激光打标机理及打标质量特性
Laser Marking Mechanism and Quality Characteristics

Marking contrast can be achieved by surface material removal or color change. When infrared lasers are used, marking contrast relies on thermal effects. When UV lasers, such as excimer lasers are used, marking contrast can be achieved through a photo-chemical transformation, i.e., color change. The process is non-thermal and thus has its unique markets for applications.

1. Laser Marking Mechanism

When a laser beam is focused on the surface of a target material, many phenomena may occur as shown in Figure 1.

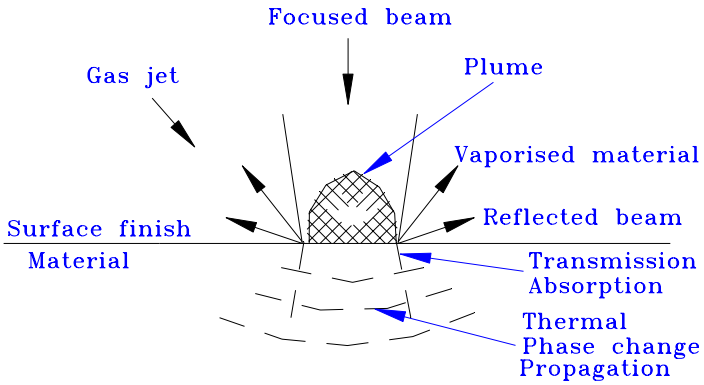

Figure 1: Physical phenomena in laser marking

(1) Vaporization

The laser beam is focused to a small spot, which greatly increases the energy density. When the energy is high enough, and the surface temperature is raised well above the melting point, most of the material on which the beam is focused will vaporize. The efficiency of this vaporization process depends on the absorption of the wavelength of the laser radiation. Organic materials and certain glasses have very good absorption of the 10.6 μm wavelength, often 100%. Metals absorb the 1.06 μm wavelength very well but a fraction of the laser energy will be reflected, which may be dangerous.

In the marking process, the energy density used is often high enough that the desired vaporization completes in microseconds. A series of vaporized craters in a surface usually alters its appearance sufficiently to be visible if characters are formed. The marking contrast depends on the chemistry of the material, the surface finish and color. A good mark edge resolution is achievable. The mark depth and width is controllable. Materials such as plastic, glass, ceramic, rubber and metals will be slightly engraved with a distinct change of the surface structure.

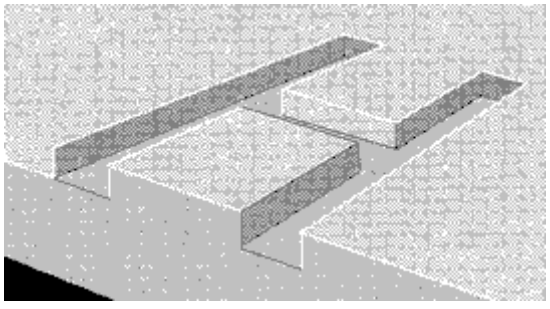

Figure 2: Marking through material removal

(2) Softening/Melting

Some materials are melted by infrared laser radiation, e.g. metals, epoxies and glass (Figure 3). In the case of metals, mark contrast is achieved by oxidation or incorporation of impurities into the melt. In the case of plastics, the material melts and forms ridges. Depending on types of material, different colors may appear. If the energy density exceeds the ignition point, carbonization occurs, which leads to black lettering. The durability is, however, not good since the carbonized material will wear off, impairing the legibility.

