Comparison of laser beam, oxygen and plasma arc cutting methods in terms of their advantages and disadvantages in cutting structural steels

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Abstract. The laser beam, plasma arc, and oxygen cutting methods are widely used in metal cutting processes. These methods are quite different from each other in terms of initial setup cost and cutting success. A powered laser beam is used in laser beam cutting, plasma is used in plasma arc cutting, flammable gas - oxygen mixture is used in the oxygen cutting method. In this study, the cutting success of these methods was investigated on tensile specimens. Microstructure, hardness (HV 0.1), surface roughness, and strengths were investigated after the cutting process. The tensile test implemented with tensile samples cut from the same material by these three methods, it was observed that the strength values of the samples changed by about 8% in tensile strength depending on the cutting process. The hardness of the cut surfaces in plasma arc cutting increased from 150 HV to 230 HV for S235JR material. For this reason, it is difficult to perform machining operations after plasma cutting. The hardness value reached after laser beam cutting is 185 HV. Plasma arc cutting is more cost-effective than laser beam cutting. 1-3° vertical inclination (conicity) occurs on the cut surface in plasma arc cutting, while this inclination almost does not occur in laser cutting. In plasma cutting benches, cutting is done with oxygen, and in cutting with oxygen, the taper is seen in a small amount.

1. Introduction
The cost and time of production are of great importance in terms of competition in the machinery manufacturing industry. The industry needs to rapidly create prototypes for new designs, develop and produce on a mass scale in a short time. In the manufacturing industry, ~85% of the basic raw material form consists of sheet metal. In the manufacturing industry, the cutting of these sheet metal sheets is one of the first steps in the production of a particular part or product [1,2]. Well-chosen cutting technology affects the inputs and outputs of the entire production process. Cutting requires the use of different techniques depending on the need. The choice of technique depends on the type of material to be cut, the size and thickness of the sheet, its shape, and the level of precision required. Industrial sheet metal cutting on a 2D platform is now widely performed with Plasma arc, Oxygen, and Laser beam cutting methods. These machines work automatically with the data of the product outputs prepared with computer-aided design. Although there are no big differences in terms of operation in transferring the design data to the workbenches, there are mechanical and microstructural differences in the parts obtained after the cutting process.
Plasma arc cutting is a process in which electrically conductive materials are cut with the generated plasma utilising an accelerated jet of hot plasma. Typical materials cut with a plasma torch include steel, stainless steel, aluminium, brass, and copper, but other conductive materials can also be cut [3]. Laser beam cutting technology is essentially a thermal cutting process in which a focused laser beam is used to melt material in a localised area. A coaxial gas jet is used to eject the molten material and create a notch. A continuous cut is produced by moving the laser beam or the workpiece under CNC control [3]. There are three main types of laser cutting: fusion, flame, and remote cutting. These methods are widely used in industrial and scientific activities. There are several scientific studies on these cutting methods. Salonitis et al. [4] conducted an experimental study of plasma arc cutting to assess the quality of the cut. They measured cut quality, kerf width, kerf taper angle, surface roughness, and hardness in the heat-affected zone. Quality characteristics were evaluated by varying machining parameters such as cutting speed, workpiece thickness, plasma power, and gas pressure. They found that the surface roughness and taper were mainly affected by the cutting height, while the heat-affected zone was mainly affected by the cutting current. Aldazabal et al. [5] investigated the mechanical properties and microstructure of the cut edges in the thermal cutting processes of steel plates. They presented the characterisation results of the edges by cutting a 15 mm thick S460M steel plate with a plasma arc cutting device. They concluded that the CHAZ (Cut Heat Affected Zones) resulting from the plasma arc cutting process are narrow (~700 µm) and homogeneous in plate thickness. Harničárová et al. [1] compared the cutting costs associated with plasma, oxyfuel, and laser cutting. They emphasised that the choice of these methods depends on the business requirements. They found that plasma arc cutting is the most economical cutting method. Yılbaş et al. [6] concluded that the cutting quality in laser cutting depends on the quality of the plasma created in the cutting process. They monitored the surface plasma generated during the laser beam cutting process using the Langmuir probe. They studied the microstructure at the cut edges with a scanning electron microscope. However, the electron number density depends on the rate of mass removal from the shear section and the rate of exothermic reaction between neutral atoms and oxygen in the plasma. Barényi et al. [7] investigated the effect of cutting temperature on microstructure and mechanical properties in plasma and laser cutting processes of high-strength steels. They concluded that the apparent HAZ (heat affected zone) depth of plasma arc cutting surfaces is significantly greater compared to laser cutting. Thomas et al. [8] investigated the changes in the critical surface properties and microstructural properties near the cutting edge after laser and plasma cutting of S355 structural hot rolled steel. Boujelbene et al. [9] investigated the effects of various laser cutting parameters such as laser power and cutting speed of S235 low carbon steel on laser cutting quality. As a result, it has been determined that laser power and cutting speed are effective on the cutting surface. Klimpel et al. [10] experimentally investigated the effects of the laser beam and plasma arc cutting parameters on the edge quality of various steel grades and thicknesses. Analysis of the effect of selected plasma arc cutting parameters on the geometric quality of the cutting edges found that the effect of chemical composition was also evident, but not as strong as in the case of laser cutting [10].

