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Study on mechanical and microstructural properties of advanced high-strength welded sheet metal

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Abstract

Continuous research is carried out in the automotive industry to decrease the weight of automobile bodies without reducing durability. For this purpose, the use of welding sheet metal is one of the successful technics. Welded sheets are formed by combining two or more flat materials with different thicknesses and different mechanical properties, using the welding method, before being shaped in order to provide superior properties. This situation requires more attention during the shaping stages. It is important to calculate the pressures to be applied to the welding areas and to apply the shaping steps in a way that will not reduce the material strength. For this reason, the production stages of the dies to be used in the manufacture of these parts are just as important. In this study, an innovative die design is carried out for the production of welded sheet metal. The microstructure and mechanical properties of the welded sheet formed by the die were examined. The effect of the forces applied to the welding areas on the material and the mechanical properties of the materials of different thicknesses were determined. Within the scope of the study, microstructure analysis, hardness and tensile tests were carried out and the results were examined. When the results obtained were examined, it was seen that the strength and hardness values of the samples obtained from the welded area were higher than the other areas.

1. Introduction

With the developing technology, vehicle use rates are increasing. During the production and use of vehicles, energy consumption and the amount of carbon emitted into the environment increase. Studies are being carried out to reduce this situation. Reducing vehicle weights can be a solution to these problems. In the automotive industry, tailor welded blank (TWB) technology is an important technology for weight and cost reduction [1-3].

TWBs are a combination of several metal sheets with different thicknesses, materials and coatings. Before forming, two different parts are welded together. Lighter structures and products with higher strength are produced with TWBs [1,4]. It offers advantages such as reduced final vehicle weight, reduced number of automobile parts, improved raw material utilisation and scrap reduction, and improved functional performance [3]. Traditional welding methods are used for the bonding process. Examples include laser welding, TIG welding, seam welding, and plasma welding. Seam and laser welding are commonly used [3].

Welding of sheets of different thicknesses or quality before forming requires more attention during the forming stages. It is important to calculate the pressures to be applied to the welding points and to apply the forming stages so as not to reduce the material strength. For this reason, the production stages of the dies to be used in the production of these parts are just as important. Die design and production contain many parameters and components. The material to be used in the dies is selected according to the part to be produced. Die design and production stages have a significant impact on final product properties. For this reason, design and production stages need to be planned and followed with great attention [5,6].

In the literature review, it is seen that TWB technology is one of the best ideas in the automobile industry to produce lighter cars and reduce production costs, and studies on the application of TWB technology. Abbasi et al. [7] investigated the effects of formability parameters such as thickness ratio, rolling direction with respect to the weld line, and direction of major stress with respect to the weld line on the formability and weld line movement of TWBs in an experimental study. The results showed that formability is maximised when the major stress and rolling direction are along the weld line. It was also concluded that geometric discontinuities reduce formability. Tuncel et al. [8] joined DP600 and DP1000 steel sheets bilaterally by pulsed Nd:YAG laser welding. The welding of DP steel sheets is an inevitable demand in the automotive industry. Similar (DP600-DP600, DP1000-DP1000) and non-similar (DP600-DP1000) steel sheets were welded in the flat position by butt joining. Microstructure studies and mechanical tests were carried out to evaluate the weld performance. The tensile strength of similar welded joints is lower than that of base metals. The microstructure of the welded joints was found to consist of martensite, retained austenite and bainite in the fusion zone and a mixture of martensite, bainite, ferrite, retained austenite and tempered martensite in the heat-affected zone (HAZ). Kinsey et al. [9] proposed a new method since the welding process creates formability concerns in conventional forming processes due to material property changes in the weld and in the heat-affected zone adjacent to the weld. This method is the clamping of the specially welded blank along the weld line during forming. The numerical simulation results they obtained reduced the maximum stresses along the weld line by about one-fifth in the examined blank. The effectiveness and applicability of the proposed technology were concluded. Öztürk and Arıkan [10] investigated the effects of laser power and welding speed on the mechanical properties of TWBs produced using laser welding. Flow behaviour was investigated from tensile tests. By revealing the microstructures of the base material and TWBs, quantitative analyses of the microstructures were carried out. The results showed significant variation in stress distribution and strain depending on the grain size of the components and the thickness ratio of the TWB. Riahi and Amini [11] investigated the effect of variations in the position of the weld zone and thickness combination of TWB sheets on tensile properties and forming capabilities. The tensile properties of the weld samples were determined by the uniaxial tensile test perpendicular to the weld line. The results show that by moving the weld line towards the thick sheet, the formability of TWB specimens increases and the weld zone does not have much effect on the TWB formability. In addition, the formability of TWB sheets is increased by reducing the thickness difference.

