Influence of mill scale on oxygen laser cutting processes

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Abstract. Mill scale formed on the surface of hot rolled steels consists of magnetite (Fe₃O₄), hematite (Fe₂O₃) and wustite (FeO) layers, which can protect the steels from corrosion and other atmospheric effects. Existence of mill scale on the specimens’ surface has shown to be able to decrease the cut edge quality. Since the mechanism behind influence of mill scale on the laser cutting process is unknown, this work performs direct observation of oxygen laser cutting processes on specimens with and without removed mill scale layers. Oxygen laser cutting processes were carried out using Ytterbium fibre laser 1070 nm along the edge of 20-mm-thick steel specimens which were attached to a borosilicate glass. Focal point of the laser beam was positioned to be 0.7 mm below the specimens’ surface. A high speed imaging system was arranged to face the glass, recording the cut front and kerf dynamics during cutting processes. It was found that cut front inclination angle increase when the mill scale was removed from the specimens’ surface. This implies that mill scale on the specimens’ surface seem to contribute in increasing the exothermal energy during laser cutting processes.

1. Introduction

Laser cutting is a common and well-established manufacturing technique. The process involves focused laser beam to melt the materials and assisting gas to blow out the molten materials. Oxygen is the most common assist gas in laser cutting due to its ability in initiating exothermal reaction which adds energy to the process [1]. Although there is an increased trend of nitrogen usage in laser cutting, the oxygen laser cutting still offers the best cut edge quality in thicker specimens. Laser cut edge quality is determined by the striations mark on the cut edge, which is parallel grooves appearing as periodic lines on the cut edge surface. A good cut edge quality has minimum striations mark on the cut edge surface.

The laser cutting process itself is a complex process which can be influenced by the chemical composition and surface conditions of the specimens [2,3]. For instance, mill scale is oxide layers formed on the surface of hot-rolled steel products after reheating processes, hot rolling and subsequent controlled cooling [4]. Wustite FeO, magnetite Fe₃O₄, and hematite Fe₂O₃ are the main types of mill scale with its own chemical and physical properties [5]. Mill scales has benefit of protecting the steel from corrosion and environmental impact [6]. However, it was found to influence the laser processes. For instance, mill scale causes CO porosity in laser welding of mild steel which indicates a lack of deoxidizing element and increase of oxygen content in the fusion zone [7,8]. In laser cutting, a study tested varieties of hot rolled steels found that hot-rolled pickled and oil steels produce much more consistent cut and better cut quality than steels cut straight-from-the-mill [9]. The study concluded that
a smooth and homogenous surface condition is necessary for a consistent and good cut quality. Furthermore, SSAB and ESAB have seen that removing mill scale on the surface of thick specimens can reduce the cut edge quality. Studies on surface tension and viscosity of molten iron showed that surface tension and viscosity of molten iron are lower for higher oxygen content [10,11]. Lower viscosity and surface tension can affect the melt dynamics in laser cutting. As mill scale consists of oxides, it has potential to influence the surface tension and viscosity of molten steel during oxygen laser cutting, affecting the cut quality. Therefore, it is necessary to study the influence of mill scale on the oxygen laser cutting for process optimisation.

Observations of the laser cutting processes have been carried out using high speed imaging in many ways, such as having a high speed camera facing a cut intersection to observe the cut front morphology or replacing the specimen’s edge with a glass to enable a side view of the process [12,13]. Both methods enable recording of dynamics in the cut kerf during the process and improve our knowledge in laser cutting. For instance, low inclination angle of the cut front can reduce the striation marks on the cut edge [14]. The inclined cut front change the melt flow direction and dynamics, affecting the cut edge quality [1,15]. This study uses a glass as replacement edge to record the cut front and kerf dynamics during the processes. Analysis is thus focused on the cut front inclination angle and melt flow direction to understand the influence of mill scale removal on the oxygen laser cutting processes.

2. Methodology

2.1. Experimental set-up

To answer the research question, oxygen assisted laser cutting processes using an IPG Ytterbium fibre laser 1070 nm were carried out on two different types of materials with chemical compositions listed in Table 1. The specimens were prepared in three conditions; (1) without treatment, (2) removed mill scale on the top side, and (3) removed mill scale on both top and bottom side. Mill scale removals were performed using laser oxide removal at SSAB.

| Materials | Thickness | C    | Si   | Mn   | Cr   | Ni   | Mo   | Al   |
|-----------|-----------|------|------|------|------|------|------|------|
| Steel A   | 20 mm     | 0.07 | 0.008| 0.81 | 0.029| 0.02 | 0.004| 0.049|
| Steel B   | 20 mm     | 0.19 | 0.21 | 0.71 | 0.8  | 0.06 | 0.022| 0.055|