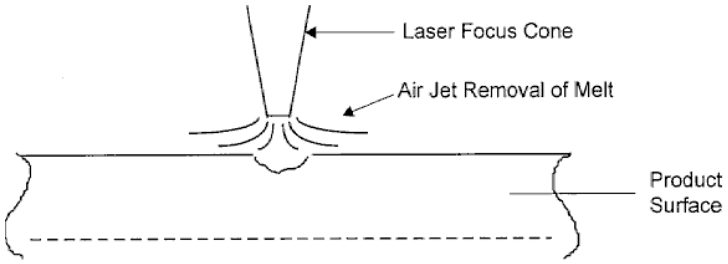

Figure 3: Softening and melting marking

(3) Layer removal/ablation

Layer removal/ablation is actually a form of controlled vaporisation (Figure 4). A thin layer of plastic film, paper, ink or paint is vaporized exposing the different colored under-layer. By controlling the heat input, the depth material removed can be controlled and the damage to the underlying surface minimized. Applications of this type of marking include instrumentation panels and consumer products etc..

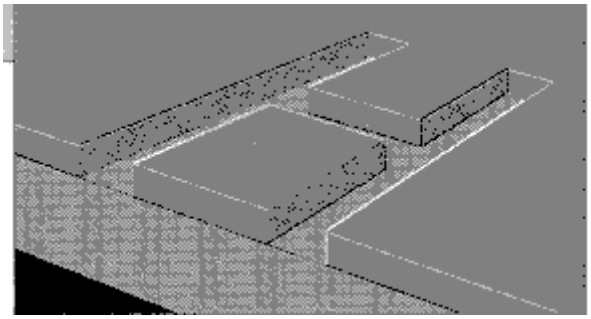

Figure 4: Marking through layer removal

(4) Color change

At certain energy densities (below melting point), materials can undergo chemical changes when exposed to laser radiation of a specific wavelength. The chemical change can be either light or heat induced, e.g. excimer laser induced photo-chemical color change for aircraft cable marking (white to black), and CO_2 laser-induced (heat-induced) colour change on PVC (gray to red-brown). The color change is due to changes in chemical composition or in molecular structures.

Pigments are often added into base plastic materials at an appropriate ratio for color change. Following are a few commonly-used pigments.

- inorganic : white TiO_2, yellow iron oxide $Fe_2O_3.H_2O$, black iron oxide Fe_3O_4; green chromium oxide (Cr_2O_3 and $Cr_2O_3.2H_2O$); chrome orange $(PbCrO_4)x.(PbO)y$, cadmium yellow (mixed CdS/ZnS) etc.
- Organic : yellow di-chlorobenzidine derivatives; orange dianisidine derivatives; red toulidine reds etc.

When using pigment, the following factors should be considered:

- selection of pigment with respects to base material (transparency to laser wavelength)

- effects on base material properties
- additional process and cost
- could the color degrade with time?

Figure 5 shows the laser marking through colour change.

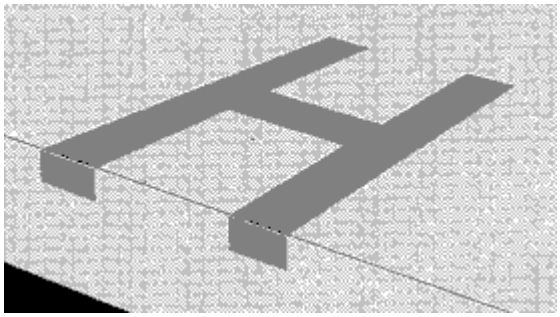

Figure 5: Marking through colour change

2. Laser Marking Process Parameters

(1) Effects of average, peak power and pulse energy

The best marking results are obtained only when there is a proper combination of pulse energy, pulse duration, average, and pulse repetition rate. The pulse duration (μs) is defined as the period during which the laser power intensity exceeds 50% of the maximum power intensity. The peak power is determined by the following equation:

$$P_p = \frac{E_{ov}}{\mu} \qquad (1)$$

For a laser with high pulse repetition rate, the peak power is usually expressed in terms of average power:

$$P_p = \frac{P}{\mu \bullet PRR} \qquad (2)$$

where P is the average power, and PRR is the pulse repetition rate.

