning time.

3. Running the laser cleaning with 2 or more laser beams at the same time would largely improve the cleaning efficiency and quality. In some professional cleaning companies, the cleaning laser is a line consisted of several laser beams, which means 1 time equals several times cleaning. By installing more laser beam and running at the same time, the cleaning procedure would only be needed to run for one time, and the roll would be totally clean.

Chapter 4 Design and results of the experiments for laser post-melting

4.1 Determine the SA

The principle of the laser post-melting is similar with the laser cleaning. When melting the cells, we want the beam spots to be averaged distributed on the surface and have minimum visible influences. Still, as the reasons stated before, SA = 45° seems to be the best choice.

4.2 Determine the BD

The principle of determining the BD is the same with the laser cleaning case – BD should be small enough to provide high laser power intensity to blast away the ceramic dust. In the meantime, the intensity should not be too strong to damage the top wall of the cells. And considering the production efficiency, the BD should be as large as possible to get lower SCL and higher EPR (Engraving Pitch Rate), which means lower processing time.

Here is an example (see pdf "Han – 92") showing the micro images before and after the post-melting. As can be seen, before the melting, the dust from the engraving is fully covered on the surface. With the post-melting, most of the dust could be cleaned away. In addition, with a bit melt and re-solidification, the top of the cell wall became shinier.

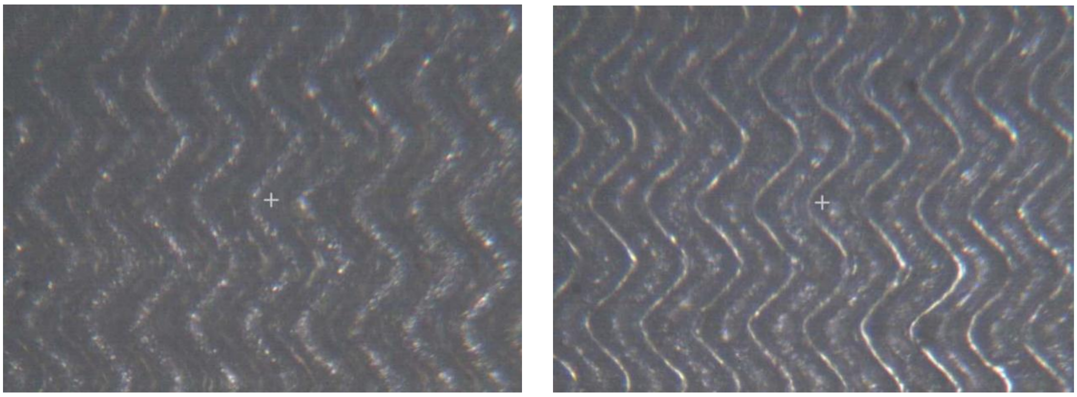

Figure 4.1 Comparison between the micro images before and after the post-melting

A roll with GTT structure was chosen. A series of experiments were done on this roll for testing the proper BD. Figure 4.2 shows a comparison between a) the original surface after air blowing and b) the surface after normal finishing process. As shown, after liquid washing and polishing, both the top and bottom of the surface would be quite flat and smooth compared to the original one just after engraving. To reach the result as Figure 4.2 b) shows by the post-melting is our goal.

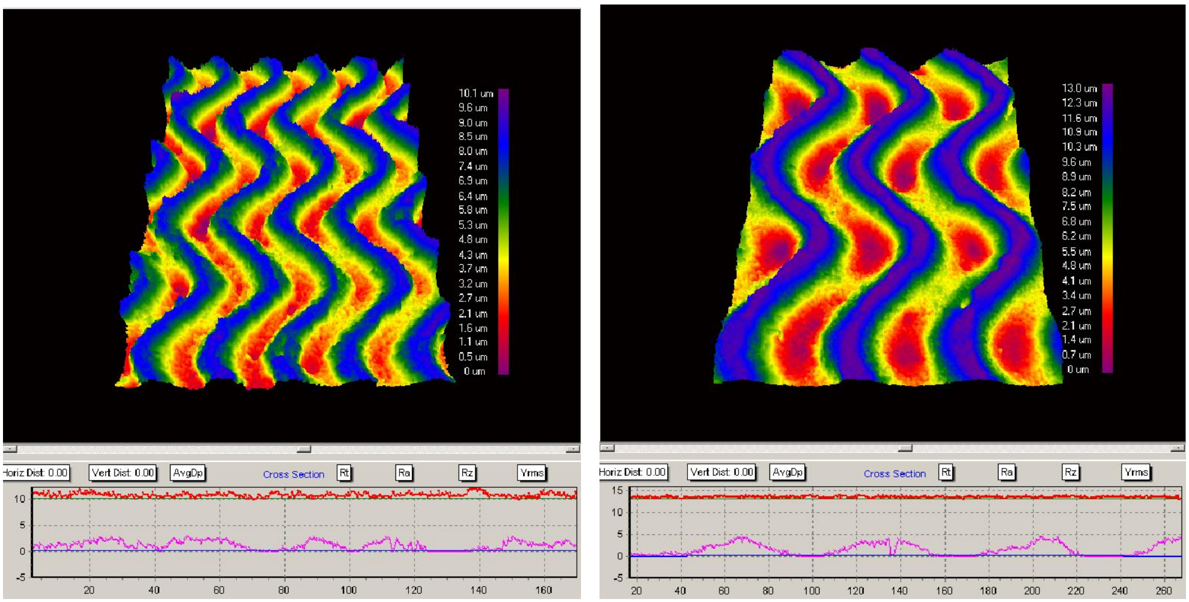

Figure 4.2 Comparison between a) the original surface after air blowing and b) the surface after normal finishing process.