In situ high speed diagnosis technique was used to record the laser cutting processes [13]. The technique employed borosilicate glass as a replacement edge allowing a direct view on the cut kerf during the process. A high speed imaging equipment and a continuous illumination laser were placed facing the specimen edge as shown in Figure 1(a). The laser beam was placed at the specimens’ edge and moved along the positive X-axis. The edge quality of specimens cut using glass is comparable to the specimens cut under normal laser cutting condition. Accordingly, the dynamics seen through the glass can represent the dynamics during actual laser cutting condition. The laser cutting parameters and recording frequency were kept constant for all specimens as shown in Table 2.

| Laser power   | 4500 W |
|---------------|--------|
| Focal position of the laser beam | 0.7 mm below specimens’ surface |
| Cutting speed | 0.7 m/min |
| Gas           | Oxygen |
| Gas pressure  | 1.75 bar |
| Nozzle diameter | 1.5 mm |
| Distance between specimen surface and nozzle | 0.3 mm |
| Camera recording frequency | 10240 Hz |
2.2. Analysis
Observation was carried out on the specimens’ cut edge and cut kerf using macroscopic pictures and recorded high-speed videos as shown in Figure 1(b) and (c). Figure 1(b) shows an example of a cut edge where three zones (top, middle, bottom) can be distinguished according to the visible striations. The amount of striations per centimetre was counted for each zone respectively.

The recorded videos were also observed according to the distinguishable zones on Figure 1(b). Figure 1(c) shows a frame taken during a laser cutting process. The frame reveals an inclined cut front and melt pool direction during the process. The inclination angle was measured for each zone by comparing the cut front to the normal axis, while the melt pool width was measured along the visible melt on the cut edge up to the cut front. The melt pool width was measured at five different heights within each zone on three frames from a laser cutting process. The standard deviation of the melt pool width was calculated for each zone based on the measurement from three frames to show how big the melt pool width varies along the height.

![Figure 1](image)

Figure 1. (a) Illustration of the experimental set-up including (b) observation on the cut edge and (c) recorded videos.

3. Results
Untreated specimens (1A and 1B) have flat cut edge for both materials as seen in Figure 2(a) and (b). Specimen A with removed mill scale on the top surface (2A) shows a concave cut edge while specimen B (2B) shows a rather flat edge (Figure 2(c) and (d)). Removing the mill scale on both top and bottom side results in a flattened cut edge (Figure 2(e) and (f)) compared to specimens with removed mill scale on the top side. Dross can be seen on all specimens and specimens with removed mill scale show visible heat affected zone close to the cut edge as seen in Figure 2(o) – (r), (w), (x).

Figure 3 shows examples of the frames taken during laser cutting processes. The cut front inclination angle and melt pool width seen on the cut edge increase at the bottom zone for all processes. Specimens with removed mill scale on the top side (2A and 2B) show a gentle slope in their general cut front appearance compared to the other specimens.

In Figure 4(a), the top zone shows more striations compared to the other zones and removing mill scale leads to reduced amount of striation per cm for both steel A and B. The cut edge of steel A with removed mill scale on the top side (2A) has the smallest amount of striations among the examined specimens due to wider groves shown in Figure 2(i).
Figure 2. Macroscopic images of the specimens showing the side view (a) – (f), cut edge surface (g) – (l), top (m) – (r) and bottom view (s) – (x) of the specimen, including cutting direction shown in arrows and dots.

Figure 3. Frames taken during laser cutting processes for steel A and B at three mill scale conditions; (a) (d) with mill scale, (b) (e) removed mill scale on the top side, and (c) (f) removed mill scale on both the top and bottom side.
The tendency of having a high inclination angle at the bottom zone shown in Figure 3 is confirmed in Figure 4(b). Steel A with removed mill scale on the top side (2A) shows an increased inclination angle at the top and middle zones, portraying a gentle slope cut front in general dissimilar to the reference case (1A). This behaviour is also shown in Figure 3(b). However, steel A with removed mill scale on both the top and bottom side (3A) show similar inclination angle behaviour to its reference (1A). Significant change in the inclination angle due to mill scale removal is not found for the steel B specimens.

During the process, the melt pool seen on the bottom zone was the widest among the top and middle zones for all specimens while in general, steel A with removed mill scale on the top side (2A) shows the widest melt pool (Figure 4(c)). Steel B with removed mill scale on the top side (2B) shows an increased width at the top zone, but decreased width at the bottom zone. In addition, the specimens with removed mill scale on both the top and bottom side (3A and 3B) have similar melt pool widths compared to the untreated specimens (1A and 1B).

Melt pool seen on the cut edge widens at the middle and bottom zone where a significant widening happens at the bottom zone. This can be seen on the standard deviations of the melt pool widths for all specimens (Figure 4(c)). At the bottom zone, the standard deviation is higher for steel A than B. Mill scale removal does not seem to affect the standard deviation of the melt pool width.

