

Article

Study of the Microstructure and Mechanical Property Relationships of Gas Metal Arc Welded Dissimilar Protection 600T, DP450 and S275JR Steel Joints

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Abstract: The need for combining dissimilar materials is steadily increasing in the manufacturing industry, and the resulting products are expected to always have high performance. While there are various methods available for joining such material pairs, one of the commonly preferred techniques is fusion welding. In this study, three different steel materials (Protection 600T, DP450, and S275JR) were joined using gas metal arc welding (GMAW) in different combinations (similar/dissimilar). The microstructure and mechanical properties of the joints were evaluated. Tensile test, Vickers microhardness (HV 0.1), bending, Charpy V-notch impact testing, and microstructure examinations were conducted to analyze the weld and heat-affected zone. The tensile strengths of the base metal materials Protection 600T, DP450, and S275JR were found to be 1524.73 ± 18.7 , 500.8 ± 10.4 , and 508.5 ± 9.5 MPa, respectively. In welded samples of similar materials, the highest efficiency was found to be 103.05% for DP450/DP450, while in dissimilar welded joints, it was 105.5% for the DP450/S275JR pair. Hardness values for the base materials Protection 600T, DP450, and S275JR were measured as 526.5 ± 10.5 , 153.8 ± 1.8 , and 162.5 ± 5.2 , respectively. In all welded samples, there was an increase in hardness in the weld zone (due to the welding wire) and the heat-affected zone (due to grain size refinement). While the impact energy values of similar material pairs were close to the base material impact energy values, the impact energy values of dissimilar material pairs varied according to the base materials. In addition, in joints made with similar materials, the bending force was close to the base materials, while a decrease in bending force was observed in joints formed with dissimilar materials. As a result, the welding of DP450 and S275JR materials was carried out efficiently. Protection 600T was welded with other materials, but its welding strength was limited to the strength of the material with low mechanical properties.

Keywords: dissimilar steel joints; gas metal arc; welding strength; mechanical properties; Protection 600T; DP450; S275JR steel



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1. Introduction

With the development of technology around the world, the need for high-strength steel materials is steadily increasing [1]. Therefore, it is very common in the industry to enhance the quality of materials/steels by using them in conjunction with other materials. There are various structures and systems produced by using dissimilar materials together. Especially in industrial applications and academic research, it is observed that high-strength steels such as armor steels, Twinning-induced plasticity (TWIP) steels, transformation-induced plasticity (TRIP) steels, and Dual Phase (DP) steels are used together with structural steels [2,3]. Furthermore, in specialized sectors such as nuclear power plants, oil refineries, and defense industries (including military vehicles), the utilization of dissimilar materials together holds significant importance [4,5]. Moreover, combining thin yet high-strength

components instead of thick ones offers the advantage of lightness [2]. Therefore, understanding the behaviors of materials in joining technologies (such as welding processes, etc.) is crucial in industries for their safe and efficient utilization [6]. In research conducted for this purpose, it has been determined that gas metal arc welding is one of the most effective techniques in joining dissimilar metal materials [7–11]. Gas metal arc welding of dissimilar metal materials typically involves joining at least two metals or alloys with different chemical compositions, melting temperatures, and thermal expansion properties [12]. Due to the change in physical properties in the weld zone during the process of joining materials with different chemical and mechanical characteristics, it is not easy to evaluate weld strength [13]. The proper and accurate execution of welding depends on selecting the appropriate welding process, process parameters, metal properties, and operating conditions [14]. Changing a parameter in the welding process significantly affects the welding properties. Due to the different thermal expansion of dissimilar metals, various undesired defects may occur during welding, such as stress corrosion cracking, residual stress formation, and disruption of stress concentration on both sides of the weld [15,16]. For this reason, some researchers focus on improving the mechanical properties of welded parts by controlling the parameters of the welding process [17]. The scientific literature on joining armor steels, which is the focus of this study, with other metals using gas metal arc welding has been carefully reviewed. Armor steels are materials with ultra-high strength and hardness, resistant to penetration by bullets and explosives. They are used in equipment resistant to ballistic impact and collision applications such as tanks, armored vehicles, and helicopter components [18].

S. Naveen Kumar et al. [19] observed that there was no study on the welding of armor steels of dissimilar qualities. Therefore, in their study, they joined Ultra-high Hard Armor (UHA) steel with Rolled Homogeneous Armor (RHA) steels using gas metal arc welding. RHA steel, which makes up 75% of armored combat vehicles, is used together with UHA steels, which have a high strength–weight advantage, to improve vehicle mobility. Austenitic Stainless Steel (ASS), Duplex Stainless Steel (DSS), and Low Hydrogen Ferritic (LHF) filler wires were used for welding. Researchers examined the effects of filler materials on the ballistic resistance of welded parts and the metallurgical characterization of both armor grade steel joints made using gas metal arc welding (GMAW).

Magudeeswaran et al. [20] evaluated the metallurgical properties of welded joints of Quenched and Tempered High Strength (Q&T) Steels used in armored vehicle manufacturing. In the welding of armor-grade Q&T steels, issues such as post-weld cold cracking caused by hydrogen in the heat-affected zone (HAZ) and softening of the HAZ due to the welding thermal cycle exist. The results revealed that these conditions adversely affect the ballistic properties of the steel.

Researchers [21] examined the effect of plate thickness on the microstructure and hardness of The Protection 500 series armor steels welded using the robotic GMAW method. The characterization of the weld using ER110S-G filler metal was completed by micro hardness tests and micro and macro structural examinations. It has been observed that as the plate thickness increases, the width of the softening zone decreases significantly, and the same amount of heat input slightly increases the microhardness. Depending on the heat changes during the welding of armor steel, their internal structure and, accordingly, their mechanical properties in different regions change.