Different BD was implied on the same ceramic surface for comparison. The original sample, Volume: 4.16 BCMs; Depth: 10.10 μm.

80: Laser cleaning parameters. ES = 150 cm/s, SA = 45°, SCL = 200, BD = 100 μm, DC = 8.5. After treatment, Volume: 4.44 BCMs; Depth: 10.79 μm.

83: ES = 150 cm/s, SA = 45°, SCL = 50, BD = 400 μm, DC = 15. After treatment, Volume: 4.05 BCMs; Depth: 9.59 μm.

84: ES = 150 cm/s, SA = 45°, SCL = 50, BD = 600 μm, DC = 25. After treatment, Volume: 4.24 BCMs; Depth: 9.78 μm.

88: ES = 150 cm/s, SA = 45°, SCL = 50, BD = 1000 μm, DC = 45. After treatment, Volume: 4.17 BCMs; Depth: 9.61 μm.

Figure 4.3 shows four micro images using different BD and a critical DC which makes the ceramic a bit melted. From the images, we can see that all the four images are not as flat and smooth as the one after normal finishing process. In fact, in macroscopic view, if you use a blade to slightly scrape the surface, you can judge the roughness by the feeling from the blade. The finished surface is smooth, and has optical reflection. While the original surface is relatively rough and have no optical reflection, and the ones after post-melting have similar roughness, just a little smoother than the original one. This means, **using the post-melting method could not achieve the smoothness as normal finishing process could achieve**.

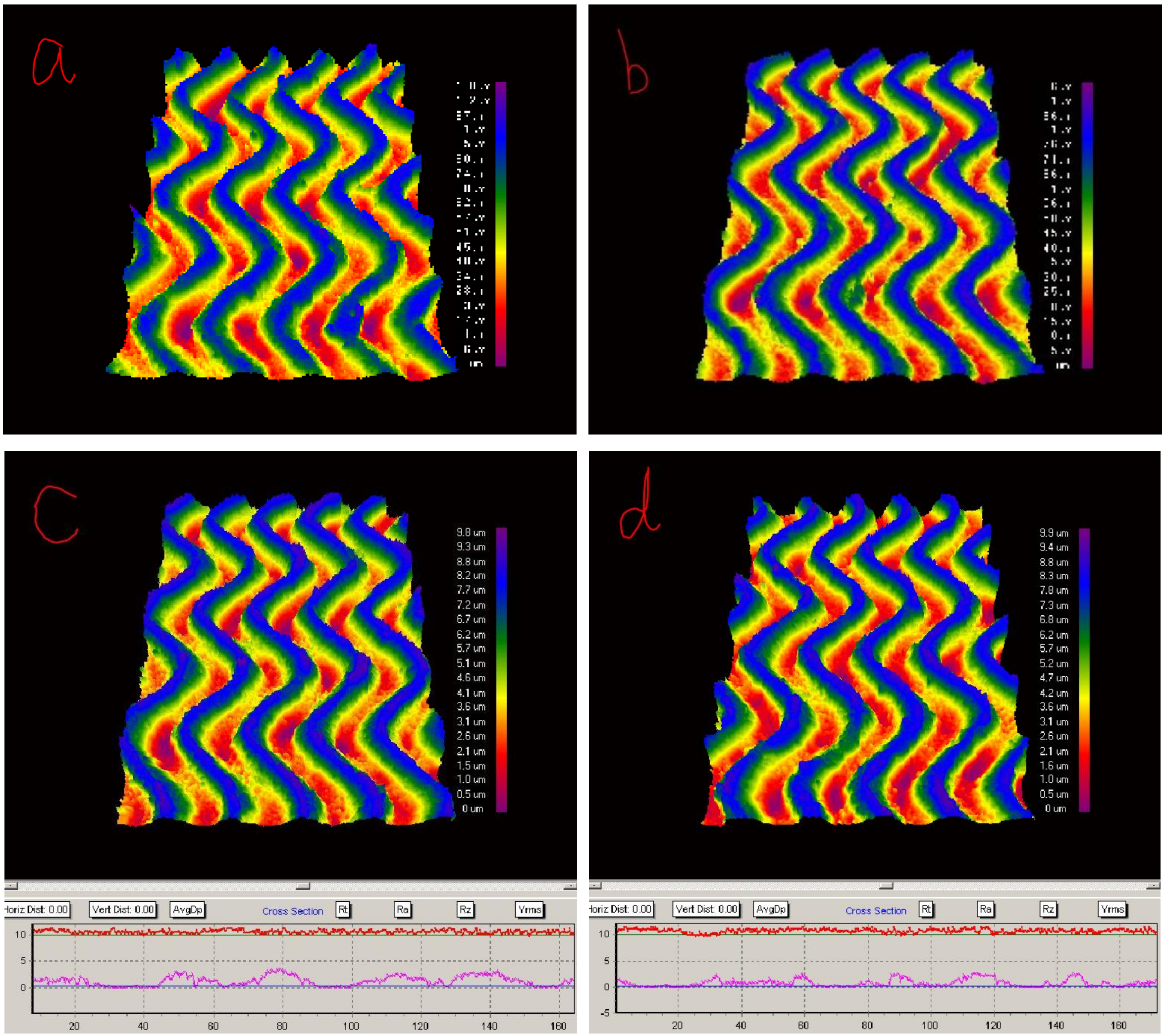

Figure 4.3 Micro images using different BD and a critical DC which makes the ceramic a bit melted. a) Test 80. b) Test 83. c) Test 84. d) Test 88.

