

# Laser Engraving of Micro-patterns on Roll Surfaces

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A pattern engraving method was developed with argon ion laser combined with an electro-optic (E-O) modulator and its control units. Image data was first encoded, processed and transferred to the laser modulator after which the patterns were printed on a photosensitive polymer coated on the cold mill roll surface. Once the pattern printing was complete, the roll was put through an etching process for final pattern engraving. Experimental results provide validation that the proposed technology and its performance are quite promising. This developed technology is fairly general and multiple patterns can be imprinted on any target body with the resolution of the  $\mu\text{m}$  unit.

KEY WORDS: laser engraving; etching process; argon ion laser; E-O modulator; DSP board.

## 1. Introduction

Patterned surface stainless steel sheet is widely used for kitchen goods and building construction due to its excellent surface qualities, aesthetically pleasing aspects and corrosion-resistant properties. Patterns are engraved on these sheets by rolling them with a roll whose surface is already engraved with the patterns. Various methods have been proposed to engrave patterns on roll surfaces<sup>1-11)</sup>: knurling, electrical discharge texturing (EDT), shot blasting, film masking, and laser engraving. In the knurling process, a roll is either struck with a thorned hammer or knurled by rolling it with a thorned roll. But due to mechanical and technological limitations, this method proves difficult in forming regular and equal-sized patterns and the thorn is bound to wear as the process is repeated. EDT is a process whereby a roll is immersed in water charged with electricity, which dulls its surface. The problem with EDT is that the equipment is complicated and the discharge electrode has a limited life. Shot blasting is a process whereby fine metal granules are shot blasted to a roll surface at a very high speed. Shot blasted rolls are widely used in dull-skin pass rolling, but the resulting products are likely to have nonuniform surfaces so this method is not adequate for uniform treatment of roll surfaces. Finally, film masking is commonly used in the roll surface treatment process, but its primary disadvantage is that film patterns are not easily changed and pattern discontinuity arises at the film joint. Skilled technicians are usually required to ameliorate pattern discontinuity.

To solve the above shortcomings, a laser engraving technology is introduced in this paper. According to this method, computer-generated patterns are transferred to a laser modulator and the corresponding laser beam pulse train is projected on the roll surface to realize desired pro-

jections and indentations. Then, by rolling this roll on a cold-rolled steel sheet, the same patterns can be engraved on it. Patterns formed by using laser beams are superior to those formed by using conventional methods: the projections and indentations are uniform in size and depth throughout the roll surface. Therefore, steel sheet surfaces processed by this method become sharper in reflection and is more resistant to die galling at the time of pressing. The other advantage of this method is that a pattern image can be transferred either in bitmap or encoded format. With the encoding technique, the image data can be transferred more efficiently.

This paper is organized as follows. Section 2 describes the developed laser engraving system, Sec. 3 the pattern printing procedure, Sec. 4 provides experimental results, and Sec. 5 presents conclusions.

## 2. Laser Engraving System Development

### 2.1. Engraving System Overview

The hardware configuration of the proposed engraving system is depicted in **Fig. 1**. The system consists of a laser beam generator; an E-O modulator controlling the laser beam; a roll rotating device that supports and rotates the roll; a linear motion (LM) guide that moves a platform on which the optical devices are mounted; a step motor that moves the LM guide; a rotary encoder that detects the rotational angle of the roll; a processor board that reads encoder signals, outputs pulses to the step motor driver, stores fragments of image patterns and controls the output pulses of the E-O modulator; and a host PC with a slave processor board that runs host and slave programs and provides a man-machine interface (MMI) environment (**Fig. 2**).