Kaçar and Emre [22] investigated the gas metal arc welding capabilities of pairs formed from Armox 500T armor steel and AISI 304 steel. They stated that successful joining of these materials could be achieved with proper selection of welding parameters. Gas metal arc welding (GMAW) is commonly used for joining armor steels. Günen et al. compared the effects of different welding techniques (cold metal transfer arc welding (CMT) and hybrid plasma arc welding (HPAW)) on the microstructure and mechanical properties using GMAW. In all three different welding processes, both the hardness of the weld metal and the heat-affected zone were found to be higher than that of the base metal. Optimization of welding parameters has assisted in obtaining defect-free welds [23].

Qingguo Wang et al. [24] conducted multi-pass gas metal arc welding using ZGMn13Mo manganese steel and A514 low alloy steel, each having a thickness of 25 mm, with ER309L stainless steel welding wire.

In this study, Protection 600T armor steel, DP450 (Dual-phase steels), and S275JR steel (structural steel) were used. S275JR steel is a non-alloy, low carbon, mild steel grade. Dual-phase DP 450 steel, on the other hand, exhibits better cold formability and strength compared to low carbon and high-strength low-alloy steels [25]. They are preferred in the automotive industry due to their high strength and ductility [26,27]. Fusion welding processes such as gas metal arc welding (GMAW) are used to join DP steel materials [28]. These materials can be combined with each other due to their properties. As a result of these joining processes, engineering advantages such as cost and weight savings are achieved. Protection 600T material is high-resistance armor steel with ultra-high hardness against ballistic penetration. To the best knowledge of the researchers, there are no studies in the literature on the welding of Protection 600T material, which is frequently used in the manufacturing industry, with DP450 and S275JR materials. This study will contribute to the literature by presenting the joining of Protection 600T, DP450, and S275JR steels using the GMAW method.

As industrial needs change, high-strength steel types are also developing. When joining high-strength steels with other steels, it is very important to investigate the microstructure and mechanical properties in terms of welding safety. Metallurgical compatibility of strength and material pairs should be considered during the process. For this reason, the compatibility of Protection 600T, DP450, and S275JR steels was investigated in this study. Microhardness (HV 0.1), bending, impact, and tensile tests were performed for base metals and welded joints. The results were analyzed comparatively.

2. Material and Method

2.1. Properties of Steel Materials and Welding Wire

In the experiments, three different grades of steel materials were used. The first is Protection 600T steel (Miilux Oy, Manisa, Turkey), known for its ultra-high hardness and high resistance against ballistic penetration. The other material is DP450 steel (Ereğli Iron and Steel Factories, Zonguldak, Turkey) which is widely used among dual-phase steels for its high strength and good formability capability. Dual phase (DP) steels, particularly when compared to high-strength steels, have higher ultimate tensile strength (UTS) and lower yield strength. These characteristics have made DP steels indispensable in automotive applications [29]. The other material used in the study is S275JR (Yucel Pipe and Profile Industry Inc., Kocaeli, Turkey) general structural steel, which has good welding properties and strength and is used in many applications in construction and various industries, including production facilities and general buildings [30,31]. AWS A5.28:ER70S-A1 wire (Gedik Company, İstanbul, Turkey) with a diameter of 1.2 mm was used as welding wire. The yield strength of the welding wire is 460 MPa, tensile strength is 550–670 MPa and elongation is 22%. The preferred welding wire is used to join high-strength steels by gas arc welding [32–34]. The chemical compositions of steel materials and welding wire are given in Table 1.

Table 1. Chemical composition of the steels and the welding wire (wt%).

Material	C	Mn	Si	Cr	Ni	Mo	P	S	B	Fe
Protection 600T	0.45	0.80	0.70	0.50	3.0	0.60	0.015	0.004	0.003	balance
DP450	0.057	1.077	0.206	0.501	-	-	0.090	0.002	-	balance
S275JR	0.071	0.307	0.008	0.019	0.016	0.001	0.010	0.012	-	balance
ER 70 S-A1	0.1	1.1	0.6	-	-	0.5	-	-	-	balance

2.2. Preliminary Studies for the Welding Process

In this section, information about pre-welding preparations and the welding process is given. The samples to be welded were prepared in dimensions of 120 mm × 500 mm × 4 mm. The experimental design planned for welding base steels is given in Table 2, and the welding parameters are given in Table 3. The groove size created in the steel plates before welding is shown in Figure 1a. A 5 mm weld opening was opened at the joints of the plates at a V 60° groove angle, leaving a 2 mm root gap.

Table 2. Experimental design for welding.

Experimental Number	Material	Material
1	Protection 600T	Protection 600T
2	DP450	DP450
3	S275	S275
4	Protection 600T	S275
5	Protection 600T	DP450
6	DP450	S275

Table 3. Welding parameters.

GMAW Welding	Properties
Shielding gas	M21 (82% Ar + 18% CO ₂)
GMAW wire	ER 70 S-A1 GEKA Ø 1.2
Welding current (A)	120–130
Welding Voltage (V)	19–20
Welding speed (mm/s)	5.7

