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MECHANICAL AND MICROSTRUCTURAL COMPARISON OF WIRE ELECTRICAL DISCHARGE MACHINING, LASER BEAM AND PLASMA ARC CUTTING PROCESSES

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Highlights

- Comparison of industrial methods used in cutting sheet metal.
- Cutting is one of the most basic processes of production and directly affects the next process.
- Plasma, laser, and wire electrical discharge machining methods affect the microstructure and mechanical properties of metals.

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Abstract

In this study, laser, plasma, and wire electrical discharge machining (WEDM) cutting methods were experimentally investigated by cutting S355JR structural steel and Hardox 450 martensitic steel. The effects of cutting processes on production speed, edge quality, surface quality and production tolerances are presented. The mechanical and microstructural effects of the cutting method on the cut samples were investigated. Laser beam, plasma arc cutting methods are widely used in industry. The WEDM method, on the other hand, has a more limited area of use compared to these two methods. It has been observed that the strength values of the samples cut from S355JR and Hardox 450 steels with these three methods affect the tensile and bending strengths depending on the cutting process. The maximum hardness values detected on the surfaces cut by WEDM, laser and plasma methods are 435, 440 and 481 HV, respectively. It was determined that 5 ± 0.72° vertical inclination (conicity) occurred on the cut surfaces of 8 mm thick sheets in plasma cutting, while a vertical inclination of 0.3 ± 0.15° occurred in laser cutting. In the WEDM method, it was determined that the cut edge did not form in this way. When the cut surface is examined, it can be sorted as Wire electrical discharge machining, plasma cutting, laser method in terms of dimensional tolerances and surface roughness success.

1. Introduction

The cutting processes of metal materials form the essence of industrial production processes. The material and geometry of the object are two important parameters in the cutting process (İrsel & Güzey, 2021)(Yilbas, 2008). In many steel structures, cutting edge quality affects production efficiency. Surface and dimensional irregularities accelerate the formation of damage in systems (Klimpel et al., 2017). Cost, dimensional accuracy, cutting speed, microstructural and mechanical effects after the cutting process are the main factors determining the industrial applicability and selection of the cutting method. These factors also directly affect the manufacturing stages following the cutting process. Laser and plasma cutting methods are widely used in the cutting process of sheet metal materials (Boujelbene, 2018)(P. Patel, Nakum, Abhishek, & Rakesh Kumar, 2018)(Celik, Rennie, & Akinci, 2017). WEDM, on the other hand, has a more limited use. The workpiece obtained after WEDM processing has superior surface properties and dimensional accuracy. For this reason, it is used in the manufacture of molds, the manufacture of aerospace, medical and surgical instruments, the automobile industry (P. Patel et al., 2018)(Karpat & Yuce, 2020). The WEDM method, which is an unconventional cutting method, is gaining popularity today. In these three methods, in which designs created with computer aided engineering software are cut using numerical workbenches, it is carried out automatically (Ho, Newman, Rahimifard, & Allen, 2004). In these three methods, there are differences in terms of production speed, mechanical and microstructure of the parts obtained after the cutting process.