Microhardness measurements within the heat-affected zone provide important information and insight into the thermal effect on a base material. A common denominator is a good cut quality [2]. Górka et al. [11] studied the air plasma, oxygen, laser beam cutting processes on quenching and tempering S 960QL steel surface quality. They found that changes in the material during that cutting processes had a significant effect on the final quality of the manufactured parts. The choice of cutting method depends on the requirements and technical capabilities i.e. type and thickness of the material, dimensional tolerances, economic factors, cutting speed or shape of the element. The analysis of surface roughness after cutting showed that achieved quality depends on the cutting process and its parameters. The lowest values of surface roughness – 14 µm were obtained during the HD plasma cutting process.

This study examined the comparative analysis of the cutting methods, which are lacking in the literature, in terms of mechanical and microstructural changes in the material (S235JR) at the end of the cutting process. It has been seen that the surface formed after the plasma cutting process is often too hard for machining. However, laser cutting is more convenient in this regard. The study investigated and evaluated both methods in terms of economy as well as transaction speed.
2. Experimental details
In this study, the cutting of plates from S235JR material with laser and plasma cutting methods and the advantages and disadvantages of the methods were investigated. S235JR steel is a widely used material as general structural steel. Low-carbon EN 10025 (S235JR) steel (0.17 wt % C) with a microstructure of ferrite (α) and a small amount of pearlite (α + Fe₃C) phases was selected for the current work. The chemical composition of the S235JR structural steel is shown in Table 1.

| Element | Composition (wt. %) |
|---------|---------------------|
| C       | 0.17                |
| Mn      | 1.4                 |
| P       | 0.035               |
| S       | 0.035               |
| N       | 0.012               |
| Cu      | 0.55                |
| Si      | -                   |
| Cr      | -                   |
| Ni      | -                   |
| Mo      | -                   |
| Fe      | Balance             |

It is frequently used in the construction of cranes, machine parts, and bridges. The properties and strength values of S235JR steel may vary slightly for different material producers. The tensile samples from plates were cut with a CNC milling machine (Delta SEIKI 1050 Mitsubishi interface) to ensure that the mechanical properties and metallurgical structure were not affected by temperature. The cutting parameters were 6000 rpm rotating speed and 800 mm/min feed rate with a 5 mm diameter milling cutter. Mechanical properties of the S235JR structural steel are shown in Table 2. Steels are delivered in the metal plate shape with various thicknesses. The metal plates with thickness 3, 5, 6, and 8 mm of every used S235JR structural steels were cut using plasma arc and laser beam cutting technology to prepare the experimental samples. A standard metallographic preparation procedure was used to prepare the experimental samples for optical metallography. First, the samples were cut in the form of a rectangular prism with a surface area of 1 cm² from the areas to be examined using a precision cutting device and diamond cutter (make: Teskon) for microstructure examinations and were subjected to bakelite mounting. After embedding (make: Metkon ECOPRESS 100), the samples for metallographic examination along cross-section were ground using 180, 320 grid waterproof SiC paper followed by polishing with 1 μm alumina suspension and 6, 3, 1 μm (make: Teskon) 6, 3, 1 μm diamond, respectively. The specimens were cut and polished to achieve a mirror-like finish for metallographic analysis. The surface was cleaned with pure ethanol. The polished specimens were subjected to chemical etching using 2.5% nitral (97.5 ml ethanol + 2.5 ml nitric acid) reagent for 15 s after being mechanically polished to reveal the microstructure. Microstructure examination of the weldment was carried out using a metal microscope (Make: Olympus CX41 optical microscope).