Among the four images, it can be seen that the surface from “(c) Test 84” has the best shape, considering the remove of the dust and the damage of the cells wall. When the BD = 1000μm, as “d) Test 88” shows, the laser intensity is not strong enough to blast away all the dust covered, leaving a coarse top surface. In the meantime, when BD = 100 or 400μm, there is a large possibility that the wall would be damaged by the high intensity of the laser. Overall, it turns out that BD = 600μm is a good choice for the post-melting process.

4.3 Determine the SCL

If the relation between the BD and SCL would be the same with the one in the laser cleaning process, as Figure 3.6 shows, if the BD = 600μm, the SCL would be 33.33 l/cm. Through the test 94 and 97 (see pdf), the result from the microscopic image is acceptable. However, from the macroscopic view, because of the SCL is low and also the relatively high DC for melting, visible 45° engraving cells would be observed, which is not allowed. Therefore, larger SCL is needed to increase the coverage rate of the laser beam on the surface, to prevent the uneven distribution of the melt area. After tests, SCL = 50 l/cm seems to be a good choice.

If in the future, there are still optical side effects on the surface, then the measure would be increase the BD, i.e., increase the value on the “focus clock”, and in the meantime increase the SCL.

4.4 Find the relation between ES and DC

In different engraving cases, the ES would be different. Therefore, to adapt the post-melting system into the engraving system, the ES of the post-melting is required to be the same with the ES of the engraving. In order to have the same melting effect at different ES, a form was made for the convenience of the operators. See Table 4.1, corresponding to one ES, there is a range of DC provided for the operators to adjust in case of practical situations (the DC value in the bracket is the recommended value for making the ceramic a bit melted). About this testing roll, the micro structure is hexagon, with the original Volume: 7.88 BCMs; Depth: 21.15 μm.

BD = 600μm, SCL = 50 l/cm, SA = 45°, A bit melted of the top wall	Test No.	ES (cm/s)	DC (%)	PL (μs)	Volume (BCMs)	Depth (μm)
	100	45	9 - 14 (12)	75.4	7.85	21.20
	101	80	15 - 20 (18)	63.6	7.75	20.81
	102	115	21 - 26 (24)	59	7.90	20.87
	103	150	29 - 34 (32)	60.3	7.77	20.84
	104	185	35 - 40 (38)	58.1	7.82	20.87

Table 4.1 The range of DC in order to melt the surface a bit corresponding to each ES

An example, test 99 (see pdf), was made to illustrate how “a bit meted” would be like. See Figure 4.4.

99: ES = 150 cm/s, SA = 45°, SCL = 50, BD = 600 μm, DC = 32.

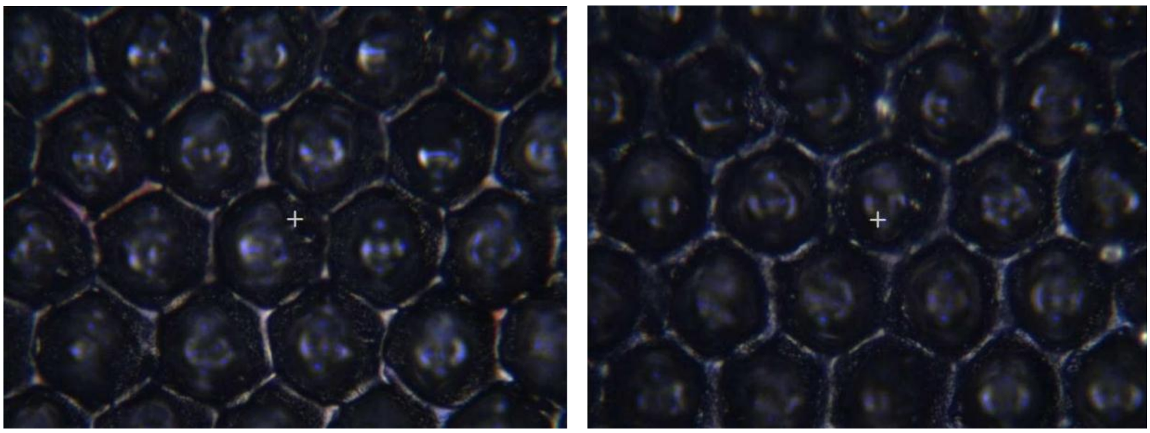

Figure 4.4 Micro images of test 99 before and after post-melting

As can be seen in Figure 4.4, before post-melting, the call wall is thin and sharp. After the melting, the wall is a bit melted and the thickness increases, which may improve the properties of the cell structure. Meanwhile, from Table 4.1 it can be seen that the **volume and depth nearly not change**, which means if the post-melting is processed right after the engraving, the operators could make the volume just the same as the customers ask, instead of making it 1-3 BCMs larger.

In addition, as table 4.1 shows, with fixed other parameters, the ES and DC have corresponding linear relationship to melt the surface a bit, which can be also illustrated by the almost fixed pulse length (PL) – around 60 µm. By knowing this, operators could test out the proper DC under different ES with higher speed and accuracy, like Figure 4.5 shows.