The developed laser engraving system consists of several subsystems: a photosensitive polymer coating/etching sys-

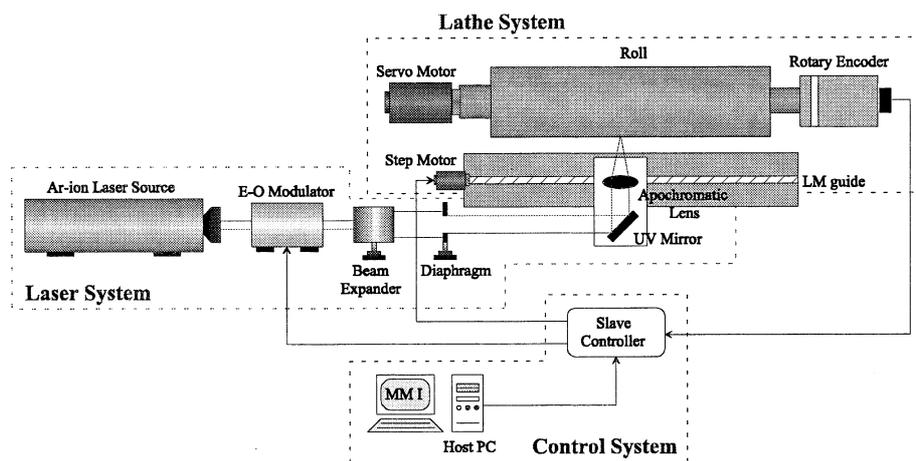


Fig. 1. Pattern engraving system hardware units.

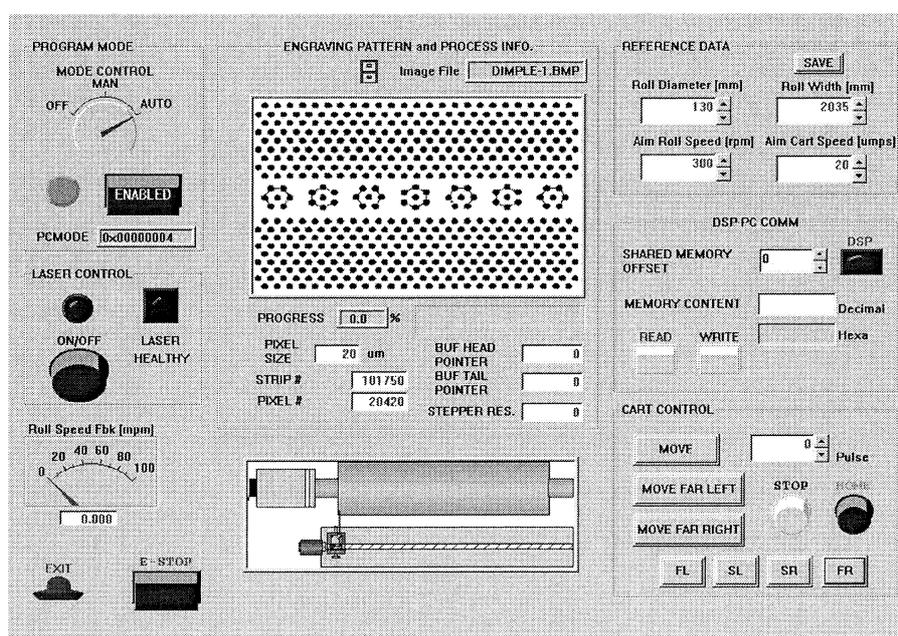


Fig. 2. MMI screen for laser engraving system.

tem, a lathe system, a laser system, and a control system. Lathe system components are already described above but the details of photosensitive polymer coating/etching steps are omitted in this paper because they are essentially the same as conventional procedures. Pattern engraving system hardware units are shown in Fig. 1.

## 2.2. Laser System

The laser system is an optical system that transmits laser beams to engrave patterns on a roll surface. The system consists of a laser source, a modulator that controls the laser's ON/OFF operation, and a laser beam focusing module.