| Mechanical Properties | S235JR structural steel |
|-----------------------|-------------------------|
| Yield strength (MPa)  | 235                     |
| Ultimate tensile strength (MPa) | 370               |
| Elongation %           | 26                      |
| Charpy V-notch Impact toughness (J) | 27                |

Tensile specimens were cut from the same material plates with Plasma (Make: Yıldırım Knuth) and a Laserbeam (Make: BYSTRONIC BYSPEED 3015 5200W) according to the dimensions shown in Fig. 1 (ASTM E8 standard). 3, 5, 6, and 8 mm thick plates were cut by laser beam and plasma arc, and 15
mm thick plates were cut by oxygen and plasma arc cutting methods. After the cutting process, cross-section measurement, surface roughness in the cutting area, hardness measurement, and strength tests were performed on the samples. Cutting processes were implemented with the parameters seen in Table 3, Table 4, and Table 5 for all specimens.

![Figure 1. Schematic showing tensile test specimen.](image)

| Cutting thickness (mm) | 3    | 5    | 6    | 8    | 15   |
|------------------------|------|------|------|------|------|
| Cutting speed (mm/min)  | 4000 | 3450 | 2900 | 2400 | 1400 |
| Current I, A           | 100  | 110  | 118  | 135  | 180  |
| Power (W)              | 5000 | 6200 | 7100 | 8500 | 10200|
| Nozzle diameter (mm)   | 0.8  | 1.0  | 1.0  | 1.2  | 1.6  |

| Cutting thickness (mm) | 3    | 5    | 6    | 8    |
|------------------------|------|------|------|------|
| Lens type              | 7.5  | 7.5  | 7.5  | 7.5  |
| Laser power (W)        | 1200 | 3000 | 3000 | 3250 |
| Nozzle diameter (mm)   | H10  | H12  | H12  | NK1515|
| Cutting speed (mm/min)  | 2700 | 2600 | 2300 | 1700 |

| Cutting thickness /mm   | 15   |
|-------------------------|------|
| Cutting speed mm/min    | 600  |
| Nozzle diameter /mm     | 1.4  |
| Oxygen pressure /MPa    | 0.6-0.7|

The tensile test was performed according to the ASTM E8 standard, and tensile test specimens were prepared with 220 mm lengths and 15 mm widths at speeds of 5 mm/min. A tensile test has been
performed at room temperature (Make: ALŞA, 30 kN, calibration number: AB-0066-K). Specimens cut by laser beam and plasma arc cutting method (3, 5, 6, and 8 mm thickness) are shown in Fig. 2.

The Vickers microhardness test was conducted along the transverse section of the tensile specimens cut by laser beam and plasma arc using a microhardness tester (Make: Delhi Metko) with 0.5 mm intervals according to the reference position. During microhardness testing, each sample with a different method of cutting technique was impressed with loads of 100 grams (0.98 N) for only 15 seconds dwell time. Noticeably, there were no cracks on the surface of the material, thereby providing a size of the Vickers diamond indentation that allowed measurement of the surface hardness of the material. The surface roughness (Make: Mitutoyo Surftest SJ 310) of the samples cut with plasma, laser, and additionally oxygen were measured.

![Figure 2. Specimens cut by laser beam and plasma arc cutting method (3, 5, 6 and, 8 mm thickness).](image)

3. Result and discussion
The first operation was the cutting of the plates in the manufacturing processes in which sheet metal plates were used. This cutting process may affect the production quality, cost and production time. In this study, laser beam and plasma arc cutting methods are discussed in detail in terms of initial setup cost, processing speed, processing capacity, cutting quality, cutting cost, microstructural and mechanical differences after the cutting process, and geometric precision [12]. The advantages and disadvantages of these two thermal cutting methods, which are actively used today, were examined mechanically and microstructurally, and their advantages and disadvantages were presented in detail.