A high peak power is often preferred in marking process for fast vaporisation. As described in Equation (1), the peak power is determined by the pulse energy and the pulse duration. Shorter pulses have higher peak power. The thermal interaction time is also shorter, which lead to smaller heat-affected-zones, and thus better hole quality. However, it should be noted that the pulse energy is usually high for high order beam modes, which produce large divergence angles. In the case of very fine marking, this situation is undesirable except for mask projection marking such as excimer laser marking.

(2) Effects of beam focal position

A beam of finite diameter is focused by a lens to obtain a smaller beam spot, as shown in Figure 6. If the diameter of the focused spot, d_0 , is defined as the diameter which contains 86% of the focused energy, the focus spot size is determined by

$$d_0 = \frac{2f\lambda}{D} \qquad (3)$$

where, f is the focal length of the focus lens, D is the entrance beam diameter, and λ is the wavelength.
If the total beam divergence angle θ is known, the diameter of the focus spot size is given by

$$d_0 = f \bullet \vartheta \qquad (4)$$

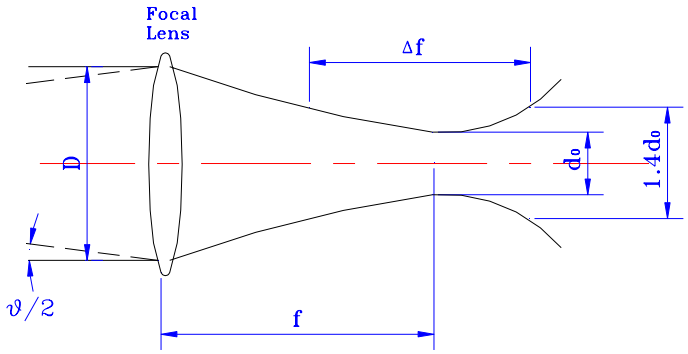

Figure 6: Focusing of a Gaussian beam

As the Gaussian beam focuses from a lens down to a waist and then expands, there is a need to define a depth of focus. Normally, it is defined as the distance between the $\sqrt{2}$ d_0 spot size points or 2 times Rayleigh range. It can be written as

$$\Delta f = 2Z_R \approx 2\pi\lambda F^2 \qquad (5)$$

or

$$\Delta f = \frac{2f^2\theta}{D} \qquad (6)$$

where F is the f-number of a focusing lens, which is defined as

$$F = \frac{f}{D} \qquad (7)$$

It is concluded from Eqs. (3) to (7) that a lens with a longer focal length gives a greater depth of focus and a larger focus spot size than a lens with a shorter focal length. Thus the focal length of the focus lens should be selected properly according to the marking requirements.

(3) Effects of beam mode and spot size

Because the order of the beam mode has great effect on both the focused spot size and the depth of focus, the beam mode structure plays an important role in laser materials processing. A laser beam with a higher-order mode structure diverges more rapidly, focuses to a larger spot and has a shorter depth of focus than a TEM_{00} Gaussian beam.

Because in laser marking, it is generally desirable to achieve highest possible speed and therefore the highest possible power density, the lowest order mode is desirable (TEM_{00} or Gaussian mode for stable resonators). However, a low-order mode structure often means a lower conversion efficiency and thus less laser output power. Therefore the process must be optimised for good processing quality, proper processing speed, and laser output power.

(4) Laser wavelength

Generally, shorter wavelengths are much better absorbed by materials. The wavelength also determines the theoretical minimum focused spot size. For a TEM_{00} laser with diffraction-limited optics, the focused spot size, s, is given by

$$s = 1.27\lambda(f / d) \qquad (8)$$

where λ is the laser wavelength, f is the lens focal length, and d is the diameter of the beam (entering the lens). It is obvious that the focused spot is proportional to the laser wavelength. When the laser wavelength is halved, the spot size is reduced by a factor of two.

The wavelength also determines the interaction mechanism - thermal or photochemical. The reflectivity of a material is a function of the wavelength, as shown in Figure 7.