In the study, a die was designed and manufactured for the forming of TWBs. The forming process was carried out with the die and the sheet material was examined before and after forming. The effect of forming on the sheet was observed. Microstructure analysis and mechanical tests were carried out with samples taken from the welded sheet and the test results were evaluated.

2. Experimental studies

2.1 Die design and manufacturing

The design and production of the die to be used in the forming of flat products joined by the welding method have been realised. The design was made using the CATIA program. Measurements such as height, width, length and baling channel were calculated for the die components. After the design, the accuracy of the process was checked with program modules. After the design was completed, the materials and production methods to be used were tested with the GOM Inspect simulation program. Optimum parameters were determined. GOM Inspect is reliable quality control software for 3D point clouds created from any source (laser scanners, optical scanners, etc).

During the die production stage, machining, steel machining, sub-assembly, 3D machining, assembly and map operations were carried out.

The produced die was subjected to heat treatment. Heat treatment was carried out in the range of 1030 – 1050 °C in three tempering processes. The heat treatment lasted about 24 hours. After the process, the die was screened on the CNC machine. The conformity of the obtained measurements was checked with computer-aided design (CAD) software (CATIA). A reverse engineering process was carried out within the scope of the study. Sample measurements were compared with the design measurements.

2.2 Welded sheet metal design

The design of the sheet material used in the study was created by the CATIA programme and is presented in Figure 1.

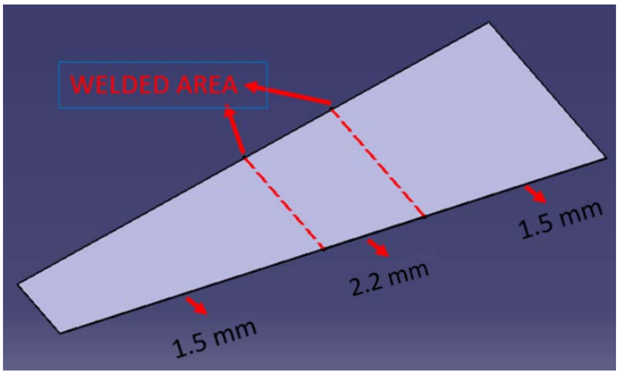

Figure 1. Welded sheet metal physical model

The welded sheet consists of 2 different thicknesses, 1.5 mm and 2.2 mm. The material type is specified as CR440Y780T-DH-GI40/40-U, which is a multi-phase steel group for cold forming. The chemical compositions (heat analysis) of the material obtained for the welded sheet are given in Table 1 as in percent by weight. The mechanical properties of the material are given in Table 2 (VDA 239-100 standard) [12].

Table 1. Chemical composition of the alloy used in the study

Element	Min. wt. %	Max. wt. %
C		0.18
Si		0.80
Mn		2.50
P		0.050
S		0.010
Al_{total}	0.015	1.0
Ti + Nb		0.15
Cr + Mo		1.40
B		0.005
Cu		0.20

Table 2. Mechanical properties (longitudinal)

Property	Value
Yield strength $R_{p0.2}$, MPa	440 – 550
Tensile strength R_m, MPa	780 – 900
Total elongation A_{80}, %	≥ 18
Bake-hardening index BH_2, MPa	≥ 30
Hardening exponent (*n*-value)	≥ 0.13

Cold forming is performed by presses and rollers to form the correct shape and size with high speed and pressure without changing the internal structure of the metals. Since they are not formed by heat, they are lighter and more flexible than other steels. They have improved formability. Formed welded sheet metal pictures are given in Figure 2.