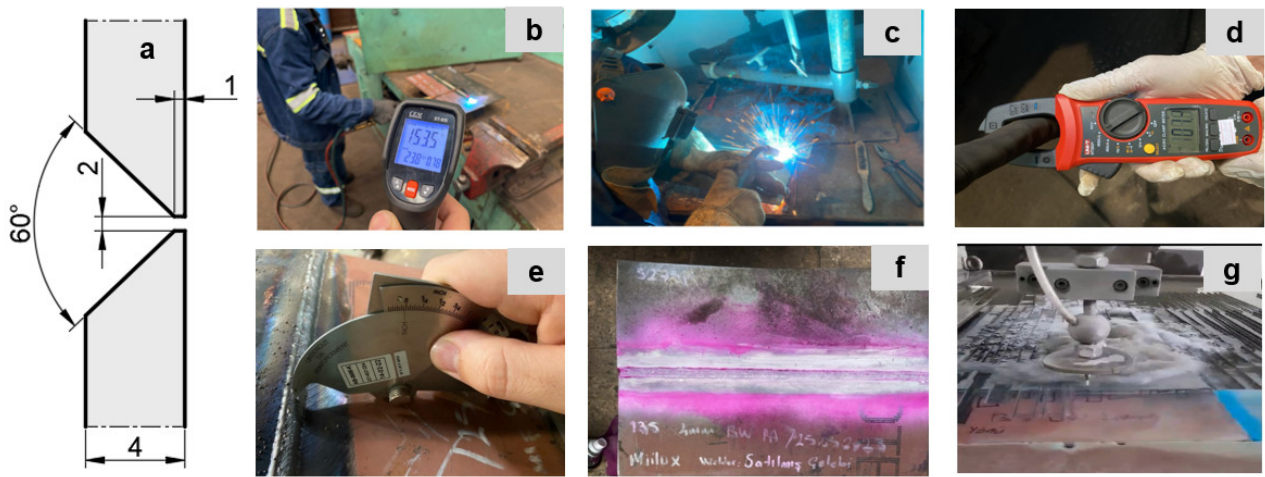


Figure 1. Preliminary preparation for welding and images taken during welding ((a). The groove size, (b). Thermal monitoring, (c). Welding process, (d). Measuring the welding voltage, (e). The weld cap height, (f). Penetrant test, (g). Specimen preparation process).

Due to the use of different grades of steel, carbon equivalences were examined. Since the lowest carbon equivalent (S275JR) was 0.40, the plates were annealed before welding at 150–190 °C. The pre-annealing temperature for the welding process was measured with a Cem DT-835 model (0–800 °C) thermometer (Figure 1b). A Lincoln LF-33 gas arc welding machine was used for the welding process (Figure 1c). Welding parameters are given in Table 3. The welding was conducted in four passes with 12 m³/sec gas flow using 82% Ar + 18% CO₂ shielding gas during welding and ER 70 S-A1 brand welding wire. Verification was made by measuring the welding voltage with a clamp meter during welding (Figure 1d). Post-welding cooling was carried out in a controlled manner by

wrapping the welded samples in stone wool. After welding, the weld cap height was measured using a weld cap gauge (Figure 1e). Finally, the weld seams were checked with a penetrant test (cleaner: CR60, penetrant: CR51, developer: CR70) (Figure 1f). The samples required for mechanical tests were cut using MJT4000 waterjet brand water jet with 4000 bar pressure and 300 mm/min cutting speed (Figure 1g).

2.3. Preparation of Mechanical Testing and Microstructure Samples

Figure 2 shows the dimensions of the samples used to determine the mechanical (tensile and bending, hardness, impact notch) and microstructural properties after the welding process. Hardness distribution in welded samples was conducted using the QNess 10 A+ brand micro-Vickers hardness tester by applying a 9.81 N pressure load for 15 s at 0.5 mm intervals, perpendicular to the weld line. To determine the impact energy, the impact absorption energy of the sample was measured using the JBN-300 pendulum testing machine, in accordance with the ISO 9016 standard [35], including the weld line and heat affected zone (HAZ). To determine the strength of the welded samples, a 60-ton Zwick Roell brand tensile device was used at a speed of 2 mm/min at room temperature. Finally, the material internal structure was examined with an electron microscope (Nikon Epiphot 200 Inverted Metallurgical Microscope, Artisan Technology Group, Kansas City, MO, USA). Welding efficiency is calculated using the following formula [9,36].

$$\text{Weld efficiency (\%)} = \frac{\text{UTS of welded joint (MPa)}}{\text{UTS of base material (MPa)}} \times 100 \quad (1)$$

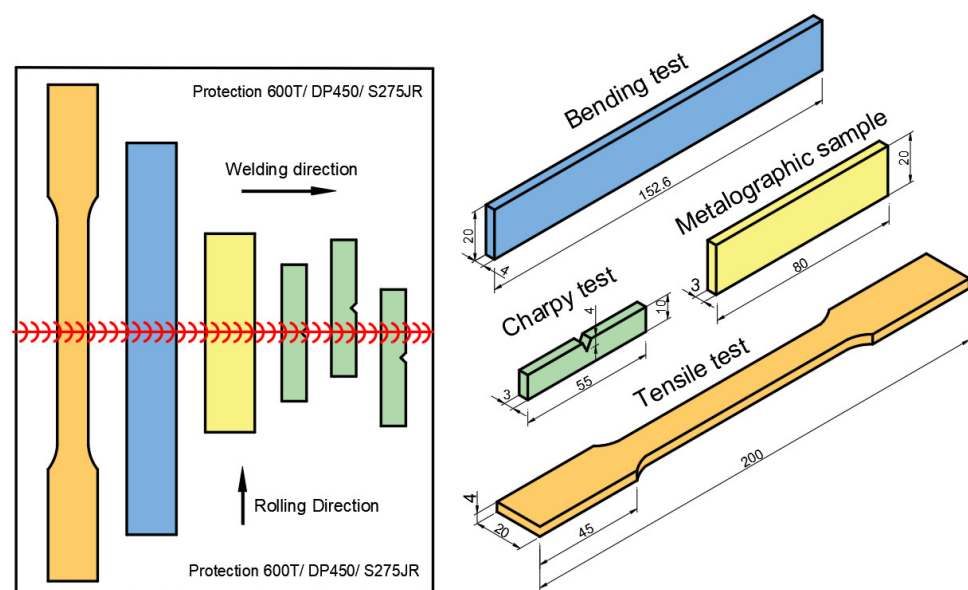


Figure 2. Dimensions of samples prepared for mechanical testing and microstructure.