### 2.2.1. Laser Source

The laser used in the experiment is a continuous wave (CW) argon ion (Ar-ion) laser that generates ultraviolet (UV) light with maximum power of 1 W. The original laser source comes with multi-line (333.6–363.8 nm) characteristics and the photosensitive polymer used in the experiment responds best under this wavelength range. It is modified,

however, to achieve single-line (351.1 and 351.4 nm) characteristics by adjusting the rear mirror of the laser cavity. This arrangement was made to eliminate chromatic aberration of the original laser beam and then to minimize the spot size of the beam. In fact, if collimated light with certain wavelength range is focused by a condensing lens, a chromatic aberration is bound to occur that limits the minimum obtainable spot size. The output power of a laser with single-line characteristics becomes 0.5 W, enough to harden the photosensitive polymer because the selected single-line has dominant power in the multi-line range. The laser beam in our system is linearly polarized. A vertically polarized beam is stronger by a factor of 100 than a horizontally polarized beam, which means that the theoretical ON/OFF power ratio is 100:1.

In printing certain patterns on a rotating roll, the laser beam ON/OFF operation is crucial. A pulsed or a CW laser is normally used to realize the sequential ON/OFF operation of a laser beam.<sup>15)</sup> With a pulsed laser, it is possible to produce a single shot laser beam according to the command

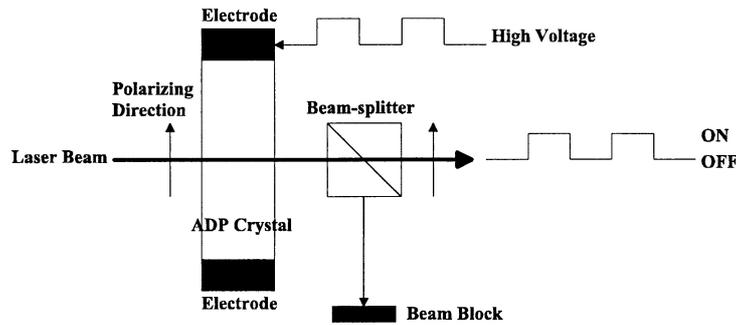


Fig. 3. Modulation of laser beam by electro-optic effect.

of a laser controller. Moreover, a circular shape laser spot can be printed without deformation because the time interval of a laser beam pulse is very short compared to the rotational speed of a roll. However, a pulsed laser is not generally suitable for high speed processing because the repetition rate of the laser beam generation is low. By contrast, a CW laser is suitable for high speed processing because it uses a laser beam modulator which makes high frequency ON/OFF beam operation possible. Since a laser engraving system requires very high speed ON/OFF operation, a CW Ar-ion laser is naturally selected here as a beam source and an E-O modulator is used to control ON/OFF operations.

### 2.2.2. E-O Modulator

There are two types of modulator: acousto-optic (A-O) and electro-optic (E-O).<sup>16)</sup> For the majority of surface engraving applications, A-O modulators have been widely used for ON/OFF modulation<sup>3,10)</sup> which sequentially deflects the propagation direction of laser beams that transmit ultrasonic fields formed inside a crystal. However, the incidence angle of laser beam onto the crystal surface must equal the Bragg angle determined by the wavelength of the laser beam and the characteristics of the crystal. Obviously, it is not easy to align the laser beam and maintain the incidence angle when it is open to external vibration. Moreover, A-O modulators require complicated power supply schemes to generate amplitude modulated high frequency voltage. Due to these difficulties, the A-O modulation technique is not suitable for pattern engraving applications and the E-O modulation method is adopted instead.

As shown in Fig. 3, the laser beam polarized in a vertical direction passes through an ammonium dihydrogen phosphate (ADP) crystal. As it passes through the ADP crystal, some laser beams pass through a polarizing beam-splitter and the rest are reflected. Initially, when no voltage is applied to the electrode, the polarizing directions of laser beams before and after they pass through ADP crystal are identical. In this case, the amount of transmitted laser beam should be set to maximum by adjusting the direction of the polarizing beam-splitter. Once the laser beam is calibrated this way, some voltage is then applied to the electrode and the polarizing direction of the laser beam starts to rotate according to the electro-optic effect and the amount of transmitted beam at the polarizing beam-splitter declines accordingly. In this case, the transmitted laser beam reduction ratio varies with the voltage magnitude applied to the crystal. Therefore, if we apply high voltage to a selected frequency, the laser beam then turns on and off with the same

frequency. This technique facilitates easy installation and simple maintenance of equipment since it is rarely affected by laser beam incidence angle. Moreover, the ON/OFF operation of the laser beam through DC voltage modulation simplifies its control.