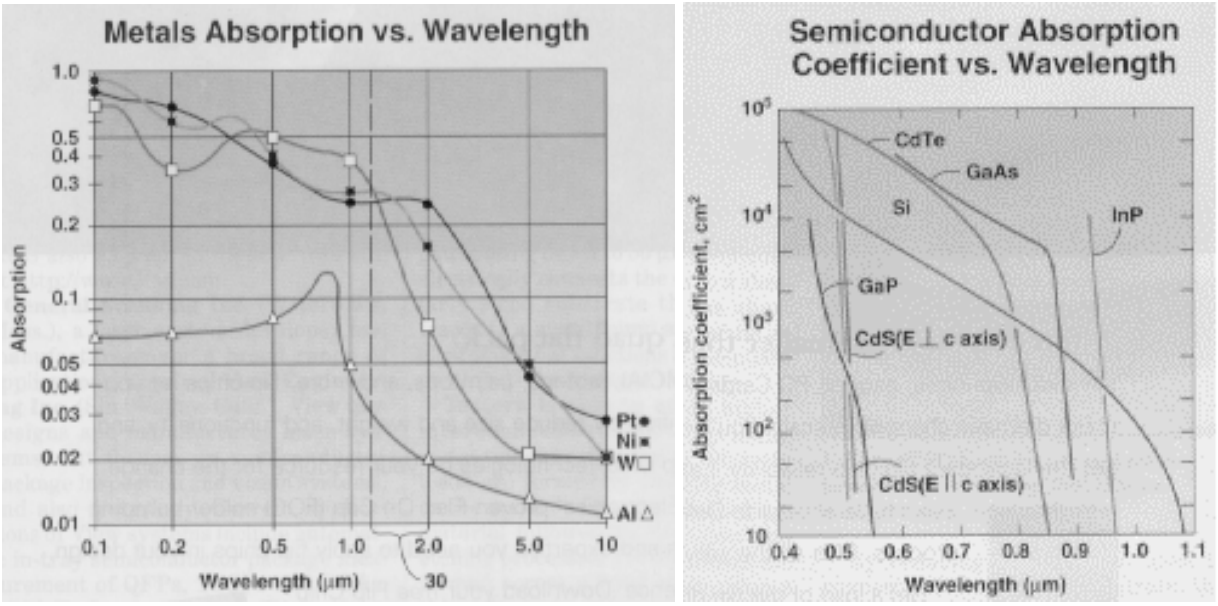

Figure 7: Absorption vs. wavelength

(5) Material properties

For any material, absorptivity, reflectivity, and transmissivity will satisfy

absorptivity + reflectivity + transmissivity =1

In general, metals absorb the Nd:YAG laser beam energy well, while paper and most transparent materials (e.g. polymers and glass) absorb the CO_2 laser energy well. Almost all materials absorb well the short wavelengths of excimer laser beams.

Surface finish or coating affects the absorptivity. Bare metal surface will be difficult to mark by CO_2 lasers, but can be easily marked by Nd:YAG or excimer lasers. Glass and transparent plastics are not suitable for Nd:YAG laser marking. Nearly all materials can be marked by excimer lasers with a shallow engraving.

(6) System requirements

In order to obtain the minimum linewidth and highest power density, laser beam shall focus on the work piece surface. Overlap is another important factor affecting mark depth, width, and continuity. The PRR and the marking speed together determine the percentage overlap in the laser spots. A good deal of overlap can ensure that the engraving lines are continuous and that splattering will be kept small. If the percentage overlap (in %) is defined as μ = x/s, then

$$\mu = \frac{x}{s} = \left(1 - \frac{l}{s}\right) \times 100\% \qquad (9)$$

where *s* is the spot size, *x* is overlap length, and *l* is the centre-to-centre spacing between the pulsed spots, which is given by

$$l = \frac{v}{PRR} \qquad (10)$$

where PRR is the pulse repetition rate in pps, and v is the engraving speed in m/sec.