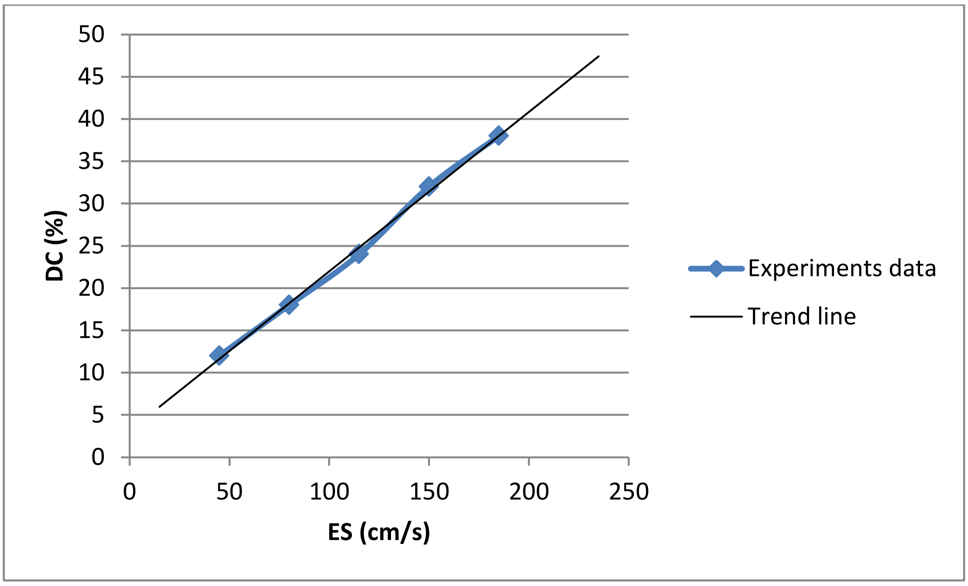

Figure 4.5 Relationship between ES and DC when slightly melting the ceramic surface

4.5 Conclusion and prospects

A new production process concept was proposed. After engraving, instead of moving the roll to finishing process, including liquid washing and polishing, the roll would be kept at the same lathe and accept a post-melting process. The purpose of the post-melting is to blast the dust away and also try to make a smoother surface and thicker wall with better structure properties.

See Table 4.2, corresponding to one ES, there is a range of DC provided for the operators to adjust in case of practical situations (the DC value in the bracket is the recommended value for making the ceramic a bit melted). With other ES, different DC would be predicted and tested out by using table 4.2 and Figure 4.5.

BD = 600µm (Table 2.4), SCL = 50 l/cm, SA = 45°, A bit melted of the top wall	ES (cm/s)	DC (%)
	45	9 - 14 (12)
	80	15 - 20 (18)
	115	21 - 26 (24)
	150	29 - 34 (32)
	185	35 - 40 (38)

Table 4.2 The range of DC in order to melt the surface a bit corresponding to each ES

All of the sets of the parameters shown in Table 4.2 could blast the dust away and make the cells a bit melted, which can make a smoother surface and thicker wall with better structure properties. When operators engrave the rolls, they can make the volume just the same as the customers ask. Because after the post-melting, the volume and depth would nearly not change.

In addition, one of the functions of the post-melting is to eliminate the optical defects produced during the engraving. One set of parameters, as stated in Chapter 3.2 (Test 62, 63, 64), is now usually used for post-melting if optical defects were found after engraving. **With the new parameters, for example Test 103 and 104, the melting effects would be expected to be similar while the processing time could be half and even more less**.

Chapter 5 Roughness changes after laser treatment

The device used to measure the roughness of the anilox rolls is the "Perthometer M2" produced by Mahr. The device is shown below in Figure 5.1.

Figure 5.1 The sketch of the measurement device - Perthometer M2

The plan is to use different kinds of laser beams to process the unengraved ceramic surface, and compare the different roughness changes. Figure 5.2 shows the practical measurement on the anilox roll.

Figure 5.2 The practical measurement on the anilox roll

The measurement process is to put the detector stable and horizontal on the roll, set the “auto” mode, press “start” button. The measuring distance is 5.6 mm, therefore the laser processed area should be longer than 5.6mm. Because of the random error of the measurement device and the random roughness on the roll, the measurement way is to measure three different places on each laser treated area, and then calculate the average value.

First of all, the original smooth surface was tested, data was shown in Table 5.1 below.

		a	b	c	average
Original smooth surface	Ra (um)	0.263	0.282	0.272	0.272
	Rz (um)	2.970	3.060	3.020	3.017
	Rmax (um)	3.870	3.960	4.780	4.203
	Rk (um)	0.460	0.440	0.470	0.457

Table 5.1 Roughness data of the original unengraved surface of a anilox roll

In the table, a, b, c means the number of times that the detector measures. Roughness average Ra is the arithmetic average of the absolute values of the roughness profile ordinates.

$$R_a = \frac{1}{l}\int_0^l |Z(x)|\, dx$$

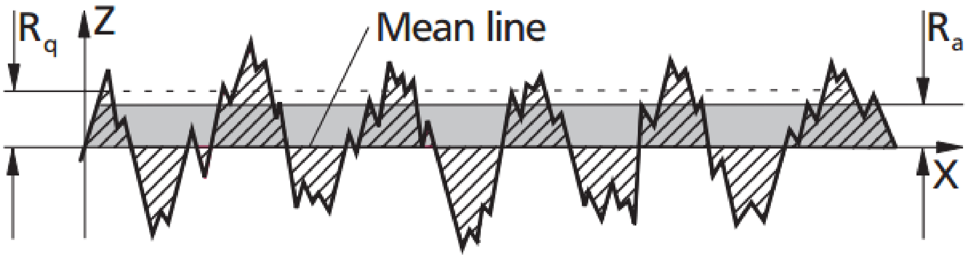

Figure 5.3 Explanation for Ra

Single roughness depth Rzi is the vertical distance between the highest peak and the deepest valley within a sampling length. **Mean roughness depth Rz** is the arithmetic mean value of the single roughness depths Rzi of consecutive sampling lengths:

$$R_z = \frac{1}{n}(R_{z1} + R_{z2} + \dots + R_{zn})$$

Maximum roughness depth Rmax is the largest single roughness depth within the evaluation length.