### 2.2.3. Laser Beam Focusing and Delivery Module

In irradiating the laser beam on a roll surface, we first focus the beam with an optics module and project it onto the roll surface. The optical focusing and laser beam delivery module consists of beam expander, diaphragm, UV mirror, apochromatic lens, and a platform on which these optical devices are mounted. Since the laser source beams are of Gaussian distribution, the spot size focused by the lens is inversely proportional to the diameter of beams incident on the focusing lens. For this reason, a beam expander is used to obtain a larger beam diameter, thereby realizing the focused spot size with high energy density on the roll surface. It is also used for laser beam collimation by continuously adjusting the expansion ratio, thereby minimizing the divergence of the original laser beam. A diaphragm trims the outer part of the expanded laser beam to generate a uniform beam diameter and pass only the high density part of the beam. Taking engraved pattern accuracy into account, the laser beam is controlled to a diameter of 20–30  $\mu\text{m}$  in the experiment. The UV mirror converts the direction of the laser beam by 90°. The apochromatic lens focuses the laser beam reflected by the UV mirror and reduces the beam diameter by compensating both spherical and chromatic aberration.<sup>17)</sup>

The platform that delivers the beam on the roll surface is set to move in parallel with the roll axis. The UV mirror then reflects the laser beam by 90° and renders the beam to be injected perpendicularly onto the roll surface (Fig. 1). With this structure, we are able to maintain a constant distance between the roll and the apochromatic lens while the platform is moving. Even if the target roll changes for other experiments, this distance can be kept the same by using the translation stand that can move the apochromatic lens back and forth along the normal direction to the roll surface.

## 2.3. Control System

Control system and its individual components are shown in Fig. 4. The personal computer (PC) runs a host program and the digital signal processor (DSP) board runs a slave program. The DSP board is connected to the PC via peripheral component interconnect (PCI) bus and performs core

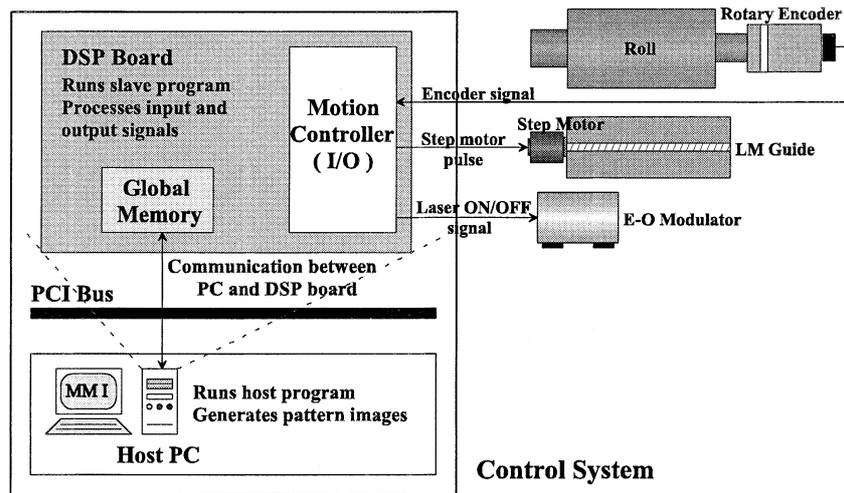


Fig. 4. Control system configuration.

functions of the system. It is based on the 40 MHz TMS320C44 32bit floating-point processor. A commercial M44MOT board is used as a motion controller and is mounted piggyback on the DSP board which manages all the input and output signals and controls the step motor to move the LM guide.

The LM guide used in our experiment is designed for high accuracy and smooth motion, which guarantees precise laser positioning. The performance of the step motor affects positioning accuracy, positional repeatability, and straight line accuracy of the LM guide. The precision limit of the step motor is 50 800 steps/rev. As an input format, either step/direction or clockwise/counterclockwise pairs can be used. With slow and constant speed operation, the LM guide is moved with the speed of  $\mu\text{m}/\text{sec}$  range. In our system, the speed of 40–150  $\mu\text{m}/\text{sec}$  is used.