Figure 2. Formed welded sheet metal

The welded sheet serves as a support element for the roof panel of the car. It is installed on the vehicle for locking the front doors and installing the hinges of the rear doors. It also functions as the place where the seat belt fasteners on the front seat of the car.

TWB is an innovative way for car manufacturers to reduce the weight of vehicles while at the same time increasing safety. Joining sheets of different thicknesses and quality by welding is more important than the forming stages. It is necessary to calculate the pressures to be applied at the weld zone and to shape it in a way that will not reduce the material strength.

Laser welding, one of the traditional welding methods, was used for the joining process. The laser welding method produces a narrower weld seam and ensures that a small area is affected by heat. In addition, since the materials do not need to overlap, the laser welding method performs better in weight reduction. Applying a continuous weld seam leads to higher structural hardness and good crash performance [13].

The laser emits light through an optical amplification process based on the stimulated emission of electromagnetic radiation. Laser beam welding is a non-contact fusion welding process. The high travelling speed and low heat input associated with laser welding produce narrow, deep penetration welds with minimal distortion. It is commonly used in the automobile industry.

Finally, the welded sheet metal forming process was carried out using the manufactured die.

2.3 Heat treatment

Continuous annealing and rolling methods are generally used in manufacturing. Another manufacturing method, the box annealing method, is still in the development stage.

In the continuous annealing method, hot and cold rolled sheets are annealed in continuous annealing furnaces for a short time (1 – 2 min) at temperatures in the "ferrite + austenite" zone and cooled at an appropriate rate without being rolled. Depending on the furnace temperature as well as the movement speed of the sheet in the furnace, the properties of dual-phase steels produced by this method change. In the continuous annealing method, the extra heat treatment step applied to hot or cold rolled sheets is a factor that increases the cost. However, the homogeneity of the mechanical properties of dual-phase steels produced by the continuous annealing method is the advantageous side of the method and makes it preferable.

In Japan in 1976, a new continuous annealing method was developed for unalloyed low-carbon steels. In this method, the sheet metal is annealed in the "ferrite + austenite" phase zone and then rapidly cooled by spraying water on it in a specially designed device and tempered at 25 – 300 °C. With this continuous annealing method, alloying can be kept at the lowest level and dual-phase microstructure can be formed in thick section steels. In addition, reducing energy consumption, shortening the heat treatment time and reducing the number of personnel are among the advantages of this method [14].

2.4 Obtaining samples and microstructural analysis

Tensile tests, hardness tests and microstructure analyses were performed on the obtained welded sheet within the scope of examining the mechanical properties. Samples were prepared with laser cutting equipment. Equipment information is given in Table 3.

Table 3. Sample preparation equipment

Machine	5 axis (3D)	3 axis (3D)
Brand	Prima Power	Bystronic
Model	Rapido	BySprint
Limits, mm	3000 × 1500 × 600	3000 × 1500
Cutting power, W	3000	3000 fiber
Cutting gases	nitrogen-oxygen-air	nitrogen-oxygen-air

Tensile test samples were taken from 3 pieces of 1.5 mm thickness, 2 pieces of 2.2 mm thickness and 3 pieces of seam points. Hardness samples were taken from 3 pieces of 1.5 mm, 3 pieces of 2.2 mm and 3 pieces of 2 × 2 cm of seam points. Microstructure samples were taken from 2 pieces of 1.5 mm, 2 pieces of 2.2 mm and 2 pieces of 1 × 1 cm of seam points.

The samples were subjected to a metallographic sample preparation method for microstructure and hardness analysis. The Bakelite removal process was carried out for easy disintegration of the samples. The sanding process was done with papers with different grit sizes. Then, the polishing process was carried out using diamond solutions. Finally, etching was done with a 3 % nital solution.