The first success criterion expected from the cutting process was that the cut plate dimensions were compatible with the targeted geometric dimensions. In this context, a dimensional difference of ±0.1% was determined in the process performed with laser beam cutting, when a conical cut occurred in plasma arc cutting due to intense heat and plasma formation. An angle of 1-3° has been formed on the cut plate edges. Moreover, in a linear progression, a cut-up line (shearing line) of about 0.15 mm was observed
in the 8 mm thickness due to the intense plasma effect. That value had been changing with the sheet thickness. That taper was also present in oxygen cutting, but it was significantly lower than in plasma cutting. In laser beam cutting, the taper was almost nonexistent.

Roughness measurements were made on the cut surfaces. The roughness was 13.7 μm in laser beam cutting, 26.6 μm in plasma arc, and 33.2 μm in oxygen cutting (Table 5). The high roughness ratio on the cut surfaces is undesirable as it requires additional arrangement in assembly processes and on the contacting surfaces. Roughness measurements of cutting surfaces for 8 mm thickness of plates for plasma arc and laser beam cutting 15 mm thickness of plates for oxygen cutting process are shown in Table 6.

**Table 6. Roughness measurements of cutting surfaces.**

|                      | Laser beam cutting | Plasma arc cutting | Oxygen cutting |
|----------------------|--------------------|--------------------|---------------|
| $R_{a}$ (μm)         | 2.1±5              | 4.5±8              | 5.1±6         |
| $R_{z}$ (μm)         | 9.8±8              | 20.1±4             | 23.1±6        |
| $R_{z\text{max}}$ (μm) | 13.7±7             | 26.6±7             | 33.2±5        |

**Figure 3.** Location of the Vickers hardness test rows.

The parts cut by laser beam and plasma arc cutting methods were compared in terms of hardness. It was determined that the surfaces cut using plasma arc cutting were harder. The hardness measurement of tensile specimens cut by laser beam and plasma arc cutting methods are shown schematically in Fig. 6. Hardness measurement was carried out starting from the middle of the tensile specimen section and with 0.5 mm intervals towards the edges. It was determined that the hardness was high on the cut surface and decreased in the heat-affected zone [13]. Moreover, while the highest hardness value obtained in laser beam cutting was 185.7 HV, the highest hardness value obtained in Plasma arc cutting was 236.8 HV. Hardness distribution using the zero point as the reference point is shown in Fig. 6. While this hardness value creates a negative situation for machining processes on the surfaces, the machining process of a part prepared by laser cutting is carried out relatively easily. Drilling/editing a plasma-cut hole later with a drill is particularly demanding [14]. Considering the hardness distribution, high hardness in plasma arc cutting is seen in the region of 750-950 μm. The edge is formed almost vertically,
has low surface roughness, and a small heat-affected zone (400-600 µm) is seen at intervals along the edge in laser beam cutting. It can be said that low ductility occurs in high hardness regions in both cutting methods. No editing or deburring is required after laser cutting. Less residual stress occurs [5]. Measurements after the cutting method make laser beam cutting superior in terms of high accuracy, technology and production method.

The test samples performed with tensile samples of different thicknesses cut using plasma arc, laser beam, and oxygen cutting method are shown in Fig. 5. The yield strength and ultimate tensile strength values of these tests are presented in Table 7.

![Hardness distribution using the zero point as the reference point.](image)

**Figure 4.** Hardness distribution using the zero point as the reference point.

![The fracture surface of the S235JR steel after tensile testing. a), b) Plasma arc cutting c), d) Laser beam cutting e) Plasma arc cutting f) Oxygen cutting.](image)

**Figure 5.** The fracture surface of the S235JR steel after tensile testing. a), b) Plasma arc cutting c), d) Laser beam cutting e) Plasma arc cutting f) Oxygen cutting.