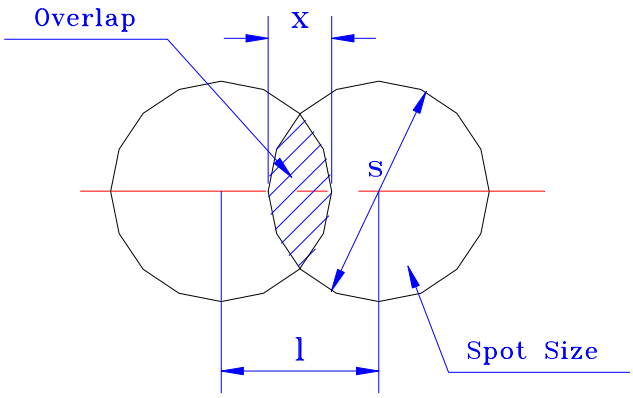

Figure 8: Spot overlap

Therefore, the required spot size is related to marking speed and pulse repetition rate by

$$s = \left(\frac{100}{100-\mu}\right)\frac{v}{PRR} \qquad (11)$$

General speaking, the spot overlap is required around 70% to 90% to ensure a good marking.

3. Marking Quality Characteristics

The quality of a mark assessed by its legibility characteristics such as mark contrast, mark with, mark depth, spattering, and microcracks. The characteristics are usually evaluated using complementary techniques such as optical microscopy, ultrasonic microscopy, electron microscopy, surface roughness measurement, and contrast evaluation devices. The acceptance of level of each of these characteristics generally depends on the manufacturer's requirements.

(1) Mark width

Mark width refers to the width of the line segment that forms a character. With the mask image marking, the mark width in the characters is essentially determined by the mask geometry and the lens imaging quality. It can be as small as a few micro-meters, which can only be read under a microscope. In beam deflected marking, the line width is mainly determined by the focused beam spot size, which varies between 20 - 100 mm. Other parameters such as scanning speed, power density and material properties also affect the line width. A toolmaker’s microscope or Talysurf surface texture measuring equipment are used for the line width measurement.

(2) Marking depth

The depth of marking depends on energy density, types of materials and the beam/material interaction time. In mask marking, the vaporization depth is often determined by the thickness of paint or oxidation layer. It is typical of a few microns to several tens of microns. In beam deflected marking, greater depth of penetration into the material can be achieved varying between a few microns to several tens of a millimeter. A further enhancement of the effect on the material can be realized by the supply of gases such as oxygen or compressed air, which assist material removal.

A RANK TAYLOR HOBSON surface analyzer or a laser beam scanning profiler can be used for depth measurement.

(3) Mark contrast

Marking contrast is the visual difference between the apparent brightness of the marked surface and unmarked surface of a workpiece. An Image Analysis System can be used for the contrast measurement. It comprises a PC, a 2-axis precision table, a CCD camera and monitor. The light source is a tungsten incandescent light bulb. A reference black and white background provides two

extreme grey levels as references in computing the mark contrast, hence compensating for the difference in illumination conditions and the variation of the electronic gain in the system.

A histogram plot of the average gray level of the mark, the background material, and the black and white backgrounds are obtained. The marking contrast, c , can be defined as a percentage value as:

$$c = \frac{\left|g_{background} - g_{mark}\right|}{\left|g_{white} - g_{back}\right|} \qquad (12)$$

The sharpness or resolution of the marked edges affects the marking contrast. This parameter is particularly important in marking “bar code”, as poor edge sharpness may fail bar code reader. High peak power or power density produces better edge resolution.

(4) Scattering

Scattering is characterized by the presence of re-solidified droplets of surface material in the marking area. These scattering are undesirable as they distort mark boundary and producing poor line definition.

Visual inspection with an optical microscope is often suffice to evaluate the effect.

(5) Microcracks

Microcracks are created due to thermal stress generated during laser marking. The micro-cracks affects mechanical properties and may induce corrosion in metals. Scanning acoustic microscope and scanning electron microscope can be used for detection and analysis.

(6) Continuity

When pulsed or Q-switched CW lasers are used, the repetition rate affects the continuity of the marking. Marking speed is another key factor. An optical scope is used to evaluate the effect.