Plasma cutting is one of the most common cutting processes for cutting flat parts or blanks from sheet materials. In the plasma cutting method, it is cut with the plasma formed with electrically conductive materials by means of an accelerated hot plasma jet. Depending on the type of plasma, this method is suitable for cutting metals such as carbon, high alloy steels, aluminum, copper, wear-resistant plates. The plasma torch contains a jet of ionized gas and a temperature of approximately 20.000 to 50.000 °C is reached. Plasma cutting is still the most economical heat cutting method for cutting (Barényi, 2016)(Masoudi et al., 2019). The selection of the parameters of the plasma cutting process changes the surface roughness of the material, the cutting angle (taper), the burr formation, the size of the heat affected zone (HAZ), the material removal rate, the cut surface quality and the metallurgical effects of the cutting. Barenyi et al. (Barényi, 2016) investigated the effect of cutting temperature on microstructure and mechanical properties in plasma and laser cutting process of armox steels. They concluded that the apparent HAZ depth of plasma cutting surfaces is significantly greater compared to laser cutting. Thomas et al. (Thomas, 2011) investigated changes in surface properties and microstructure near the cutting edge using laser and plasma cutting machining of 8 mm thick S355 steel. Plasma arc cutting and laser beam cutting methods are two cutting methods that are technically very close to each other. Laser beam cutting technology is essentially a thermal process in which a focused laser beam is used to melt material in a localized area. The processing of metals by laser cutting method has a wide application area in the industry. The high-energy focused laser beam ensures fast processing and excellent precision in operation. Because laser processing involves a high temperature gradient, mainly depending on the laser power, cutting speed, laser beam diameter, pulse frequency and focus position. This causes a thermal stress in the irradiated area. In addition, high cooling rates cause stress formation in this region (Boujelbene, 2018)(Boujelbene, Alghamdi, Miraoui, Bayraktar, & Gazbar, 2017)(Miraoui, Boujelbene, & Bayraktar, 2015). Klimpel et al. (Klimpel et al., 2017) determined that the cutting method and cutting parameters significantly affect the surface quality, microstructural and mechanical properties. Gostimirović et al. (Gostimirović, 2020) determined that in the cutting process of low carbon steels, plasma cutting is not suitable for final machining. In the two methods, the melted material is removed from the cut plate on the line to be cut and a gap is created. These methods are called thermal cutting methods and the surface quality does not give the expected result if high temperature and cutting parameters are not selected appropriately during cutting. WEDM is a form of EDM in the non-traditional machining process category (Kumar & Singh, 2012)(Verma, Upadhyay, & Rizvi, 2021). WEDM process, also known as spark erosion process used to create very intricate and complicated shapes on electrically conductive workpieces through a wire. In this method, cutting is carried out with the help of a wire with a high-intensity current (S. S. Patel & Patel, 2021). One of the advantages of WEDM is that hardened steel can be easily machined to micron precision with high precision and smooth surface finish (Ho et al., 2004). Altuğ et al. (Altuğ, 2019) investigated the effect of WEDM machinability on the mechanical and microstructural properties of Hardox 400 steel. Bobbili et al. (Bobbili, Madhu, & Gogia, 2013) applied the cutting process with the help of WEDM and as a result confirmed the effect of this cutting process on the mechanical and microstructural properties of high strength armor steel such as surface roughness, material removal rate. Borchers et al. (Borchers et al., 2020) examined the resulting cut surfaces mechanically and microstructurally after cutting AISI 4140 steel with seven different cutting methods. They attributed the hardness of the surface cut by the EDM method to the formation of martensite, which is why it is harder. Göğüş et al. (Göğüş, Cabiroğlu, Ekmekyapar, & Özakça, 2014) investigated the laser cutting, plasma cutting and WEDM cutting methods of structural steel on the tensile specimen and they obtained different heat effects and roughness values by performing mechanical tests on the cutting surface of these effects on the specimen.

In this study, the success of WEDM, plasma and laser cutting methods in sheet metal cutting processes was compared in terms of processing speed, dimensional accuracy after cutting, mechanical and microstructural changes. For experimental studies, samples were cut from S355JR and Hardox 450 steels with three different cutting methods. Metallographic and mechanical tests such as FESEM, tensile, bending, microhardness tests were performed and cutting methods were compared for two different materials.

2. Materials and Method

For the current study, S355JR general structural steel with ferrite (α) and small amount of perlite ($\alpha + Fe_3C$) microstructure and martensitic Hardox 450 plates with high wear resistance were cut by laser, plasma and WEDM cutting methods. The chemical composition and mechanical properties of these two materials are presented in Table 1 and Table 2. Elemental measurement was carried out with the Spectrotest brand TXC35 model portable metal analyzer.

Table 1. Chemical composition of the S355JR and Hardox 450 steel (wt. %).

Malzeme	S355JR	Hardox 450
C	0.20	0.19
Mn	1.60	1.50
Si	0.25	0.30
Cr	0.24	0.10
Ni	-	0.10
Mo	-	0.05
P	0.035	0.02
S	0.032	0.005
Fe	Balanced	Balanced

Table 2. Mechanical properties of the S355JR and Hardox 450 steel (wt. %).

Mechanical properties	S355JR	Hardox 450
Yield strength (MPa)	381 ± 55	1200 ± 50
Tensile strength (MPa)	595 ± 55	1400 ± 50
Elongation%	22 ± 3	10 ± 4
Elastic modulus (N/mm^2)	200000	200000
Charpy V-Notch impact toughness (J)	27 (-20 °C)	27 (-40 °C)

Test specimens were cut from 8 mm thick plates. For both S355JR and Hardox 450 materials, 20 mm length and 15 mm width tensile test specimens, 20 mm x 150 mm bending specimens, microhardness and microstructure inspection specimens were prepared.