While the roll rotates at a very high speed, the laser beam should be irradiated on a specific point on the roll. To this end, it is necessary to measure the absolute position of the roll surface. A high resolution encoder is therefore needed to detect the much smaller region than the size of the laser beam irradiated on the roll surface. The roll used in the experiment rotates at 120 or 300 rpm, and a rotary encoder with an accuracy of 50 000 pulse/rev is used.

Since the host PC and the DSP board have common PCI bus, the mailbox interrupt is used for event-type communication. The pattern images, reference inputs and the feedback data are transferred *via* global memory of the DSP board. The reference inputs include roll width and diameter, aim speeds of the roll and cart, cart home position, stepper resolution, *etc.*; feedback data includes the measured speed of the rotating roll, current position of the UV mirror, laser condition, operation mode, *etc.*

The roll diameter in the experiment was 130 mm, *viz.* 408 407  $\mu\text{m}$  in circumference. If the roll rotates at 300 rpm, the laser beam must scan 2 042 035  $\mu\text{m}$  per second. Thus, if the laser beam diameter is 20  $\mu\text{m}$ , then the on-off pulse rate should be 102 102 signal/sec. Accordingly, the controller should be able to generate a square wave with 9.8  $\mu\text{s}$  on/off duration in the worst case.

As the engraving system is installed in a factory open to various types of noise for an experiment, so a suitable mea-

sure for noise reduction is required. To this end, a surge killer is attached to the main power unit and the subsystem power units are separated from one another by using transformers to prevent noise from interfering.<sup>13)</sup> A photo-coupler is used in an interface board to prevent the parasitic noise of the power source from being propagated to the DSP board. A software filter is also used to suppress high-frequency noise included in the rotary encoder signals.

### 3. Pattern Printing

#### 3.1. Engraving Process Overview

The pattern engraving process consists of several steps: photosensitive polymer coating, laser engraving, developing, etching and polymer removing. During the photosensitive polymer coating stage, a photosensitive polymer with high photosensitivity at the desired UV wavelength bandwidth is coated on the roll surface. It is important to choose a photosensitive polymer that responds well to a certain bandwidth of UV wavelengths.<sup>14)</sup> Furthermore, care must be taken that the photosensitive polymer is spread evenly over the roll surface as uneven coatings may result in distorted patterns. During the engraving stage, a continuously oscillated laser beam is sequentially turned on and off by controlling the E-O modulator, thus the UV laser beam is selectively applied to the photosensitive polymer. In this way, predetermined patterns are invisibly printed on the photosensitive polymer coated on the roll surface. In the development stage, the photosensitive polymer on the roll is developed with a solution and the portion not applied by the laser beam is melted away. In the etching stage, patterns are engraved on the roll surface by etching the developed roll. The hardened photosensitive polymer is then completely removed by washing the roll surface and the pattern engraving process is completed.

#### 3.2. Pattern Forming

Any pattern can be engraved on the roll surface using the proposed laser engraving system. **Figure 5** shows an example of a dimple pattern.

The proposed laser engraving mechanism is different from that of a dot printer. If a dot printer mechanism is

used, we must first stop the roll and print the pattern strip on the roll surface in the direction that is parallel with the roll axis. We then rotate a target roll weighing a few hundred kilograms within the range of 20–30  $\mu\text{m}$  to print the next pattern strip. This mechanism is not practical, however, since it is extremely difficult to rotate a roll weighing a few hundred kilograms within the range of 20–30  $\mu\text{m}$ . To overcome this problem, we allow the target roll to rotate at a constant speed and set the light UV mirror to move parallel with the roll axis. First, we fix the UV mirror at a specific position and print a pattern strip around the roll while the roll rotates at a constant speed. Once the pattern strip is printed around the roll, the UV mirror is shifted by a distance equal to or less than the laser beam diameter and the next pattern strip is printed around the roll. Repeating this step, we can print patterns all over the roll surface. Even with this arrangement, however, we encounter two problems. First, the roll rotates at a constant speed during the entire process and even while the UV mirror is shifting. Consequently, the starting point of the next strip pattern will shift slightly from that of the current one. Next, while it is possible to shift the UV mirror with the resolution of the  $\mu\text{m}$  unit, it takes some time for the mirror to settle down after the UV mirror shifts to the next point. To compensate for these problems, a modified method is suggested and described below.