As a result of the tensile tests performed with tensile specimens cut with different methods, it was observed that the strength values changed depending on the cutting process (Table 7). In the hardness measurement performed after the plasma arc cutting process, it was assumed that the plasma cutting process would contribute positively to the strength since the plasma cut surface is harder. However, it
was determined that the amorphous, brittle, and rough structure on the surface, rather than the hardness, created the notch effect and contributed negatively to the maximum tensile strength (Fig. 6). When the oxygen and plasma arc cutting methods are compared, it is clear that the excessive roughness of the oxygen cutting method has an effect. Along with surface effects and cross-section irregularities, all three cutting methods have different effects on the material microstructure by heat effect [15]. A tensile test of an 8 mm thick plate for the laser beam and plasma arc cutting is presented (Fig. 7). The mechanical properties of steel plates change as the thickness of the steel plates increases according to the thermal cutting process. When the yield and tensile strength of the plates of the same thickness were highest in plasma arc cut samples, the lowest values were observed in oxygen cut samples. On the contrary, as the thickness of the plates increases, yield and tensile strengths increase in samples cut by laser beam cutting process and plasma arc cutting process. The reason for the maximum strength values in the plasma cutting process for 15 mm thickness is that the hardness values of the surfaces cut with the plasma arc method are higher.

**Figure 6.** The fracture surfaces of samples were cut by different cutting methods after the tensile test. a) laser beam cutting b) plasma arc cutting c) oxygen cutting.

**Table 7.** The effect of different cutting methods on strength.

| Cutting Process         | Thickness (mm) | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) |
|-------------------------|----------------|----------------------|---------------------------------|
| Laser beam cutting      | 3              | 335±5                | 442±4                           |
|                         | 5              | 323±5                | 445±5                           |
|                         | 6              | 315±7                | 452±5                           |
|                         | 8              | 308±8                | 439±5                           |
| Plasma arc cutting      | 3              | 318±7                | 424±5                           |
|                         | 5              | 315±5                | 412±5                           |
|                         | 6              | 290±5                | 403±5                           |
|                         | 8              | 315±5                | 401±5                           |
|                         | 15             | 346±5                | 462±5                           |
| Oxygen cutting          | 15             | 308±5                | 431±5                           |
Figure 7. Tensile test result for 8 mm thickness samples a) laser beam cutting test sample b) plasma arc cutting test sample.

The microstructure consisting of $\alpha$-ferrite and Fe$_3$C (pearlitic microstructure) may be seen in the base material when S235JR structural steel is examined utilising an optical microscope (Fig. 8). Pearlite consists of layers of ferrite and cementite stacked on top of each. When the surfaces cut with laser and plasma are examined with an optical microscope, a heat-affected zone (HAZ) is formed between the surface layer and the base material. While thermal deformation occurs in a smaller area on the surfaces cut with the laser beam cutting method, thermal deformation does occur in a larger area on the surfaces cut with the plasma arc cutting method [16]. Microstructure photos were taken from the plasma arc cutting surface at 200X magnification at 0.5 mm intervals in Fig. 9. Since the surface cut with plasma arc is affected by heat, as seen in Fig. 9 and Fig. 10, its microstructure appearance has the appearance of weld metal.

Figure 8. Optical micrograph of S235JR structural steel (500X magnification).

The laser beam focuses on the workpiece, locally heats it, and induces the phase transformation of the material. Microstructure photos were taken from the laser beam cutting surface at 200X magnification at 0.5 mm intervals in Fig. 11. The surface layer consists of distinct martensitic needles that gradually transform into a bainitic type [7,17] (Fig. 11 and Fig. 12). This bainitic structure is the result of rapid cooling after heating to austenitisation temperatures, where the cooling rate decreases as it moves away from the surface. The boundary line between the surface layer and the base material is the recrystallisation area. Martensitic structure limited by newly separated ferrites and carbides was observed in this region [7]. Unlike the plasma arc cutting method, the laser beam cutting method uses O$_2$ and N$_2$ as additional gases. These gases have a high affinity for carbon and react with the existing phases leading to partial saturation of the cutting surface. Therefore, the surface layer observed in plasma cutting appears darker than in laser beam cutting and has higher hardness due to more carbide formed on the surface. Nitrogen, which is used especially in cutting stainless steel sheets, hardens the cutting surface.
Figure 9. Plasma arc cutting surface 200X magnification using the zero point as the reference point a) 0 b) 0.5 mm c) 1 mm d) 1.5 mm e) 2 mm f) 2.5 mm.