One of the parameters determining the mechanical properties of welded joints is microstructure analysis. Samples taken from different thicknesses of the welded sheet and from the seam area were subjected to microstructural analysis. HUVITZ-HR3-RF microscope was used for examination and microstructure determination. Nikon Eclipse LV150N was used for image analysis.

2.5 Mechanical tests

Uniaxial tensile testing is frequently preferred to examine the mechanical properties of TWBs. As a result of the tensile test, strength values such as elastic modulus, yield value, tensile strength and ductility values such as elongation at break, shrinkage at break and toughness are determined.

The purpose of the tensile tests is to asses the strength and plasticity of the weld joints. The tensile testing was performed at a speed of 2 mm/min. The machine used to perform tensile testing is the universal testing machine Shimadzu AG-XPlus 250 kN. In Figure 3, the sizes of the samples used for tensile testing are provided.

Figure 4 shows where the samples were taken, with an image taken during the study.

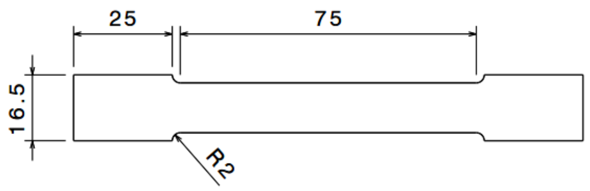

Figure 3. Sizes of the tensile testing samples

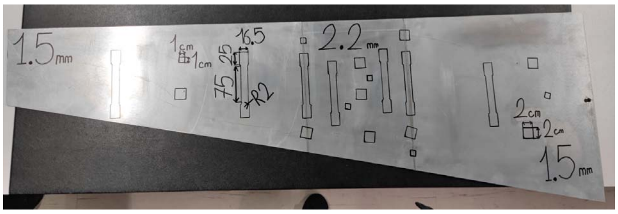

Figure 4. Study of obtaining the tensile testing samples

One of the most widely used methods for determining the mechanical properties in the weld zone is hardness measurement. Hardness measurement was made with a Vickers diamond pyramid in HV5 load mode (5 kg load) and 5 different indentations were applied for a sample. DIGIROCK-RBOV-M was used as the device.

3. Results and discussion

In this study, microstructure analysis and mechanical tests were performed on the samples taken from the welded sheet and the results were interpreted.

Figure 5 shows the microstructure images of the samples with different thicknesses. In the microstructures, white-coloured regions show ferrite and brown regions show martensite phases. The ferrite phase in the structure provides high ductility, while the martensite phase increases hardness and strength. It can be said that the microstructure of 2.2 mm thickness has a coarser-grained structure compared to 1.5 mm thickness. This may be attributed to the cooling rate as a result of the thickness increase.

At 1.5 and 2 mm thicknesses, it is seen that martensite islands are formed in the ferrite matrix, which increases the strength. Low amounts of bainite and residual austenite are also present in the microstructure. At the end of the annealing process in the hot dip galvanising line, microstructure and desired mechanical properties are achieved in the steel mill thanks to the chemical composition and targeted cooling [12].

The main structure of these materials is to increase the ferritic properties of the sheet metal by completely special annealing and thus to provide easy shaping of the material, and to form a