3. Results

3.1. Mechanical and Microstructure Properties of the Base Materials

Tensile, microhardness, impact notch, and bending tests were performed to determine the mechanical properties of Protection 600T, DP450, and S275JR materials. As a result of the tensile test, ultimate tensile strength (UTS) was found to be 2141.98 ± 23.2 MPa for Protection 600T, 500.8 ± 10.4 MPa for DP450, and 508.15 ± 9.5 MPa for S275JR steel. Microhardness values were determined as 526.5 ± 10.5 HV, 153.8 ± 1.8 HV, and 162.5 ± 5.2 HV, respectively. Since Protection 600T has ultra-high hardness with its high carbon content, its mechanical properties were higher than the other two steel materials. Figure 3 shows the stress–strain graphs of the base materials. Accordingly, it is seen that Protection 600T has high strength but low elongation capability. When the fracture elongation of the base materials was compared, the highest elongation was obtained as $25.41 \pm 1.3\%$ in S275JR

steel, while it was as $23.95 \pm 1.7\%$ in DP450 and 4.34% for Protection 600T, respectively. The tensile test, microhardness, Charpy-V, and bending test results of the base materials are given in Table 4.

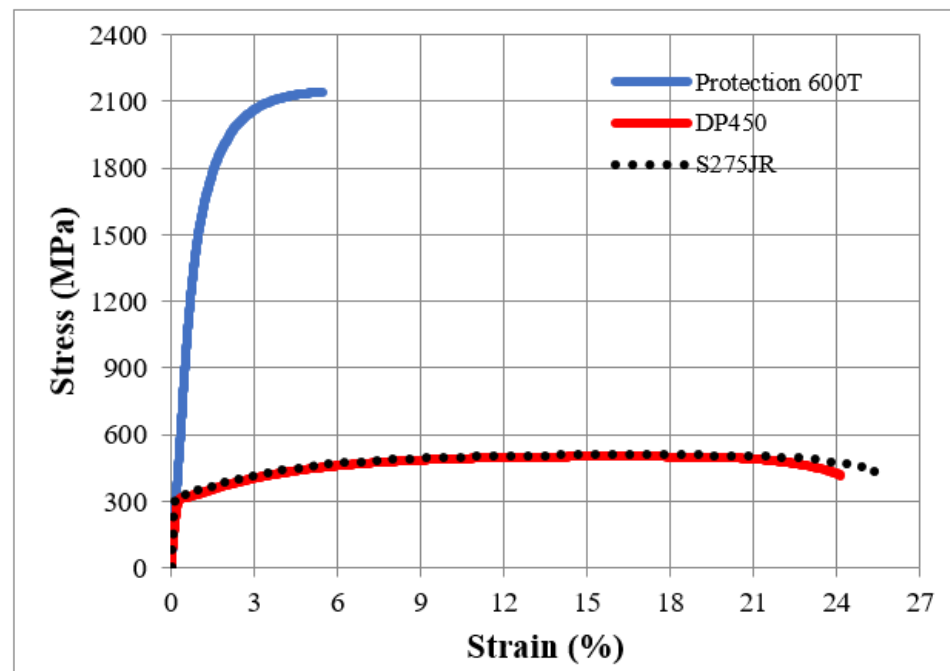


Figure 3. Stress and strain curves for base materials.

Table 4. Mechanical properties of base materials.

	Microhardness (HV)	Tensile Stress (MPa)	UTS (MPa)	Charpy-V (Joule)	Bending (kN)
Protection 600T	526.5 ± 10.5	1524.73 ± 18.7	2141.98 ± 23.2	75 ± 2.7	16.7 ± 0.4
DP450	153.8 ± 1.8	312.09 ± 11.3	500.8 ± 10.4	85 ± 3.4	11.0 ± 0.2
S275JR	162.5 ± 5.2	324.10 ± 8.2	508.5 ± 9.5	32 ± 1.2	9.3 ± 0.3

The toughness of a material is evaluated based on how much energy it absorbs. The higher the impact energy, the higher the expected toughness of the material [36]. Charpy V-notch impact energy (CVN) tests at room temperature ($21\text{ }^{\circ}\text{C}$) revealed the impact toughness of the welded samples as follows: Protection 600T exhibited a toughness of $75 \pm 2.7\text{ J}$, DP450 showed a toughness of $85 \pm 3.4\text{ J}$, and S275JR had a toughness of $32 \pm 1.2\text{ J}$. The reason for the highest impact toughness observed in the DP450 material could be attributed to the dense ferrite present in its microstructure, which enhances its energy absorption capability. Additionally, the lower energy absorption capability of Protection 600T compared to DP450 can be attributed to the dense martensite structure present in Protection 600T, which contributes to its hardness. The increase in material hardness tends to reduce the energy absorption capability of materials [37–40]. S275JR general structural steel exhibits variations in ductile behavior with temperature due to its ferritic structure. While S275JR steel becomes more brittle at low temperatures, its ductility increases at high temperatures [30]. To determine the deformation of base materials and welded samples, a 90° bend test was conducted on Protection 600T, DP450, and S275JR materials and in combinations. According to the bending test results, the maximum bending forces were determined to be $16.7 \pm 0.4\text{ kN}$, $11.0 \pm 0.2\text{ kN}$, and $9.3 \pm 0.3\text{ kN}$, respectively.