Once the engraving operation begins, the target roll rotates at a constant speed and the LM guide on which the UV mirror is mounted is set to move with a constant speed

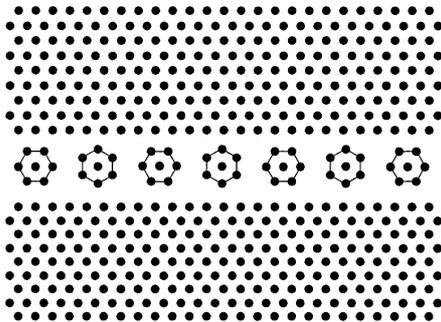


Fig. 5. Dimple pattern example.

without stopping. During this operation, the LM guide is arranged to move the distance of the laser beam diameter when the roll makes one revolution. In this way, the pattern will be engraved on the roll in a spiral fashion, but there is no need to synchronize the starting line between the consecutive pattern strips. If the pattern strip width is 30  $\mu\text{m}$ , then an engraved dimple pattern on the roll surface distorts by dozens of pm to the moving direction of the LM guide. However, this is negligible when considering the whole pattern image.

In forming the pattern, it is necessary to make a highly accurate synchronization with roll rotational speed and the ejection timing of the laser pulse. To this end, the rotary encoder detects the rotational angle of the roll and the ejection timing of the beam pulse is determined according to detected encoder readings. Consequently, the present arrangement does not require speed control of the servo motor for roll rotation.

The dimple pattern in Fig. 5 consists of numerous image strips. For example, if we wish to print a dimple 600  $\mu\text{m}$  in diameter on the roll surface, 20 image strips are needed when 30  $\mu\text{m}$  diameter laser beams are used. Obviously, the thinner strips and smaller laser beam enable us to realize finer dimple patterns. Another way of printing finer patterns is to arrange the laser beams to irradiate with overlap. This arrangement helps to make dimple patterns with sharp boundaries,<sup>3)</sup> but we must compromise between pattern quality and available work hours. In fact, as the laser beam itself is circular, beam overlap is not really required to realize fine dimple patterns as long as the dimple pattern is composed of many image strips. Experimental results validate this as shown in Sec. 4 because laser beams are not overlapped in our experiment.

The entire image to be engraved on the roll is originally stored in a host PC as an image file, which should be transferred to the global memory of the slave DSP board. However, the data size may be too large to transfer at one time so the image data are sliced piece by piece and transferred to the slave DSP board. An outlined flowchart of data processing for pattern printing is shown in Fig. 6.