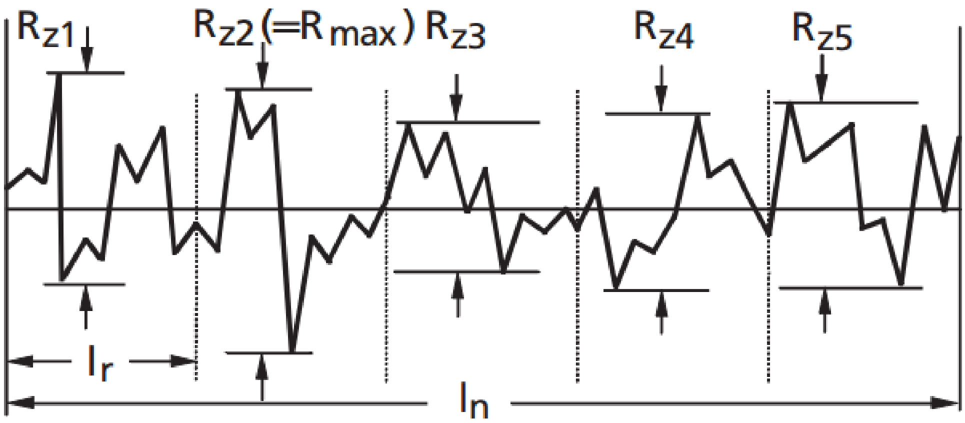

Figure 5.3 Explanation for Rz and Rmax

Core roughness depth Rk is the depth of the roughness core profile.

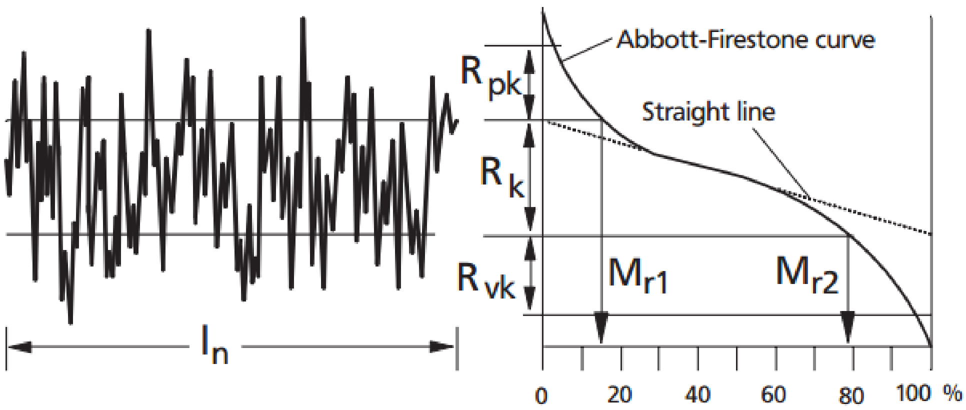

Figure 5.3 Explanation for Rk

All of these four parameters have different evaluating functions for the roughness measurement. For the laser treatment, different beam diameter and SCL were settled, in order to analyze the roughness change effects of the different beam properties. An final data sheet is shown in Table 5.2 (For all the three times roughness data, see excel file ”Roughness test”.).

Test No.	BD (um)	SCL	Ratio	DC	PF (kHz)	PL (us)	Ra (um)	Rz (um)	Rmax (um)	Rk (um)
1	100	100	2	4.2	10.606	4	0.317	3.360	4.317	0.607
2	100	200	1	8.5	21.214	4	0.337	3.730	4.473	0.687
3	100	300	0.667	8	31.819	2.5	0.352	4.237	6.240	0.653
4	100	400	0.5	8	42.426	1.9	0.337	3.883	4.910	0.593
5	300	33.33	2	9	3.536	25.5	0.297	3.553	4.907	0.530
6	300	66.67	1	15	7.07	21.2	0.316	4.06	5.787	0.543
7	300	100	0.667	18	10.606	17	0.313	4.037	5.053	0.637
8	300	133.33	0.5	19	14.142	13.4	0.31	3.89	5.080	0.660
9	500	20	2	Showing optical spots, not suitable						
10	500	40	1	20	4.243	47.1	0.298	3.413	4.263	0.560
11	500	60	0.667	23	6.364	36.2	0.312	3.763	5.823	0.617
12	500	80	0.5	26	8.485	30.7	0.273	3.58	4.680	0.537
13	500	100	0.4	28	10.606	26.4	0.293	3.513	4.583	0.573
14	500	80	0.5	34	8.485	40.1	0.33	3.933	5.410	0.737
15	500	80	0.5	42	8.485	49.5	0.381	4.517	6.847	0.913

Table 5.2 Roughness data of laser treated surface of an anilox roll

In the Table 5.2, the “Ratio” means the ratio between screen line distance and the laser beam radius on the anilox roll surface. Beam speed is 150 cm/s, SA was chosen to be 45°. The DC was chosen by the similar principle as in the laser cleaning project, is to choose the critical value of DC that would just not damage the ceramic. For each roughness parameter, a graph was made to show the comparison among different sets of BD and SCL.