For WEDM processing, tensile and bending samples were cut with Charmilles brand, Robofil 440 model at 4 mm/min speed with distilled water and 0.25 mm brass wire as electrode (Fig. 1). The cutting process occurs with the arc that occurs when the wire touches the part, and a heat of 8000~12000 °C occurs at the time of the arc. The samples are positioned in pure water and cut with a brass wire. Wire is a consumable here and is supplied from a coil. The S355JR and Hardox 450 materials were cut with a Plasma arc (Brand: Yıldırım Knuth) and a Laser beam (Brand: BYSTRONIC BYSPEED 3015 5200W).

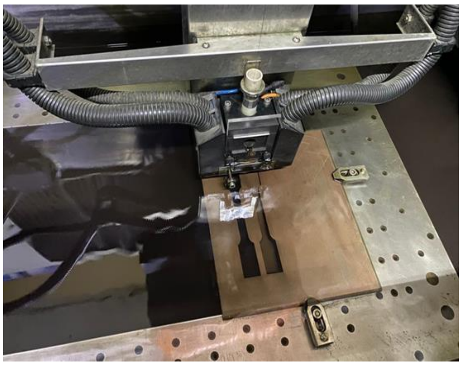

Fig 1. Wire electrical discharge machining.

Tensile test specimens of 220 mm length and 15 mm width were cut according to ASTM E8 standard (Fig 2). Bending test samples shown in Fig 3. Cutting operations were performed with the cutting parameters seen in Table 3, Table 4, and Table 5 for all samples. After the cutting process, section measurement, tensile test, bending test, microhardness measurement, microstructure analysis, FESEM and mechanical tests were performed on the specimens.

Fig 2. Tensile test samples.

Fig 3. Bending test samples.

Table 3. Cutting parameters of plasma.

Cutting thickness (mm)	8
Cutting speed (mm/min)	2400
Current I, A	135
Power (W)	8500
Nozzle diameter (mm)	1.2

Table 4. Cutting parameters of laser beam cutting.

Cutting thickness (mm)	8
Lens type	7.5
Laser power (W)	3250
Nozzle diameter (mm)	NK1515
Cutting speed (mm/min)	1700

Table 5. Cutting parameters of Wire electrical discharge method.

Cutting thickness (mm)	8
Cutting speed mm/min	60
Nozzle diameter /mm	1.4
Oxygen pressure /bar	6-7

Tensile, bending, microhardness and microstructure inspection specimens were prepared for both S355JR and Hardox 450 materials. For metallurgical examination, samples were cut with a Struer brand discotom-100 model diamond cutter precision cutting device and samples were prepared in bakelite with a Struer brand CitoPress-5 model device. The sanding process was carried out using the Struer brand Tegramin 25 model sanding and polishing device. First, sandpaper: MD-Piano 220 was carried out with water for 2:30 minutes with 40 N pressing force and 150 rpm speed. Washing was done, in the second operation sandpaper: MD-Allegro, DiaDuo-2 9 µm was polished with 40N pressing force and 150 rpm for 4:30 minutes, and then washing was performed. Sanding: MD-Dac was carried out with DiaDuo-2 3µm for 4:30 minutes at 35 N pressure and 150 rpm speed. Finally, sandpaper: MD-Nap, DiaDuo-2 1 µm 2:30 minutes, 30 N pressing force was applied and the polishing process was carried out at 150 rpm. After the base metals were prepared to obtain a mirror-like surface for metallographic analysis, the surface was cleaned with pure ethanol. After mechanically polishing the surface, it was etched with 3% nital (97 ml ethanol + 3 nitric acid) etching solution for 15 seconds. Field emission scanning electron microscopy (FESEM) provides essential information on topographic, morphological and microstructure at magnifications from 10x to 300,000x with virtually unlimited depth of field. The cutting surfaces of S355JR and Hardox 450 steels, which were cut with different methods at 1.00KX and 3.00KX magnification, were visualized using the Carl Zeiss Gemini 500 FESEM device. The Vickers microhardness test was measured using a microhardness tester (Brand: Delhi Metko) at 0.5 mm intervals from the cut edge to the center in samples cut with laser beam and plasma arc (Fig 4). Tensile tests were carried out for S355JR and Hardox 450 samples in three repetitions at 5 mm/min tensile speed with ALŞA tensile tester according to ASTM A370 standard. Bending tests of Hardox 450 and S355JR steels cut with different cutting methods were carried out according to TS EN ISO/IEC 17025:2017.