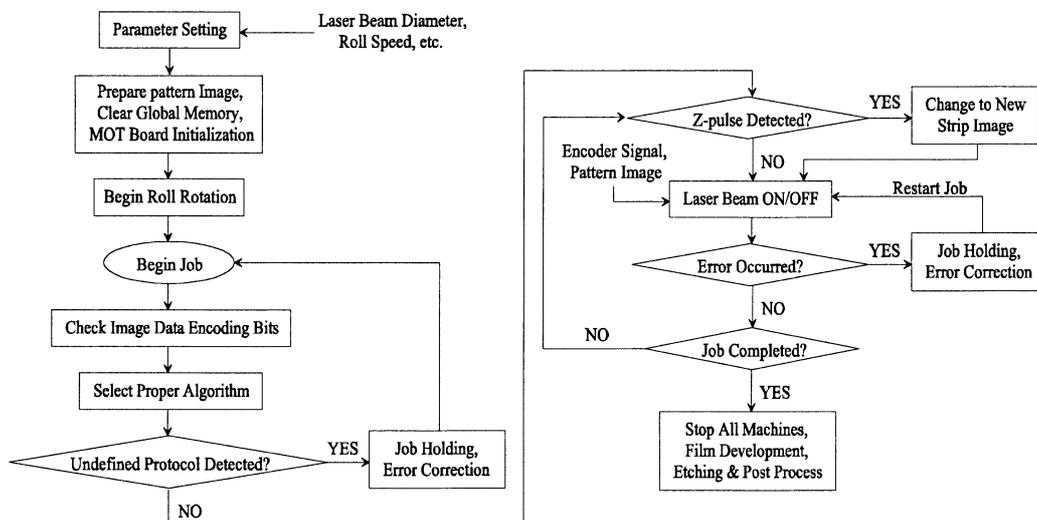


Fig. 6. Simplified data processing flowchart.

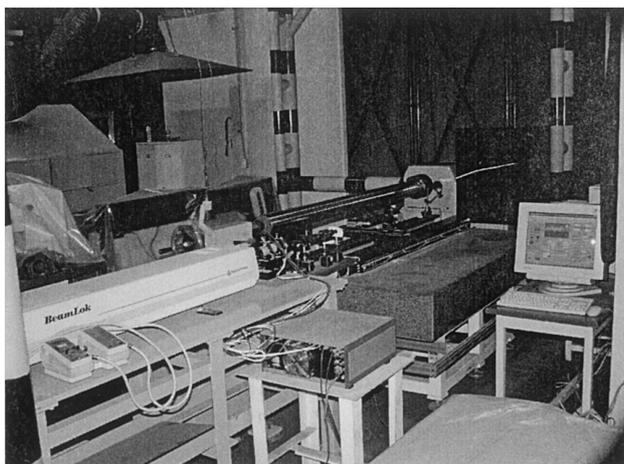


Fig. 7. Laser engraving system for roll texturing.

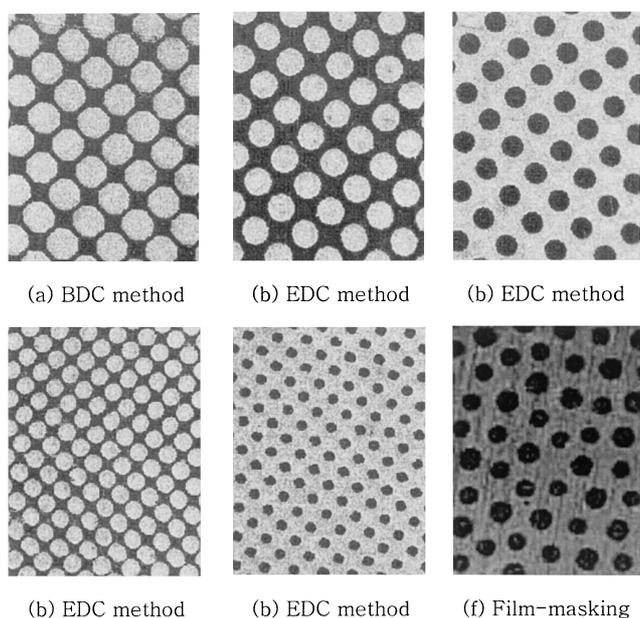


Fig. 8. Engraved patterns on a roll surface.

## 4. Experiment

Figure 7 shows the laser engraving system for roll texturing. A cold mill roll 130  $\mu\text{m}$  in diameter and 2035 mm in length is used here as the target roll. In this section, experimental conditions are listed and experimental results and discussions are stated thereafter. The image patterns in Fig. 8 are taken from the roll surface after it went through all photo-etching processes mentioned in Sec. 3.1.