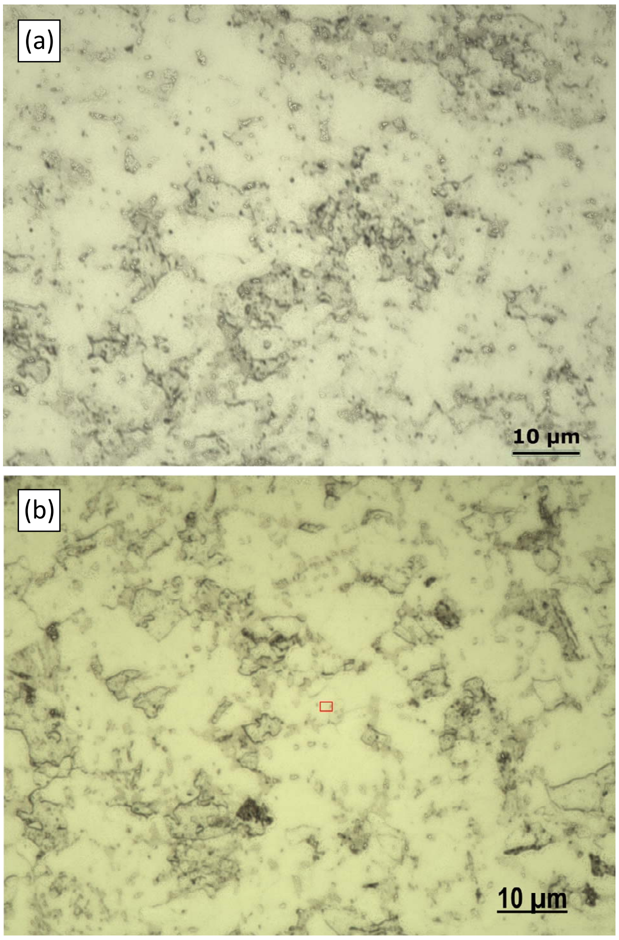

Figure 5. Microstructure of samples with different thicknesses: (a) 1.5 mm and (b) 2.2 mm; optical microscope images at 1000 × magnification

martensite phase as the second phase, which increases the strength properties with its needle-shape hard structure. These steels are characterised by a microstructure consisting of a dispersion of a hard second phase in a ferrite matrix. The second phase is martensite, usually at a level of about 20 %, but other low-temperature products and residual austenite may also be contained [14].

The application of laser welding causes the material to melt in the centre zone of the welded joint. This zone, whose peak temperature exceeds the melting point of the material during welding, forms the fusion zone (FZ). In the fusion zone, where intense heating and cooling thermal cycles occur, the microstructure is almost completely martensitic. Some researchers have observed ferrite and bainite fragments in addition to martensite in this zone. Near the FZ, on both sides of the joint, where fusion is not observed, solid-state phase transformations occur due to welding heat input, forming the heat-affected zone (HAZ) [15].

Figure 6 shows the microstructures taken from the HAZ, the formed part and the heat-affected zone of the formed part. Figure 6a shows that the HAZ microstructure is composed of ferrite and martensite phases. The temperatures obtained in the HAZ during welding were insufficient for fusion and led to complete or partial microstructural phase transformations.