5.1 Laser treatment effects on Ra

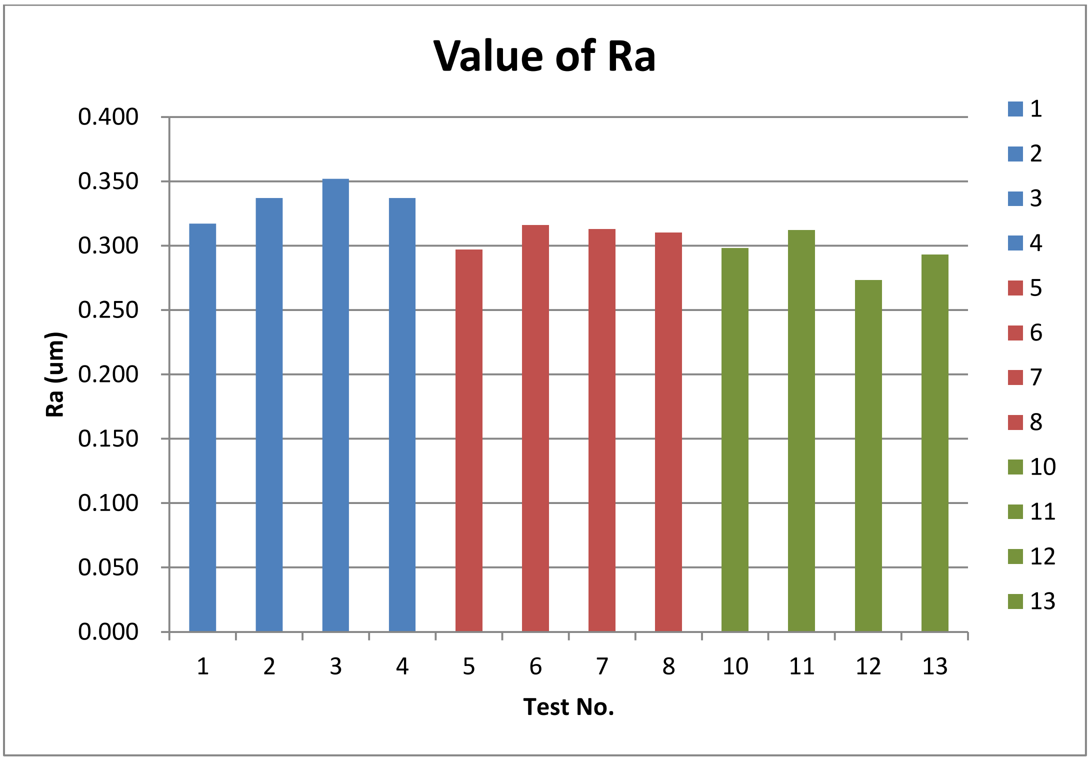

Figure 5.4 Value of Ra in tests from Table 5.2

As we can see from Table 5.2, test 1-4 BD = 100μm, test 5-8 BD = 300μm, test 10-13 BD = 500μm. And in each group, SCL increases by each test.

From Table 5.1, Ra of the original surface is 0.272μm. By analyzing Figure 5.4, it could be seen that after laser treatment, most of the Ra is above 0.3μm, which means laser treatment could increase the Ra.

With the increase of BD, we can see a small decrease trend of Ra. This means the lower the laser beam power intensity, the smaller possibility that it would influence the roughness.

And with the increase of SCL (overlap of the beam spots), i.e. the decrease of the ratio between screen line distance and the laser beam radius, there is no obvious changes on Ra.

5.2 Laser treatment effects on Rz

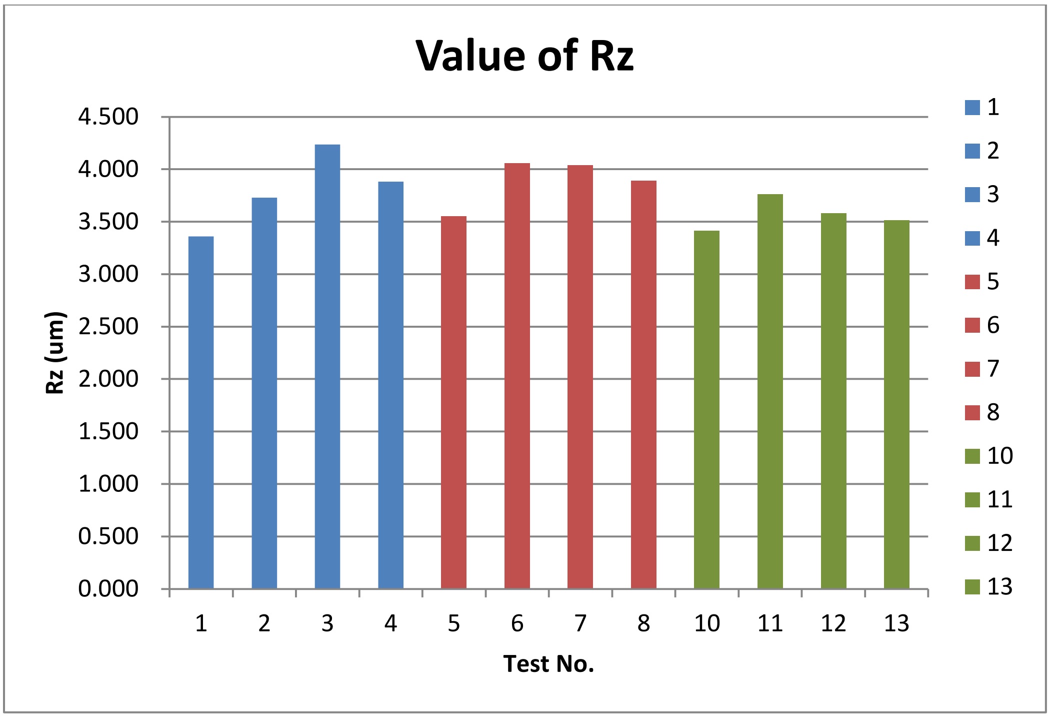

Figure 5.5 Value of Rz in tests from Table 5.2

From Table 5.1, Ra of the original surface is 3.017μm. By analyzing Figure 5.5, it could be seen that after laser treatment, most of the Rz is above 3.5μm, which means laser treatment could increase the Rz.