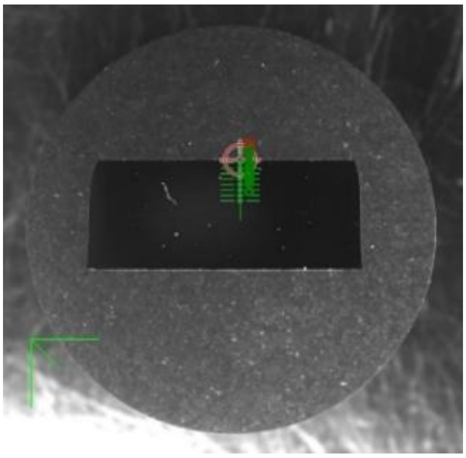

Fig 4. Vickers microhardness measuring points.

3. Experimental Findings and Discussion

In the manufacturing processes in which sheet metal plates are used, the first operation is the cutting of the plates. This cutting process greatly affects the production quality, cost, production time (Ho et al., 2004)(Harničárová, Zajac, & Stoić, 2010). In this study, wire electrical discharge machining, laser and plasma cutting methods are discussed in detail in terms of processing speed, microstructural and mechanical differences after cutting, and geometric precision. When the microstructures of S355JR and Hardox 450 steels were examined after cutting, it was seen that each cutting method affected the microstructure differently.

The first success criterion expected from the cutting process is that the cut plate dimensions are compatible with the targeted geometric dimensions. In plasma cutting, a conical cut occurred due to intense heat and plasma formation. While the upper surface of 8 mm thickness was 12.81, the lower surface was measured as 12.08 mm, which is a taper of 5 ± 0.72°. Moreover, in a linear progression, a dimensional fluctuation of about 0.15 mm at 8 mm wall thickness was also detected with the effect of intense plasma. This value will change with the sheet thickness. An angle of 0.3 ± 0.15° was formed at the edges of the plate cut with the laser. This value is such a small error that it does not require any editing on the cut plates.

After the cutting processes, the effect of different cutting methods on the same materials was investigated microstructurally by FESEM analysis. α-ferrite and pearlite phases are seen in S355JR steel. Laser and WEDM at 1.00KX magnification were similar to base metal, but dimensional growth was observed. In plasma cutting, elongation and needle-like structures were formed in the grains (Fig 5-7). It has been determined that Hardox 450 steel has a martensitic structure. When the surface of Hardox 450 steel is examined with FESEM after cutting with wire electrical discharge machining and laser beam cutting methods, a martensitic structure is observed (Fig 8-9). The maximum hardness of Hardox 450 steel, which is cut with the plasma cutting method, is based on the denser martensitic structure due to the temperature during cutting (Fig 10). For S355JR steel, grain geometries in

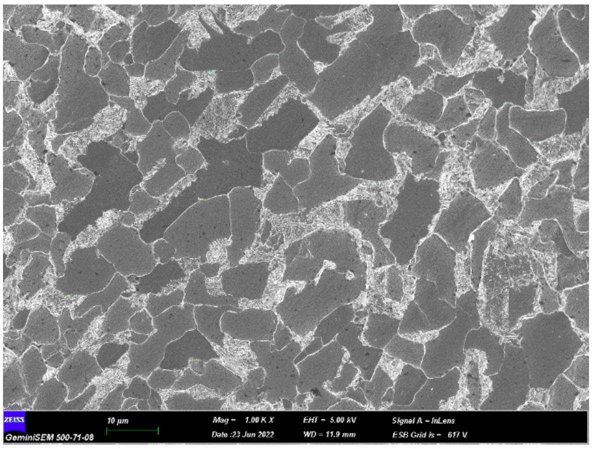

Fig 5. S355JR surface after WEDM at 1.00KX magnification.