Figure 10. Plasma arc cutting surface a) 100X b) 200X c) 500X magnification.

Figure 11. Laser beam cutting 200X magnification using the zero point as the reference point a) 0 b) 0.5 mm c) 1 mm d) 1.5 mm e) 2 mm f) 2.5 mm.
The laser beam, plasma arc and oxygen cutting methods were compared in terms of industrial use and presented in detail in Table 7. While only simple parts are cut with plasma and oxygen cutting method, complicated parts can be cut with laser beam cutting method and higher cutting quality is obtained.

### Table 8. Comparison of the cutting process.

| Cutting Process                  | Oxygen cutting | Plasma arc cutting | Laser beam cutting |
|----------------------------------|----------------|-------------------|--------------------|
| Cutting speed                    | slow           | fast              | fast               |
| Material thickness               | >15mm / thick  | medium and thick  | thin and medium    |
| Size details                     | large-very large | large and very large | small and large   |
| Shapes                           | simple         | simple            | complicated        |
| Material hardening               | yes /lower /148 HV | yes/ higher /230 HV | yes/ lower /185 HV |
| Thermal deformation              | wider area     | wider area        | small area         |
| Cutting quality                  | good           | good              | higher             |
| Conductive/ non conductive materials | yes/yes           | yes/no            | yes/yes            |
| The total cost of machine hours  | 7.75 Euro/h    | 7.66 Euro/h       | 9.16 Euro/h        |

### 4. Conclusion

The cutting process of the raw material for the target product is the first step of manufacturing in the manufacturing industry. Well-chosen cutting technology directly affects the inputs and outputs of the entire production process. Three cutting methods, which are widely used industrially today, are presented in detail in this study. The tests performed on samples for the three methods and the parameters of the methods in the process of industrial use were successfully evaluated. Based on the three cutting methods, the following conclusions can be drawn.

- The plasma arc cutting process is the most defective method in terms of geometry obtained after cutting out of the three cutting processes. The fact that the cut surfaces are conical is the most crucial reason for this technology to be gradually abandoned. Despite these flaws, it can be said
that the most economical cutting method is plasma cutting. Moreover, it is also suitable for cutting thicker sheets than laser cutting.

- Plasma arc cutting machines can perform oxygen and plasma arc cutting methods, and sheets over 20 mm thick are usually cut with oxygen in plasma arc cutting devices. Although it is possible to cut high thicknesses of 20 mm and above with laser, the laser beam cutting method required for this process has a very high cost. The laser beam cutting method is the most costly in terms of initial setup cost and operating expenses. On the other hand, it has high success in terms of cutting precision and surface roughness.

- The laser beam, plasma arc, and oxygen cutting methods produce gases and heat that are harmful to human health and nature. Although cutting with oxygen is the least harmful method for the eye, it is dangerous for eye, skin, and lung health in all three methods.

- In the three methods, high temperature is created on the cut piece and most of the time distortions occur. The heat accumulation on the cut sheet decreases in the form of oxygen, plasma arc, and laser beam sequence.

- In the three methods, the preparation of the data to be cut for cutting is carried out similarly. While sheet metal formed by laser cutting can be used directly, it is often necessary to remove burrs and remove roughness from the cutting surfaces in sheets cut with plasma beam and oxygen. Cleaning the sheet surface to be cut is important for the laser beam cutting method, it is important for plasma, in this regard, oxygen cutting is a little more tolerant.

- When the hardness is measured on the cut surfaces, the average is 185 HV, 230 HV, and 150 HV for the laser beam, plasma arc, and oxygen cutting, respectively. Machining on plasma cut surfaces is difficult due to high hardness. It was determined that ductility decreased in the cut areas, especially in plasma arc cutting. Especially, arranging the holes created by plasma arc cutting with a drill is the biggest problem in this regard.

Although these thermal cutting methods are widely used, the water jet cutting method, which is less harmful to nature and human health, should be evaluated for manufacturing processes. An appropriate cutting method should be selected considering the parameters specified in the tables within the needs.

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