Technology of thin metal sheet cutting with fiber laser

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Abstract. Laser cutting is a thermal cutting process where it is made use of the physical fact that laser light is absorbed in materials. The process is used for many materials in the manufacturing industry. Nowadays, the most suitable laser regarding range of materials, cutting speed, cutting quality is fiber laser. The article studies the correlation between cut quality and process parameters for thin plates, steel and aluminum. The laser machine used for experiments is a Continuous Wave fiber laser with 1000W power source.

1. Introduction - laser types
Laser cutting is a thermal cutting process where it is made use of the physical fact that laser light is absorbed in materials. The process is used for many materials (primarily metals) in the manufacturing industry. Nowadays, the most suitable laser regarding range of materials, cutting speed, cutting quality is fiber laser (Figure 1).

| Metal                  | CO2  | Fiber |
|------------------------|------|-------|
| Aluminum               | ●    | ●     |
| Anodized Aluminum      | ●    | ●     |
| Brass                  | ●    | ●     |
| Coated Metal           | ●    | ●     |
| Chrome                 | ●    | ●     |
| Copper                 | ●    | ●     |
| Precious metals (Gold, Silver, Platinum) | ● | ● |
| High speed steel       | ●    | ●     |
| Carbon Steel           | ●    | ●     |
| Stainless Steel        | ●    | ●     |
| Titanium               | ●    | ●     |

Figure 1. Metals range CO2 – Fiber range

The primary advantages of cutting flat sheet metal with Fiber laser technology are derived from its monolithic, Fiber-to-Fiber, compact solid-state design configuration that is maintenance free and provides a lower cost of operation than can be achieved with comparable CO₂ lasers.

Fiber laser beam characteristics also provide for much faster cutting speeds than CO₂ lasers as we will explore below.
The focused beam of even a 2 kW Fiber laser demonstrates a 5X greater power density at the focal point when compared with a 4 kW CO₂ laser. It also possesses a 2.5X greater absorption characteristic due to the shorter wavelength of the fiber laser. (see Figure 2 and Figure 3).

The higher absorption of the fiber wavelength and the higher power density created by the focused beam combine to achieve up to a five time increase in cutting speeds in materials that are less than 1/4 inch thick.

Fiber laser cutting systems can certainly cut up to one-inch thick with higher Fiber laser powers and even cut faster when utilizing nitrogen as the assist gas, but the “sweet spot” where the most significant benefits are realized is in the 5/16 inch and under range for steel when making comparisons with CO₂ systems. For certain, if you are processing stainless, aluminum, brass or copper materials, fiber laser technology is the fastest and most economical regardless of thickness [1].

The speed benefits are most profound when nitrogen is employed as an assist gas because the molten material is expelled from the kerf by the nitrogen just as fast as it is melted. The higher the laser beam power density, the quicker the material is brought to a molten state, the faster the feed rate.

2. Assist gases used in laser metal cutting

Assist gas is either reactive or inert. The types of assist gases used to eject the material from the kerf can be classified as either reactive or inert. The CO₂ gas used in CO₂ lasers is not the assist gas, but one of the gases excited to produce the laser light in the lasing cavity, usually quite a distance from the cutting process head. The most commonly used reactive assist gases are oxygen or air. Oxygen is used primarily for cutting low alloy steels and readily reacts with iron at high temperatures producing additional heat energy which enables thicker parts to be cut or greater speeds to be achieved. This gas is delivered at relatively low pressures and flow rates and the process is referred to as 'low pressure oxygen cutting'.

Inert assist gases commonly used are either nitrogen or argon. These provide no thermal assistance to the cutting process and are used simply to blow the molten material out of the kerf. They are used at pressures of around 10 bar and the process is referred to as 'high pressure inert gas cutting'. Inert gases can be used for alloys which readily oxidize in the presence of oxygen such as stainless steel, aluminum or titanium to give a very bright and clean-cut edge. Occasionally, inert gases are recommended for cutting low alloy steels where the edges are to be subsequently laser welded. This reduces the formation of an oxidized layer on the face of the cut edge and will reduce porosity in the resulting weld [2].

Article case study is focused in automotive and aero spatial domain where thin stainless aluminum plates are cut.

In case of reactive metals as aluminum and stainless steel, the most suitable assist gases are inert, as nitrogen or argon. Although argon gas gives the best cut quality, due to cost reason nitrogen is used in production.
3. Technology – cutting small holes in thin metal sheets

A schematic diagram of the laser-cutting process is shown in Figure 4. The sketch highlights the working principles of the laser-cutting process. The laser beam is directed to a certain focal length (150 mm) by adjusting the nozzle diameter (1.2 mm). The material melts at the moment of contact of the laser with the substrate. Nitrogen, oxygen or air can be used as the cutting gas to protect the lens against the smoke and dust generated during cutting, to remove ejected molten material, to oxidize carbon steel and to cool the workpiece [3].

![Figure 4. Laser-cutting process](image)

When the assist gas is flowing into the kerf, a boundary layer is developed. The momentum transfer from the assist gas to the molten material is carried out through this boundary layer. In order to maximize the transference of momentum to the molten material, the boundary layer must be kept into the laminar regime. This requirement is fulfilled for Reynolds numbers (Re) of the flow less than a critical value (Re < Re, crit = 3.2 × 105 ). When Re > Re, crit the flow turns from laminar to turbulent. This point is called separation point or boundary layer separation (BLS) (Figure 5) [4].

![Figure 5. Boundary layer separation](image)

The aspect of cut section and boundary separation line is visible, and best cutting quality is obtained above the BLS line, where assist gas flows laminar (Figure 6).