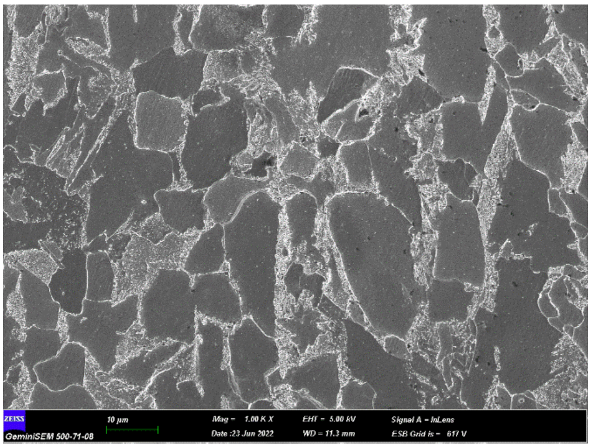

Fig 6. S355JR surface after laser cutting process at 1.00KX magnification.

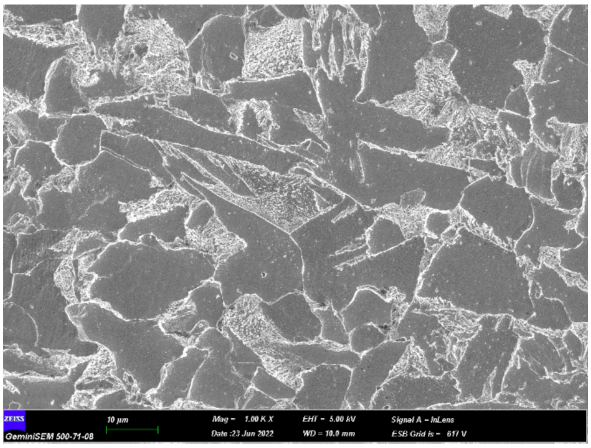

Fig 7. S355JR surface after plasma cutting process at 1.00KX magnification.

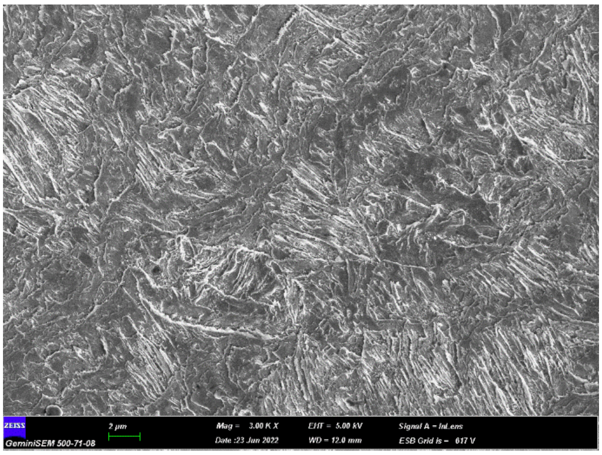

Fig 8. Hardox 450 surface after WEDM at 3.00KX magnification.

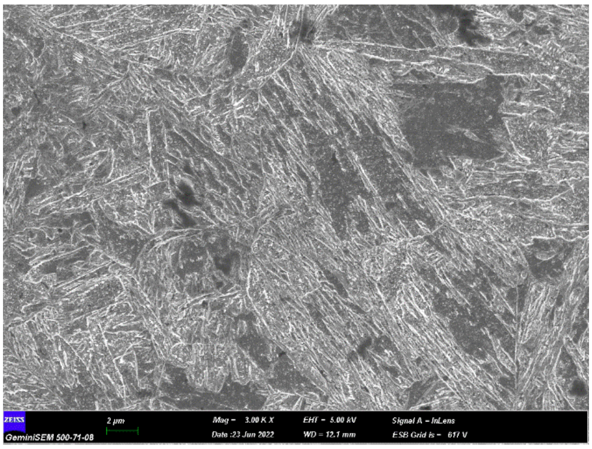

Fig 9. Hardox 450 surface after laser cuttting process at 3.00KX magnification.