Figure 4. Observation results on the amount of striations per cm (a), cut front inclination angle (b), melt pool width seen on the cut edge during the process and standard deviation of the melt pool width (c) at the top, middle and bottom zones.
4. Discussion
The observed tendencies of increasing cut front inclination angle and melt pool width at the bottom zone will be discussed in the following paragraphs. The discussion will come to explain the influence of mill scale on laser cutting processes.

The inclined cut front is known to be due to a lack of energy input to melt the materials [16]. A high inclination angle at the bottom zone implies that this zone experienced less energy input during the process compared to the top and bottom zones. Since the oxygen laser cutting process is driven by energy from the laser and exothermic reaction of Iron-Oxygen [1], the inclined cut front at the bottom zone can be related to the properties of the laser beam and local oxygen concentration. The bottom zone is located about 10 mm away from the focal position of the laser beam, meaning that the laser beam hitting this zone is defocused. The defocused laser beam then delivers a small power density to this zone. Additionally, the position of the bottom zone is far away from the nozzle opening, causing less oxygen concentration as the oxygen is contaminated by ambient air [17]. Accordingly, the bottom zones experience the least energy input from both the laser and exothermic reaction of Iron-Oxygen.

This phenomenon impacts the melt pool behaviour at the lower zones of the specimens. Less energy input can lead to a low temperature on the cut kerf. Since the energy input decreases towards the bottom zone, the temperature might also decrease towards the bottom zone. The top, middle and bottom zones are most likely experiencing temperature gradients where the bottom zone possesses the lowest temperature respectively. The temperature can influence viscosity of the molten material where low temperature leads to a high viscosity [18,19]. As the temperature is decreasing towards the bottom zone, the viscosity of the molten materials is expected to increase at the bottom zone. An increase of viscosity causes a widening of the melt pool seen on the cut edge (Figure 1(c) and 3(c)). Molten material with a high viscosity can have difficulties to flow away from the specimen and thus sticks on the cut edge.

The bottom zones have more molten material sticking on the cut edge compared to the other zone. It means that heat conduction from the molten material to the cut edge occurs longer at the bottom zone than the other zones. This situation can cause widening of the heat affected zone at the bottom side of the specimens shown in Figure 2(w) and (x). Steel A with removed mill scale on the top side (2A) also shows a wider heat affected zone than the other specimens (Figure 2(o)). The melt pool width at the top zone (Figure 3(c)) of this specimen is also the highest among the other specimens. These are indications that the appearance of the heat affected zone close to the cut edge correlates with the molten material sticking on the cut edge during the process. However, quite large dross was created in the process, which can also cause the widening of the heat affected zone. Therefore, the widening of the heat affected zone at the bottom zone can be due to both dross formation and molten material sticking on the cut edge.

Mill scale seems to influence the exothermic reaction of Iron-Oxygen during the cutting process. High cut front angles and wide melt pool widths seen on steel A with removed mill scale on the top (2A) indicate that the process experienced lower energy than the untreated specimen (1A). This means that the mill scale might contribute in increasing the exothermic reaction of Iron-Oxygen. However, removed mill scale on the bottom side of the specimen (3A) seems to reduce the impact of having high cut front angles and wide melt pool during the process as the values of the cut front angles and the melt pool widths are similar to the reference (1A). Steel B does not show significant change in the inclination angle and melt pool width after the mill scale removal. This can be due to difference in chemical composition of the two materials. Previous investigation on similar steel grade revealed that increased carbon content can reduce the exothermal energy and result in more stable cutting process with reduced risk of rough cut edge [3]. While silicon content does not seem to influence the cut edge quality, reduce amount of manganese content can improve the cut edge quality [3]. These indicate that influence of mill scale on the oxygen laser cutting processes also depends on the alloying element of the materials although more observation in this topic needs to be carried out separately.
5. Conclusion

Oxygen assisted laser cutting processes of thick materials possess varied energy input along the specimen thickness due to the characteristics of the laser beam caustic and gradual reduction of oxygen concentration. Varied energy input can lead into temperature and viscosity variation in the molten material along the specimen thickness where molten material at the bottom zone has the lowest temperature and highest viscosity. High-viscous molten material has difficulties to flow away from the specimens resulting in wider melt pool width seen on the bottom zone of the cut edge.

The existence of mill scale seems to contribute to increasing the exothermal reaction of Iron-Oxygen during the process. Accordingly, the energy input to the process zone is reduced when the mill scale is removed from the top side of the specimen. Reduced energy input causes an increase of the cut front inclination angle and viscosity of the molten material during the process which results in increased amount of striations on the cut edge. However, changing the chemical composition of the specimens or pre-treating specimens’ surfaces before cutting to have a homogenous surface condition will possibly improve the consistency of oxygen laser process and thus cut edge quality.

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