In Figure 4, the microstructure images of Protection 600T, DP450, and S275JR steels before welding are provided. When examining the microstructure of Protection 600T, it is observed that there is martensite and retained austenite inside the prior austenite matrix (Figure 4a). Prior austenite grain boundaries (PAGB) are clearly visible and exhibit

a fine-grained structure. This fine-grained martensitic structure provides high hardness and toughness to the armor steel [41]. Figure 4b–d depict the microstructure of DP450 steel. In dual-phase steels, large martensite islands are dispersed within a ferrite matrix. In dual-phase steels, mechanical properties are primarily dependent on the amount of martensite in the microstructure [42]. When examining the microstructure of DP450, it is observed that there is a dense ferrite matrix structure with a small amount of martensite. The grid method (with a grid spacing of 7.2 μm) was employed to determine the martensite phase ratio in DP450 steel (Figure 4d). The martensite phase ratio in DP450 steel was calculated as 13.3%. When examining the microstructure image of the base material of S275JR structural steel in Figure 4e,f, the black regions represent pearlite, while the lighter-colored regions represent ferrite [43]. The microstructure of S275JR steel consists of ferrite and pearlite grains, depending on the carbon content it contains [30].

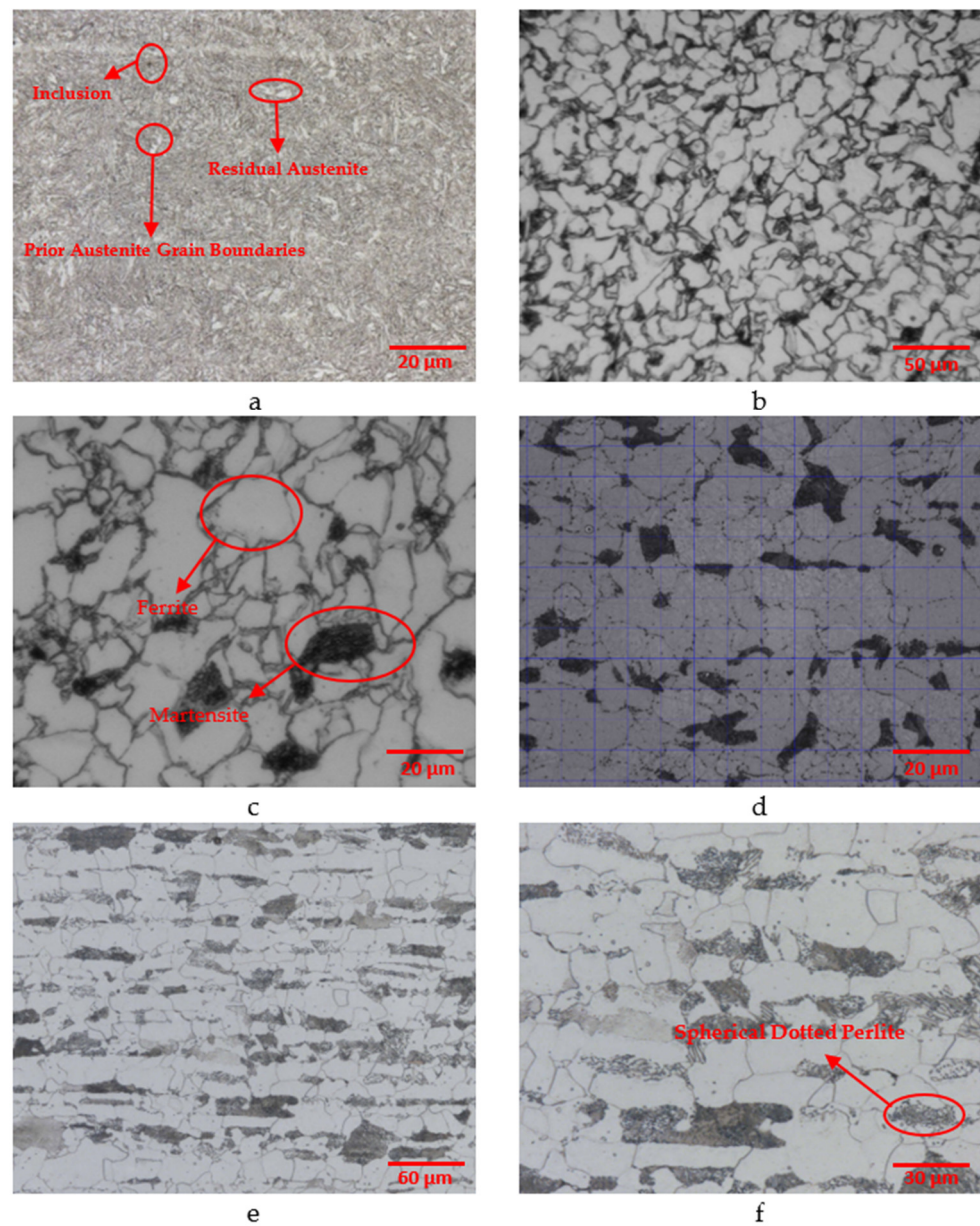


Figure 4. Base material microstructural images (a) Protection 600T (1000 $\times$), (b) DP450 (200 $\times$), (c) DP450 (1000 $\times$), (d) DP450 martensite phase ratio, (e) S275JR (200 $\times$), (f) S275JR (1000 $\times$) microstructure.

3.2. Metallographic Examination

3.2.1. Microstructure of Similar Materials after Welding

The microstructure of the HAZ and the weld zone of the Protection 600T material welded using ER70S-A1 wire is shown in Figure 5. Upon examination of the welded samples, it was determined that the transitions between the base material and the HAZ were homogeneous and smooth (Figure 5a). Although the base material has a densely tempered martensite structure, the HAZ was annealed at a medium temperature in its structure with the heat effect and tempered troostite, characterized by the gradual disappearance of the needle shape of the martensite, was observed (Figure 5b). When the microstructures shown in Figure 5c,d were examined, it was determined that the tempered martensite ratio was dominant in the weld metal, but in some parts of the martensite phase, there was a small amount of lath martensite phase aligned in parallel to form martensite beams or martensite areas. In addition, retained austenite and primary austenite grain boundaries and Weisner's tissue were detected in the weld area (Figure 5d).