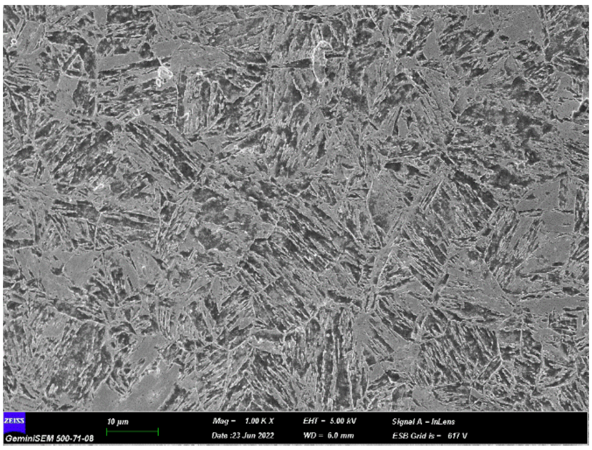

Fig 10. Hardox 450 surface after plasma cutting process at 3.00KX magnification.

The tensile test was applied to the specimens cut with three different methods. The highest tensile strength was obtained in the sample no. 1 in Fig 11 of the Hardox 450 sample cut by the plasma cutting method. The graphs of the tensile tests performed are shown in Fig 12.

Fig 11. Fracture after tensile testing.

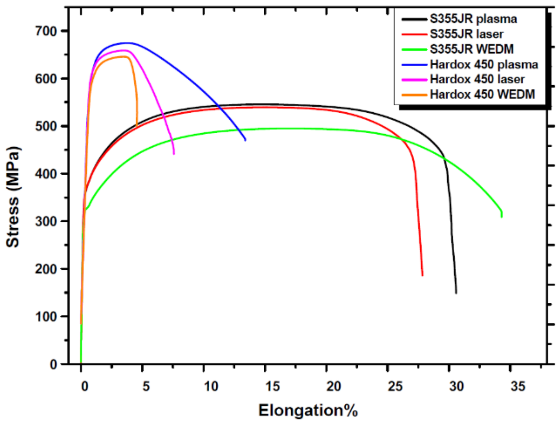

Fig 12. Tensile test graph.

The bending test was applied to the specimens cut with three different methods. According to the bending test results, the highest bending strength was obtained as 34.729 kN in the plasma cutting method of Hardox 450 steel (Fig 13). The reason for this maximum value is not due to the superiority of the cutting method, but the effect of high temperature and rapid cooling at the sample edge (Fig 10). However, no cracks or defects were observed in the specimens after bending (Fig. 14-15). Fig 14a shows the fluctuation indicated in plasma cutting.

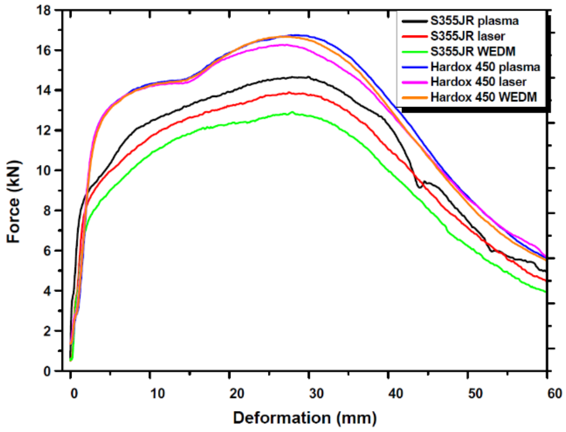

Fig 13. Bending test graph.

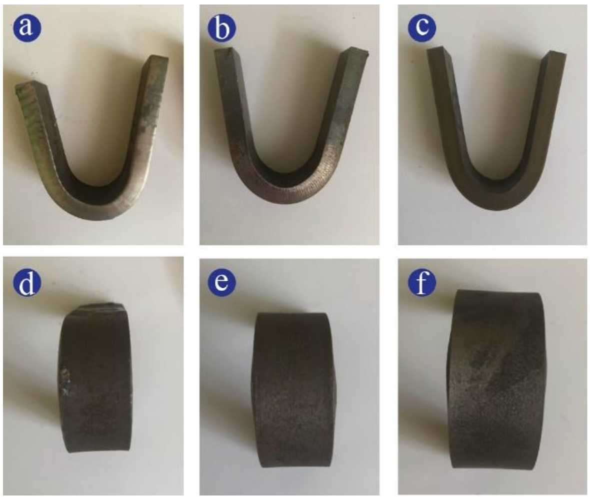

Fig 14. S355JR steel after bending test a-d) Plasma, b-e) laser beam, c-f) WEDM process.