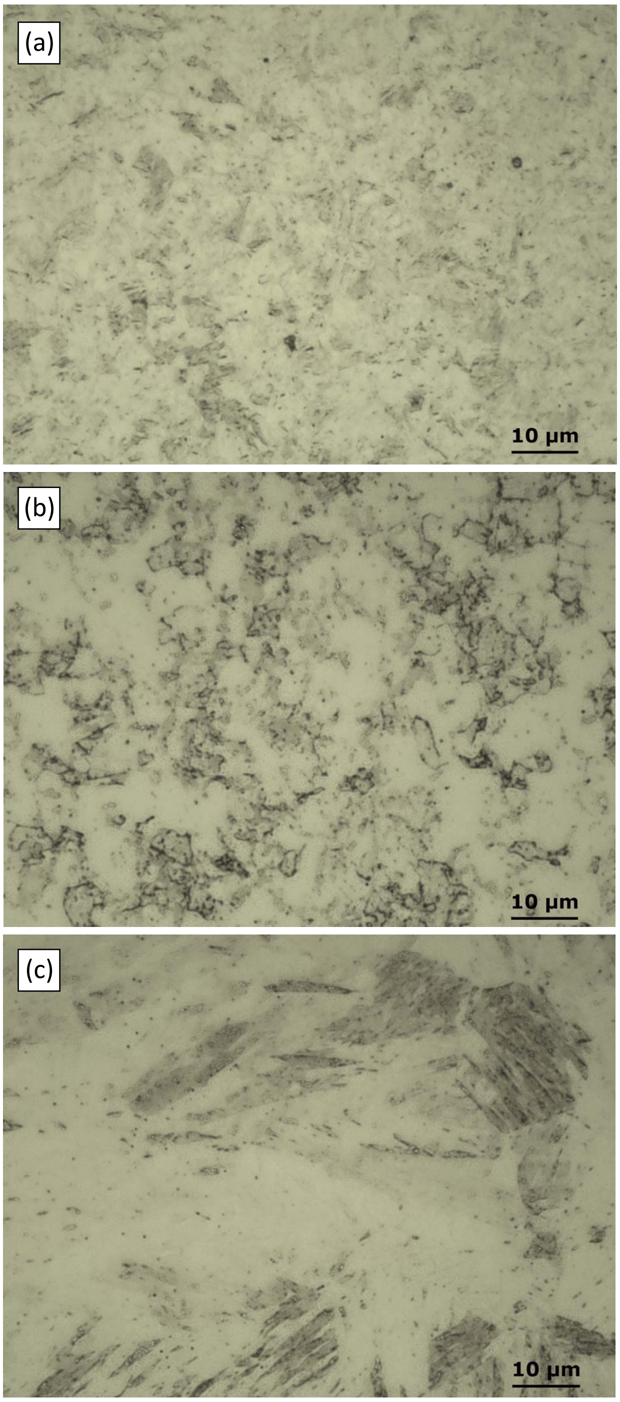

Figure 6. Microstructure visuals of different areas: (a) HAZ, (b) formed part and (c) HAZ of the formed part; optical microscope images at 1000 × magnification

Since the zone was exposed to heat, the volume-centred tetragonal structure (VCT) was transformed into a body-centred cubic structure (BCC). Some of the martensite structure has transformed into the ferritic structure. Ferritic-martensitic steels are obtained from the austenite phase by controlled cooling (in hot material products) or from the ferrite-austenite dual phase (in continuous annealed and hot-coated products) by converting part of the austenite to ferrite [16].

Since the HAZ just below the fusion boundary is heated above the austenitic transition temperature and contains lower cooling rates compared to the FZ, a microstructure containing lower transformation products of martensite and bainite is generally formed in this zone. Since the maximum temperature during the welding cycle on softened HAZ close to the base material beyond the fusion limit is below A_1 temperature (critical temperature for re-austenitization during the heating process), no austenite phase is formed in the carbon-rich martensite phase and the martensite phase is tempered and separated with regard to the impact of the temperature. Therefore, a soft microstructure emerges in this zone compared to the base metal [17].

Formability is defined as the maximum amount of strain the material can undergo during processing without suffering any damage such as tearing, shrinking or wrinkling. Material properties are a function of forming process variables. The influencing factors are yield strength, tensile strength, elongation at break, plastic deformation rate, forming speed, strain-hardening exponent, uniform elongation, chemical composition, cold/hot rolling and thermomechanical properties [18].

When the formed part was examined, a tighter microstructure was obtained due to the applied force compared to the microstructures of 1.5 and 2.2 mm thickness. The more apparent microstructure of the martensite phase due to the effect of forming can be observed in Figure 6b.

When the heat-affected zone of the formed part in Figure 6c is examined, a tighter and denser morphology is observed compared to the formed part. When the microstructure was examined, it was found that lath martensite (needle-like martensite) was formed. It is concluded that it was formed due to the highness of the forming effect and heat input.

It was observed that the ferrite microstructure coarsened due to the forming effect. As a result of microstructure examinations, it was determined that the dominant structures were ferrite and martensite. There are studies on the subject demonstrating that coarse ferrite grains undergo plastic deformation more easily [19].

During the tensile testing, values of tensile strength, yield, percentage elongation and toughness were transferred to the computer with probes around the sample. The successful findings obtained were interpreted with graphs, and the graphs were created with average values.

Figure 7 demonstrates the tensile strength values of the samples. When the graph is examined, it is seen that the strength of the 1.5 mm thick material is higher than the 2.2 mm thick material. In this case, it is evident that cold deformation has an impact. The tensile strength values of the base materials are highly dependent on the martensite volume fraction (MVF). The highest tensile strength value was obtained in the HAZ zone. It can be concluded that this is a result of the high heat applied.