There is a proportional relation between assist gas pressure and height of the layer above BLS line where we have the best quality cutting.
Figure 6. Aspect of laser cut and BLS line

Another advantage of this area is that kerf zone (the size of removed material) is minimum, and the shape is regular, with parallel faces. Under the BLS line material is removed in a turbulent way, that is why the kerf size is higher and kerf shape is very uneven (Figure 7).

Figure 7. Kerf size and shape for various assist gas pressures
Thin plates are the most sensitive to thermal bending due to heat absorbed from laser beam during cutting. The heat absorbed inside plate produces „Heat Affected Zone” HAZ which is formed 90% under BLS line.

HAZ is increased due to the additional release of heat from the solidification of the unremoved molten material after the boundary layer separation. This aspect shows clear necessity to cut thin plates only in the zone above BLS.

Increase of assist gas pressure above a threshold does not help to cut faster or thicker plate. Gas pressure is an important parameter, but is strongly linked also to the laser power.

Higher pressure means more gas and supplementary cooling effect. The only way to compensate is to increase the laser power. In fig 8 is shown the relation between gas pressure and BLS position for two usual laser power 1000W and 2500W [4], [5].

![Figure 8. BLS position versus supply gas pressure and laser power](image)

4. Technology – cutting small holes in thin metal sheets

The experiments were performed using a fiber laser with a power of 1500W. Power can be modulated continuously between 100W and maximum or in PWM Pulse Width Modulation with frequency up to 20kHz (Figure 9).

![Figure 9. 1500W laser cutting table](image)
Assist gas used was nitrogen stored in pressured tank, and the entrance pressure can be regulated between 4 and 16 Bar.

Testing materials were thin plates of 1mm, aluminum grade 308 and carbon steel grade S355. To study the maximum achievable regarding cutting quality a program for cutting 0.3mm diameter holes spaced at 0.6 mm distance was made. The arrangement of the holes was intercalated as in Figure 10.

![Figure 10. Test holes arrangement](image)

For aluminum sheet, the best parameters for these holes were 600 W laser power and 16 bars gas pressure. The holes were larger at the laser entrance than on the side where the laser exited. The diameters ranged from 280–330 μm on the entrance side, while at the exit the diameters ranged from 190–230 μm.

![Figure 11. Aluminum at 600W](image)

For carbon steel sheet, the best parameters for these holes were 700 W laser power and 10 bars gas pressure. The holes were larger at the laser entrance than on the side where the laser exited. The diameters ranged from 290–340 μm on the entrance side, while at the exit the diameters ranged from 200–260 μm.

![Figure 12. Carbon steel at 700W](image)
Both metals have the same cutting pattern for small holes. Entrance laser is higher in diameter and has molten drops, rounded edge. Hole shape is conical, with a taper which depends by laser power, cutting speed and assist gas pressure.

Exit laser circle is smaller in diameter and have sharp corner.

Another observation is dross presence, in range of 50-100 μm. If laser power is decreased to 300W, cut contour circle became irregular.

![Figure 13. Aluminum at 300W](image1)

![Figure 14. Carbon steel at 300W](image2)

The set up for aluminum was applied in regular production line. Technologically, holes smaller then 1 mm are not required, so in Figure 15 is shown the aspect of 1mm diameter hole in aluminum 1mm thickness plate.

The general design guide also advice that any hole diameter must be higher or equal with plate thickness.
5. Conclusions
There are six different mechanisms, for thin materials laser cutting, namely:
1. vaporization cutting,
2. melting and blowing,
3. burning and blowing,
4. thermal stress cutting,
5. scribing
6. cold cutting

For cutting thin aluminum and carbon steel plates, more suitable is nr. 2 which allow the finest cutting surface with smallest quantity of dross. Another condition for high quality cutting is to use enough assist gas pressure in order to cut above BLS line where gas jet flow is laminar.

Regarding gas composition, for thin plates the best quality was obtained with inert gases (Nitrogen) which are chemically inert in molten metal and do not produce oxidation layer [4].

Dross on the back side was formed regardless gas pressure and speed. Increase of gas pressure above 16 Bar for aluminum and 10 Bar for carbon steel did not have any significant quality influence, only supplementary cost due to 20-40$ more gas consumed in production.

Tapper (cone) effect of the cutting especially for ultra-small holed is significant, so inclination of hole wall was 10%
Tap effect is diminished by two factors:
• increase the laser power in the curved paths
• decrease laser cutting speed in the curved paths

For pieces with small holes and long segments cut on the same plate, the adaptive CNC laser where speed and power can be set according with the path shape is the solution for uniform quality in all cuts.

Kerf (the width of removed metal) is important and must be as low as possible, due to next reasons:
• Big kerf means high energy dissipated by laser beam and consequently increase the heat affected zine
• Dross volume is proportional with kerf width

In conclusion, for 1mm thickness metal sheet the most important cut parameters were evaluated using a quality index, with 100% corresponding to the worst result (Figure 16).

The most important results of the trials are:
• Kerf is higher when the laser power is high and speed is low. This is because in these conditions absorbed energy is higher and can melt more material
• Dross is higher when laser power is low and speed is high. This is because even tough absorbed energy is low, there are molten material which in this condition can go to solid state quickly at the exit of the laser beam
• Tapper effect (conicity of the hole) is minimum when the laser power is high and speed is high.

Taking into account all these factors, the best cut quality is when laser power is high and speed is high. Technologically, laser device must have enough power reserve and high-speed translation mechanisms on the axes in order to ensure higher speed.

Figure 16. Influence of laser speed and power over the cut quality

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