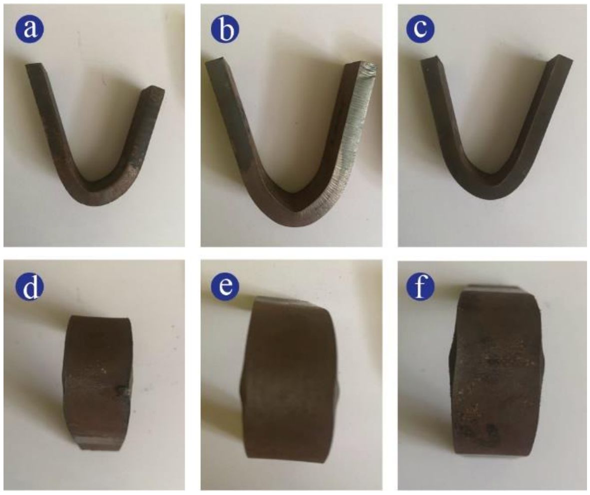

Fig 15. Hardox 450 steel after bending test a-d) Plasma, b-e) laser beam, c-f) WEDM process.

The highest hardness value was determined as 481 HV in Hardox 450 material cut with plasma. Hardness decreased as it progressed from the edge to the center and averaged 400 HV. In laser beam cutting, the maximum hardness in Hardox 450 was 440 HV, and the average hardness value of the sample was 430 HV as it went towards the center. In the wire electrical discharge machining, the maximum hardness value measured at the edge was 435 HV, while the average hardness value measured towards the center was 415 HV (Fig 16).

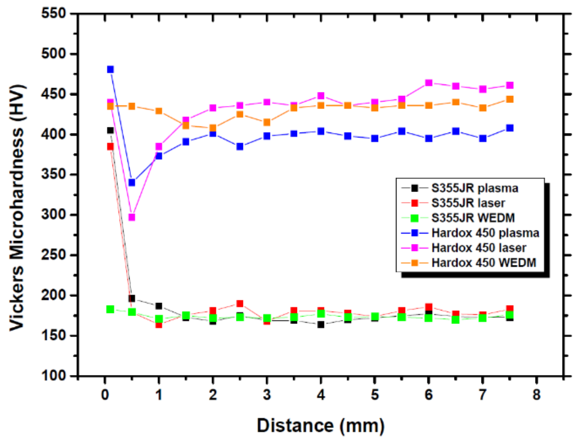

Fig 16. Vickers Microhardness graph.

4. Conclusion

Laser, plasma and WEDM methods were investigated experimentally by cutting S355JR and Hardox 450 steels. The effects of cutting process on production speed, edge quality, surface quality and production tolerances are presented. The mechanical and microstructural effects caused by the cutting methods were investigated by mechanical and microstructural tests. The findings obtained result of the tests are as follows:

1. The cutting speeds in the three methods were 60 mm/min for WEDM, 1700 mm/min for laser and 2400 mm/min for plasma. Wire electrical discharge machining has a very low processing speed compared to the other two methods. In the WEDM method, it is necessary to drill a hole through which the wire will pass before the cutting process.
2. According to the dimensions of the cut samples, an inclination of 5° ± 0.7 in plasma with a wall thickness of 8 mm and an inclination of 0.3° ± 0.15 in laser cutting were observed. In the WEDM method, there was no edge bevel due to cutting.
3. The surface formed after the plasma arc cutting process is often too hard for machining. In this respect, laser cutting method is more convenient than plasma cutting. The final product processed with WEDM has a better surface as it is precision cut and does not require machining after cutting.
4. Plasma cutting process (for 8 mm plate thickness) is 40 times faster than the WEDM method and 1.42 times faster than the laser cutting method.
5. According to the tensile test results, the highest tensile strength was determined as 1417.395 MPa in Hardox 450 steel in plasma cut sample and 545.470 MPa in plasma cut sample in S355JR steel.
6. According to the results of the bending test, the maximum force was determined as 34.729 kN in Hardox 450 steel cut by plasma cutting method.
7. It can be relatively assumed that WEDM always leads the way and performs better in processing a difficult and advanced material with precision and better surface quality.
8. Different cutting methods are effective in terms of microstructure and mechanical properties in carbon steels such as S355JR and Hardox 450, especially the plasma cutting method adversely affects the microstructure at the cutting edge.

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