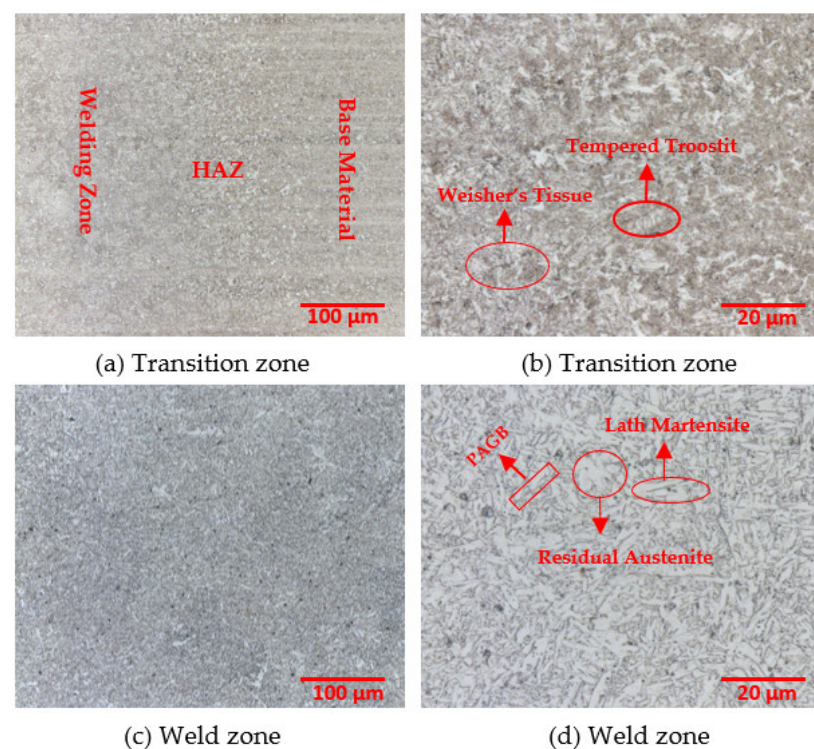


Figure 5. (a,b) Transition zone microstructures for the Protection 600T material pair (200×, 1000×) and (c,d) weld zone microstructures (200×, 1000×).

Figure 6 shows the post-welding HAZ and weld zone microstructure images of the DP450/DP450 material pair. It was determined that the martensite phase ratio was high in the HAZ (Figure 6a,b) and the ferrite ratio was high in the weld zone (Figure 6d,e). Although acicular ferrite formations were occasionally observed in the weld zone, dendritic ferrite formation was generally observed. HAZ formed a smooth transition zone with homogeneous distribution of ferrite and martensite phases. At the transition point from HAZ to the weld zone, martensite phases were arranged in columns, but upon reaching the welded structure, martensite phases were generally observed in the dendritic regions of the ferrite. The martensite phase ratio was determined to be approximately 27.2% in regions close to the melting zone (Figure 6c) and approximately 7.2% in the weld zone (Figure 6f).

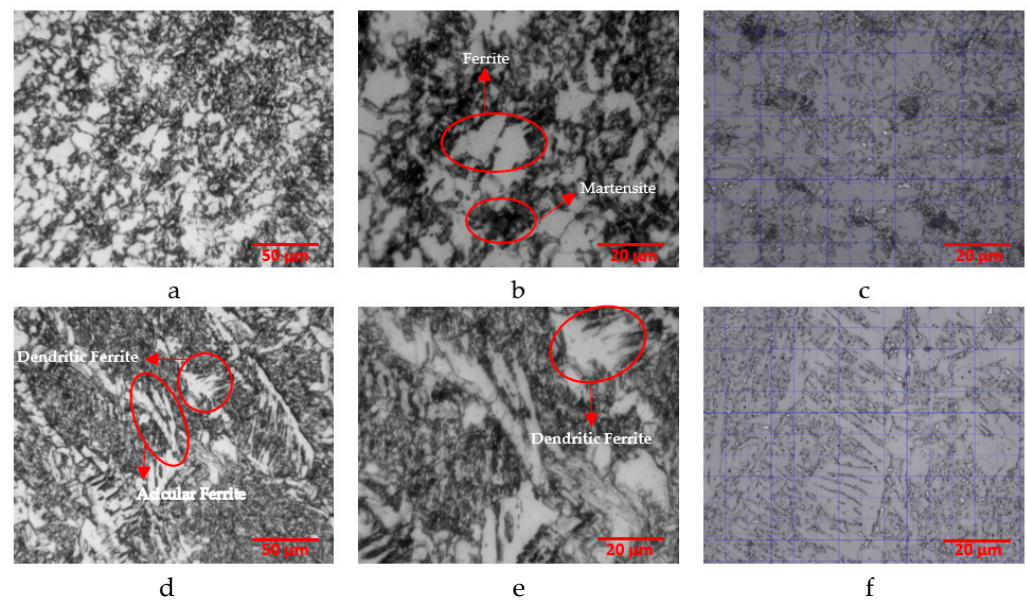


Figure 6. (a–c) HAZ region (500 $\times$, 1000 $\times$) and phase ratio, (d–f) weld zone microstructure images (500 $\times$, 1000 $\times$) and phase ratio for DP450/DP450.

In Figure 7, microstructure images of the HAZ and weld zone of the S275JR/S275JR material pair are provided. In the HAZ, a microstructure consisting of ferrite and lamellar pearlite phase (Figure 7a,b), and in the weld zone, a microstructure dominated by ferrite content (Figure 7c,d), formed. In addition, with the effect of the additional wire in the weld zone, although pearlite and Widmanstatten ferrite were observed in some areas, in general, intense acicular ferrite formation was detected. In the zones under the influence of heat, a soft transition was observed, and the ferrite and pearlite phases were distributed homogeneously, creating a soft transition zone. While pearlite and ferrite phases were arranged in columns at the transition boundary from the HAZ to the weld zone, it was observed that the ferrite phases generally turned into acicular ferrite in the weld zone.