With the increase of BD, we can see a small decrease trend of Ra. This means the lower the laser beam power intensity, the smaller possibility that it would influence the roughness.

And with the increase of SCL (overlap of the beam spots), i.e. the decrease of the ratio between screen line distance and the laser beam radius, there is no obvious changes on Ra.

5.3 Laser treatment effects on Rmax

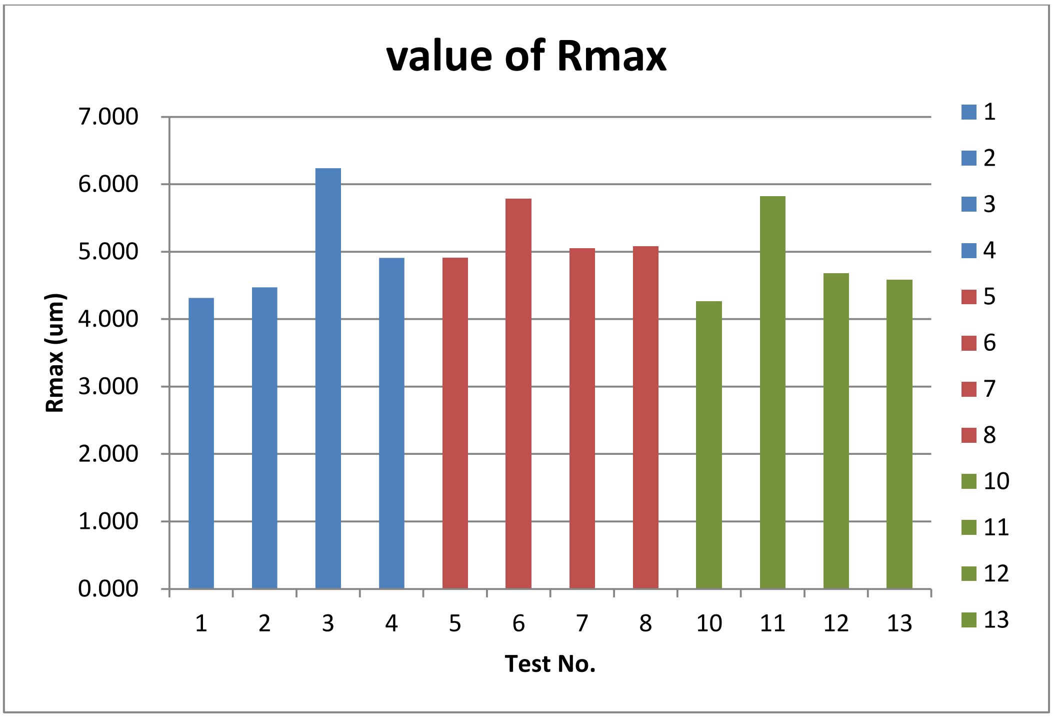

Figure 5.6 Value of Rmax in tests from Table 5.2

From Table 5.1, Ra of the original surface is 4.203µm. By analyzing Figure 5.6, it could be seen that after laser treatment, most of the Rmax is above 4.2µm, which means laser treatment could increase the Rz.

With the increase of BD, we can see a small decrease trend of Ra. This means the lower the laser beam power intensity, the smaller possibility that it would influence the roughness.

And with the increase of SCL (overlap of the beam spots), i.e. the decrease of the ratio between screen line distance and the laser beam radius, there is no obvious regulation to follow on the change of Rmax. Although relatively test 3, 6 and 11 shows apparent larger Rmax, but because of the limited data and the random error, this result could be regarded as the measurement errors.