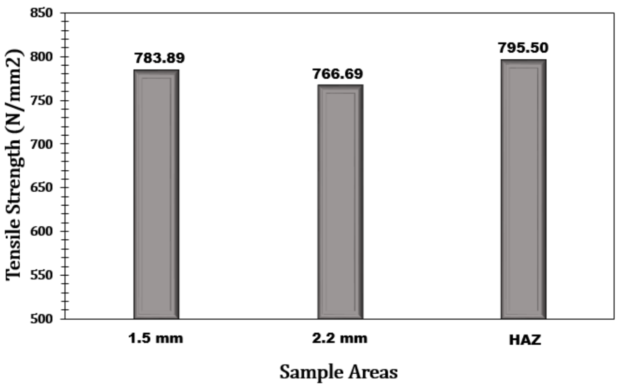

Figure 7. Tensile strength values of samples taken from different areas

The reason for the high strength is that the dominant area undergoing plastic deformation in the tensile direction has weld zones. When the related research is examined, it is found that the maximum strains occur in the HAZ and FZ regions [19].

The superior tensile properties of dual-phase steels compared to steels of similar classifications are due to the ferrite and martensite phases constituting their microstructure. When the tensile properties of dual-phase steel, a mixture of hard and durable martensite, and soft and ductile ferrite, are examined, it is revealed that the strength is determined by the martensite, and the ductility is mostly determined by the ferrite phase properties [14].

In Figure 8, yield strength values of samples taken from different regions are given. The lowest yield strength value of 460 MPa was obtained in HAZ. The highest yield strength value of 498 MPa was obtained at 2.2 mm thickness. The low difference between the thickness of 1.5 mm and 2.2 mm yield strength values is due to the similar grain sizes of the materials.

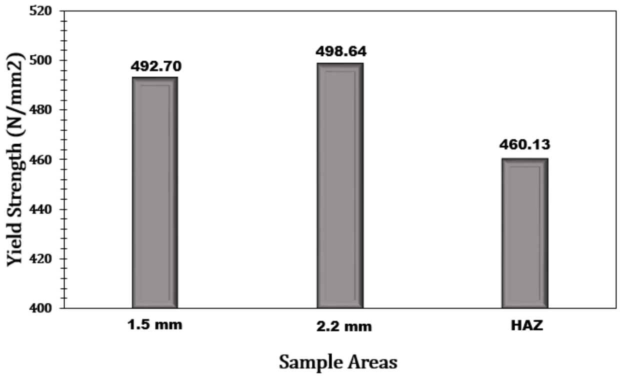

Figure 8. Yield strength values of samples taken from different areas

Figure 9 shows the percentage elongation values of samples taken from different regions. As observed, the highest value of 20 % was found at 1.5 mm thickness. Therefore, this material was found to be the most ductile. HAZ is shown in the figure as the location where the lowest percentage elongation value was obtained. This can be explained by the increased rigidity of the area.

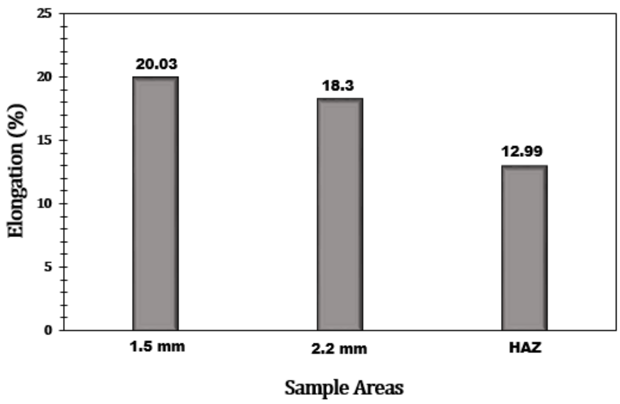

Figure 9. Elongation values of samples taken from different areas

When the related research is examined, it is determined that the total elongation values for all welding parameters were lower than the values of the base material, and the impact of welding parameters on total elongation was not regarded as significant [19].