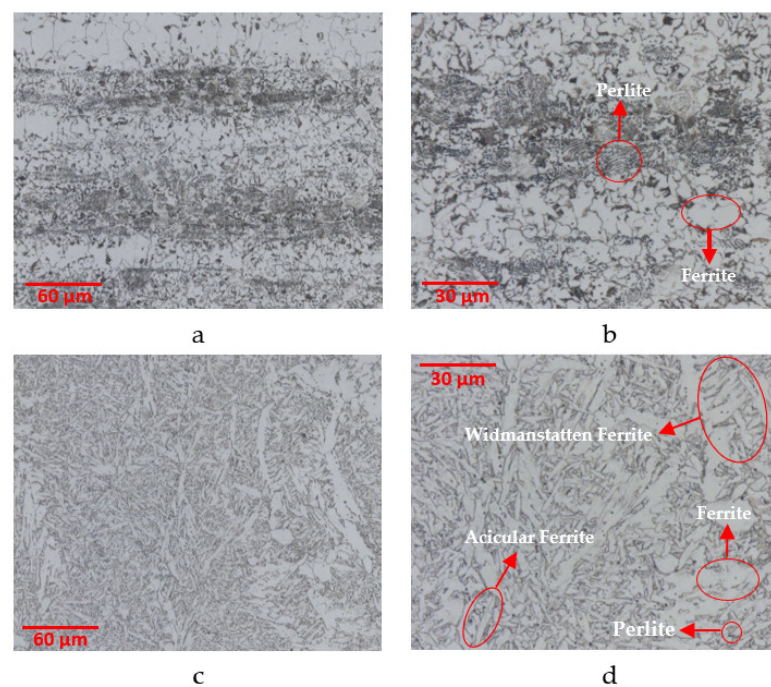


Figure 7. (a,b) HAZ region (500 $\times$, 1000 $\times$), (c,d) weld zone microstructure images (500 $\times$, 1000 $\times$) for material pair S275JR/S275JR.

3.2.2. Microstructure of Dissimilar Materials after Welding

Figure 8 shows the microstructure images of the transition zone and welding zone of the Protection 600T/S275JR material pair. It has been determined that acicular ferrite and martensite were dominant in regions in the weld zone, tempered troostite formation was seen, and primary austenite grain boundaries were observed. In the HAZ, the martensite phase was observed separately along with the ferrite and pearlite phase. In the HAZ, the martensite phase and ferrite–pearlite phases were detected as not homogeneously distributed and a sharp transition was observed.

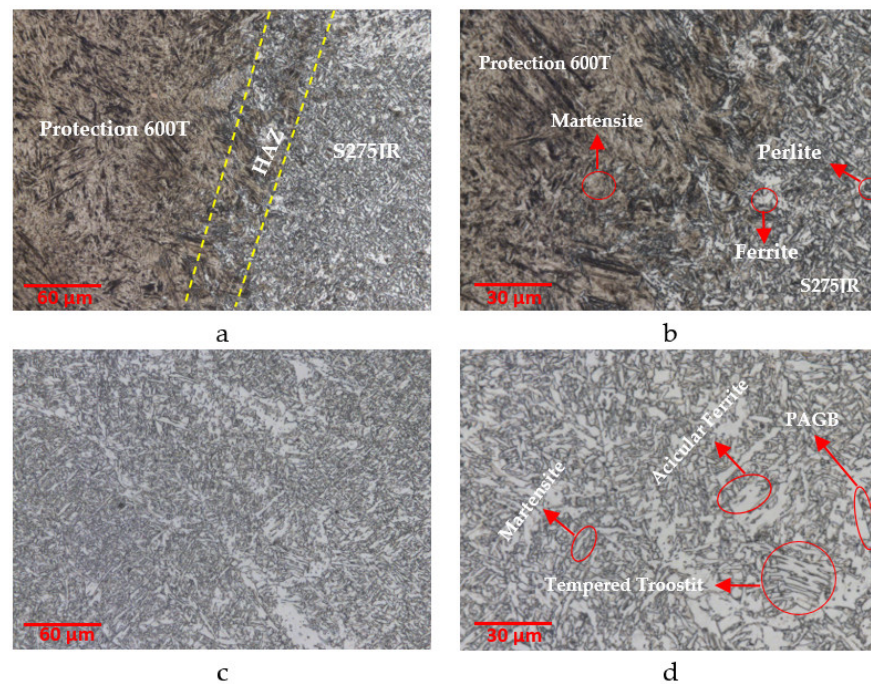


Figure 8. (a,b) HAZ (500 $\times$, 1000 $\times$), (c,d) weld zone microstructure images (500 $\times$, 1000 $\times$) for Protection 600T/S275JR material pair.

Figure 9 shows the microstructure images of the transition zone and welding zone of the DP450/Protection 600T material pair. Ferrite and martensite phases were observed in the HAZ (Figure 9a,b). In the region under the influence of heat, it has been determined that the martensite phase and ferrite phases were distributed homogeneously, and a smooth transition was observed. It was determined that ferrite and martensite were dominant in the weld zone, and residual austenite and occasionally primary austenite grain boundaries were observed (Figure 9c,d).

Figure 10 shows the microstructure images of the transition zone and welding zone of the DP450/S275JR material pair. In HAZ, a martensite phase was observed along with an acicular ferrite and pearlite phase. In the region under the influence of heat, the martensite phase and ferrite–pearlite phases were detected as not homogeneously distributed and a sharp transition was observed. Therefore, a boundary was formed in the HAZ region. It has been determined that acicular ferrite and needle martensite were dominant in the weld zone, and residual bainite and pearlite were observed. In the weld metal, intense acicular ferrite and martensite formations were observed due to the effect of the additional wire used.