### 4.1. Experimental Conditions

In the experiment, a laser source of 0.30–0.39 W in power and 20–30  $\mu\text{m}$  in diameter was used. The roll speed was set at 300 rpm (Fig. 8(a)) and at 120 rpm (Figs. 8(b)–8(e)). The brand name of polymer film is TPR produced by Tokyo Ohka Kogyo Co. in Japan. TPR is a negative photo-sensitive polymer that makes the roll surface embossed when the laser beam was irradiated and intaglioed when not irradiated. The average polymer thickness sprayed on the roll surface was about 4–5  $\mu\text{m}$ . In the etching stage, room temperature was 18–25°C and etchant was mixed solution of  $\text{FeCl}_3$ ,  $\text{HNO}_3$ ,  $\text{HCl}$ ,  $\text{HO}_2$  with a few additives. Under

Table 1. Experimental conditions.

Fig. 8	Engraving Method	Image data control method	Dimple diameter ( $\mu\text{m}$ )	
			Target	Measured
(a)	intaglio	BDC	600	750
(b)	intaglio	EDC	600	680
(c)	embossment	EDC	600	500
(d)	intaglio	EDC	300	375
(e)	embossment	EDC	300	190
(f)	embossment	film-masking	300–500	330–550

these conditions, the roll surface was etched at the speed of 0.1–0.2  $\mu\text{m}/\text{sec}$ .

Two methods are used in this experiment for image data control: one-to-one bitmap data control (BDC) and encoded data control (EDC). With BDC, the modulator turns on and off according to the binary sequence of bitmap image data, whereas in EDC, it is controlled according to the encoded sequence of bitmap image data. For the patterns shown in Fig. 8, the experiments have been performed according to the conditions stated Table 1. Finer patterns can be engraved on rolls using the EDC method than by the BDC method. The amount of data to be transferred with EDC is small because the image data are transmitted in a compressed form and the DSP board can process a greater amount of pattern data than with BDC. The superiority of EDC over BDC depends on the type of patterns used. On average, the former can transfer about four times as much image data as the latter in a given time frame. Consequently, the bitmap image size per dimple is set at 20×20 pixels when EDC is used while it is set at 10×10 pixels when BDC is used.

### 4.2. Results and Discussions

In the Fig. 8 image patterns, the white parts are corroded by etching acid and the black parts are the original roll surface protected from the etching acid. When irradiated by laser beams, the photosensitive polymer becomes hardened and cannot be melted by using a developing solution. It will be washed away during the polymer removing stage. Thus the roll surface beneath the hardened photosensitive polymer is never exposed to etching acid and remains black after the photo-etching process. The difference between the target dimple diameter and the measured one depends on which engraving method is used. This usually occurs because the laser beam on/off ratio of the modulator is not ideal (Figs. 8(a), 8(b) vs. Fig. 8(c) and Fig. 8(d) vs. Fig. 8(e)). As stated above, the patterns obtained by using the EDC technique (Figs. 8(b)–8(e)) are finer than those obtained using the BDC technique (Fig. 8(a)). Another way of producing fine patterns is to finetune laser beam divergence, pointing stability, polarization, and power stability. The laser beam diameter and other experimental parameters should be adjusted accordingly depending on the target process. The experimental results shows that the dimples obtained by laser engraving technology are as sharp as and even finer than those of film-masking technology (Fig. 8(f)).

## 5. Conclusions

A pattern engraving process was investigated and successfully implemented using laser engraving technology. A cold mill roll was selected as the target roll and an argon ion laser source combined with an E–O modulator was used for the laser system. Experimental results are as good as those obtained using film-masking technology, a common roll engraving method. In the film masking process, a pattern discontinuity arises at the film joints and skilled technicians are needed to adjust pattern discontinuity. In the presented laser engraving process, however, there is no abrasion of instruments because a laser beam is used and the pattern can be modified easily because the film pattern production step is not required. System operation is easy because it is PC-based and a GUI is used for MMI. Furthermore, overall process management and maintenance are simple compared to other methods. The developed technology is fairly general and can be used to imprint all kinds of patterns on any other target body with the resolution of  $\mu\text{m}$  units. The EDC method used in the experiment plays an important role in printing fine patterns. To engrave patterns quickly, a DSP board with high computing power may be required. Other improvements in a laser system and optical modules may increase process quality and productivity.

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