5.4 Laser treatment effects on Rk

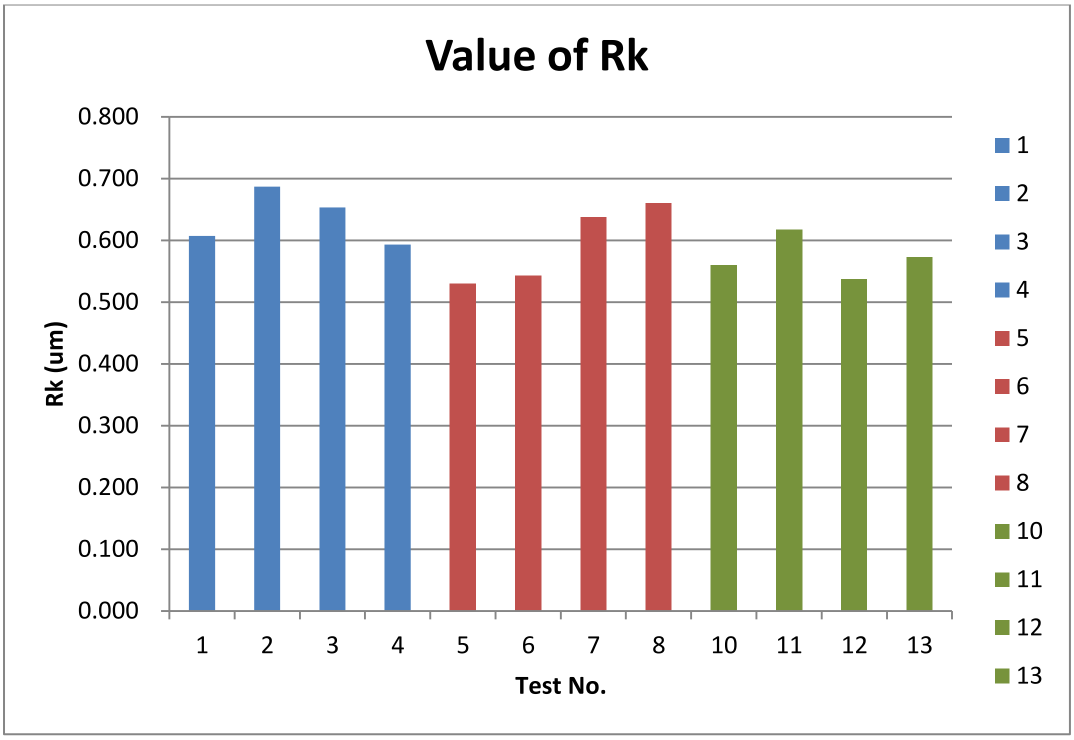

Figure 5.7 Value of Rk in tests from Table 5.2

From Table 5.1, Ra of the original surface is 0.457μm. By analyzing Figure 5.7, it could be seen that after laser treatment, most of the Rmax is above 4.2μm, which means laser treatment could increase the Rz.

With the increase of BD, we can see a small decrease trend of Ra. This means the lower the laser beam power intensity, the smaller possibility that it would influence the roughness.

And with the increase of SCL (overlap of the beam spots), i.e. the decrease of the ratio between screen line distance and the laser beam radius, there is no obvious regulation to follow on the change of Rmax.

5.5 The effect of DC on the roughness change by laser treatment

In this case, it is known that the melting of the surface could be a big factor for the roughness changing. So a set of comparison tests were made, with the same BD, SCL, SA, ES, different increasing DC, i.e. different melting level, to investigate the roughness change. A data sheet was made as Table 5.3.

Test No.	BD (um)	SCL	Ratio	DC	PF (kHz)	PL (us)	Ra (um)	Rz (um)	Rmax (um)	Rk (um)
Original surface							0.272	3.017	4.203	0.457
12	500	80	0.5	26	8.485	30.7	0.273	3.58	4.680	0.537
14	500	80	0.5	34	8.485	40.1	0.33	3.933	5.410	0.737
15	500	80	0.5	42	8.485	49.5	0.381	4.517	6.847	0.913

Table 5.3 Roughness change with the change of DC (surface melting level)

In Table 5.3, the surface in test 12 nearly not melted, the surface in test 14 melted a bit, and the surface in test 15 had an obvious melting appearance. As shown, with the increase of DC, all the parameters representing the roughness: Ra, Rz, Rmax and Rk, their values increase also. This means that the roughness of surface would increase with the melting level.

5.6 Conclusion for the roughness changes after laser treatment

From Table 5.2 and all the comparison figures in chapter 5, it could be seen that after laser treatment, most of the Ra, Rz, Rmax and Rk are obviously above their original values, which means laser treatment could increase the roughness.

With the increase of BD, we can see a small decrease trend of roughness values. This means the lower the laser beam power intensity, the smaller possibility that it would influence the roughness.

And with the increase of SCL (overlap of the beam spots), i.e. the decrease of the ratio between screen line distance and the laser beam radius, there is no obvious regulation to follow on the change of the roughness. Although relatively some tests showed apparent larger roughness values, because of the limited data and the random error, this result could be regarded as the measurement errors.

At last, with the increase of DC, all the parameters representing the roughness: Ra, Rz, Rmax and Rk, their values increase also. This means that the roughness of surface would increase with the melting level.

To get the relation between the surface tension (wettability) of the surface after laser treatment, from literature review, it could be known that for not too rough surfaces (roughness significantly below the wavelength of laser light) we can describe the effect of surface roughness by the so-called Wenzel equation. The equation predicts that if a molecularly hydrophobic surface is rough, the appearance is that of an even more hydrophobic surface. If a hydrophilic surface is roughened it becomes more hydrophilic. [13]

For further investigation, a series of tests could be done on the laser treated area shown in Table 5.2, from which we could know the relation between the roughness and the surface tension (wettability), together with the laser treatment parameters.

References

[1] International Paper - Knowledge center - Flexography: http://wayback.archive.org/web/20100816235813/http://glossary.ippaper.com/default.asp?req=knowledge/article/151.

[2] Johansson, Lundberg & Ryberg (2003) "A guide to graphic print production", John Wiley & Sons Inc., Hoboken, New Jersey.

[3] http://www.apex-groupofcompanies.com/conventional-ceramic-coated-laser-engraved-anilox-rolls/

[4] http://www.harperimage.com/AniloxRolls/Anilox-Guides/Anilox-Line-Screen

[5] www.praxair.com/printing

[6] V. Veiko, A. Samohvalov, E. Ageev. Laser cleaning of engraved rolls coupled with spectroscopic control. Optics & Laser Technology 54 (2013) 170–175.

[7] http://www.utwente.nl/ctw/wa/research/laser/

[8] M. Julkarnain, J. Hossain, K. Sharif,.A. Khan, Journal of Optoelectronics and Advanced Materials, 13,42 (2011) 485–490.

[9] https://en.wikipedia.org/wiki/Chromium%28III%29_oxide

[10] http://www.terolabservices.com/thermal_spraying/technical_papers.asp.

[11] Ziad Tariq Khodair, Gailan Asad Kazem, Ammar Ayesh Habeeb. Studying the optical properties of (Cr2O3:I) thin films prepared by spray pyrolysis technique. Iraqi Journal of Physics, 2012, Vol. 10, No.17, PP. 83-89.

[12] http://support.epiloglaser.com/article_p.aspx?cid=8205&aid=42827

[13] David Quere. Rough ideas on wetting. Physica A 313 (2002) 32–46.