It is concluded from the literature that the mechanical properties of thin and thick materials are quite similar in tensile tests. The welding seam reduces the maximum elongation and yield strength of TWBs. The tensile strength of TWBs is greater than that of base materials [20].

In Figure 10, the toughness values of the samples taken from different parts of the welded sheet are given. The toughness values of the samples were calculated from the area under the tensile curves. When the values are examined, it is seen that the increase in thickness has a decreasing effect on the toughness value. Likewise, the toughness value decreased after the welding process. The toughness value obtained in HAZ was measured as 814,181 J/cm^2. It can be asserted that the ductility of the material also decreases as a result of the decrease in the toughness value.

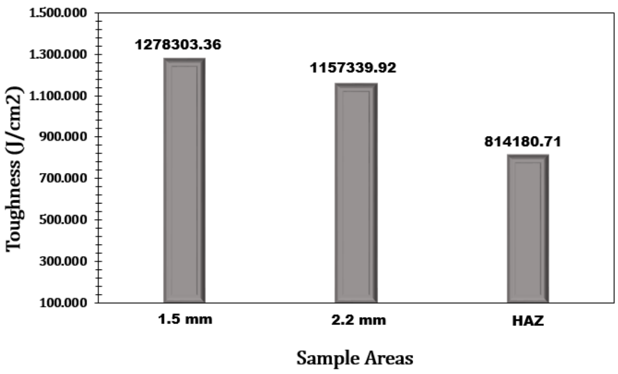

Figure 10. Toughness values of samples taken from different areas

Studies in the literature show that the ductility of TWBs decreases after welding. The level of reduction varies depending on the weld line direction, thickness ratio and welding method [1,21-23].

Figure 11 demonstrates the Vickers hardness values of the samples taken from different areas. When the values are examined, the highest value was obtained in the heat-affected zone of the formed part. The most prominent observation is that the high hardness values are within the heat-affected zones.

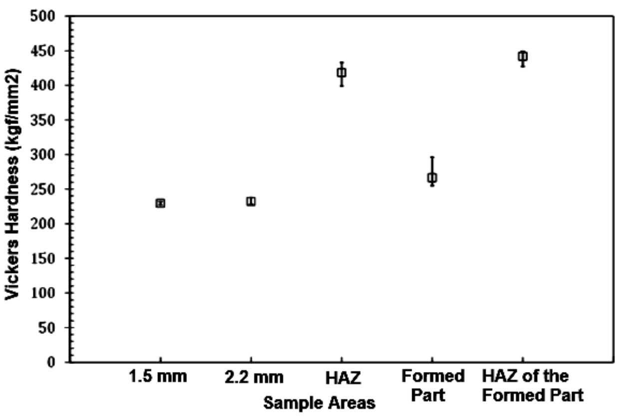

Figure 11. Vickers hardness values of samples taken from different areas

After the forming process, the hardness of the sample taken from the non-welded zone is higher than the hardness of the samples taken from different thicknesses. The hardness of the material was found to be increased after the forming process. The higher value of hardness of the material is related to the amount of martensite volume fraction it contains.

The welding process has been shown to increase tensile strength. Materials with high tensile strength have a harder and more brittle nature [24]. Related works of the literature have shown that the hardness values of the heat-affected zones of TWBs vary significantly due to the welding process [25-27].

4. Conclusions

In this study, a die design was made for tailor welded blank forming. Examinations were carried out on the product created with the die produced. As a result of the study it is concluded that:

- The grains coarsen in the microstructure with increasing thickness and phase changes occur in the heat-affected area.
- The highest strength value was obtained in the welded area.
- The lowest toughness value was obtained in the welded area.
- With the increase in thickness, the tensile strength, percentage elongation and toughness values decreased.
- The highest hardness values were obtained in the welded areas.
- The hardness of the material increased with the forming process.

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