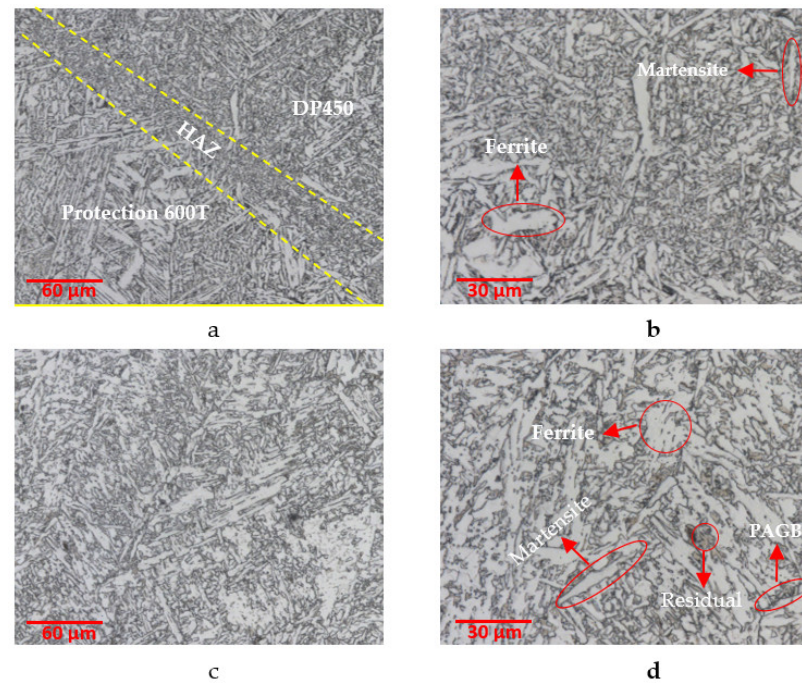


Figure 9. (a,b) HAZ (500 $\times$, 1000 $\times$), (c,d) weld zone microstructure images (500 $\times$, 1000 $\times$) for DP450/Protection 600T material pair.

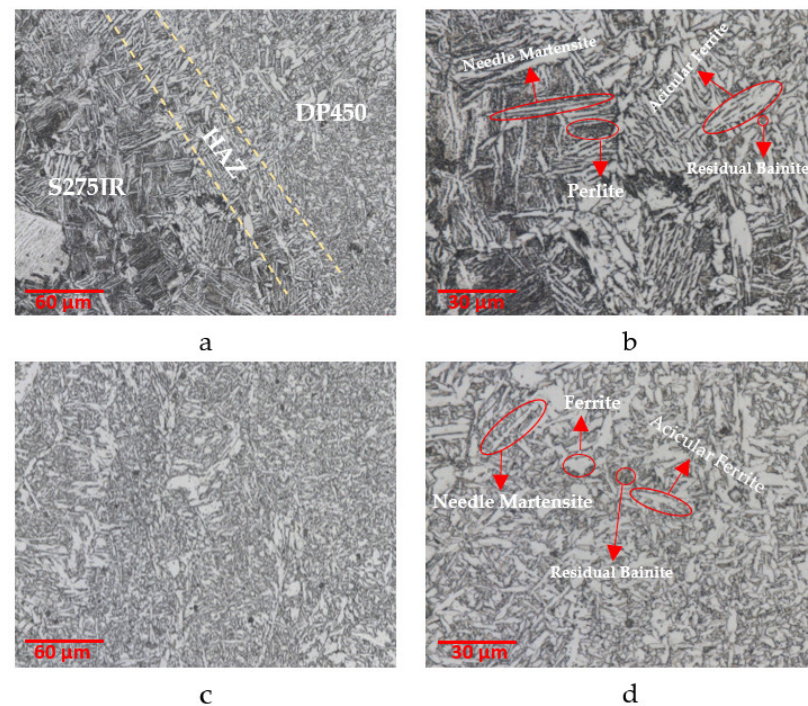


Figure 10. (a,b) HAZ (500 $\times$, 1000 $\times$), (c,d) weld zone microstructure images (500 $\times$, 1000 $\times$) for DP450-S275JR material pair.

3.3. Mechanical Test Examination

3.3.1. Microhardness

Microhardness measurements were taken after the Protection 600T, S275JR, and DP450 samples were welded using GMAW. Figure 11a–c shows the microhardness measurements of Protection 600T/Protection 600T, S275JR/S275JR, and DP450/DP450, while Figure 11d–f shows the microhardness measurements of welded samples in different combinations (Protection 600T/DP450, Protection 600T/S275JR, and DP450/S275JR). When examining

Figure 11a–c, it can be observed that the hardness increases towards the weld zone. This increase is believed to be due to the additional wire added to the weld zone during welding. Additionally, it has been determined that the microhardness value increases in the HAZ for all samples. For Protection 600T, the microhardness was determined to be 526.5 ± 10.5 HV in the base metal and 619 ± 20 HV in the weld zone. For DP450, it was 153.8 ± 1.8 HV in the base metal and 259 ± 8.1 HV in the weld zone. As for S275JR, it was 162.5 ± 5.2 HV in the base metal and 236 ± 9.3 HV in the weld zone. When examining Figure 11d,e, it is observed that microhardness values decrease from Protection 600T towards DP450/S275JR. This situation arises from the difference in mechanical properties of the materials. In Figure 11f, the highest microhardness values in the DP450/S275JR material pair were determined as follows from high to low: Heat Affected Zone (HAZ) (288 ± 26.5 HV), welding zone (232 ± 5.5 HV), and base metal (166 ± 6.3 HV).

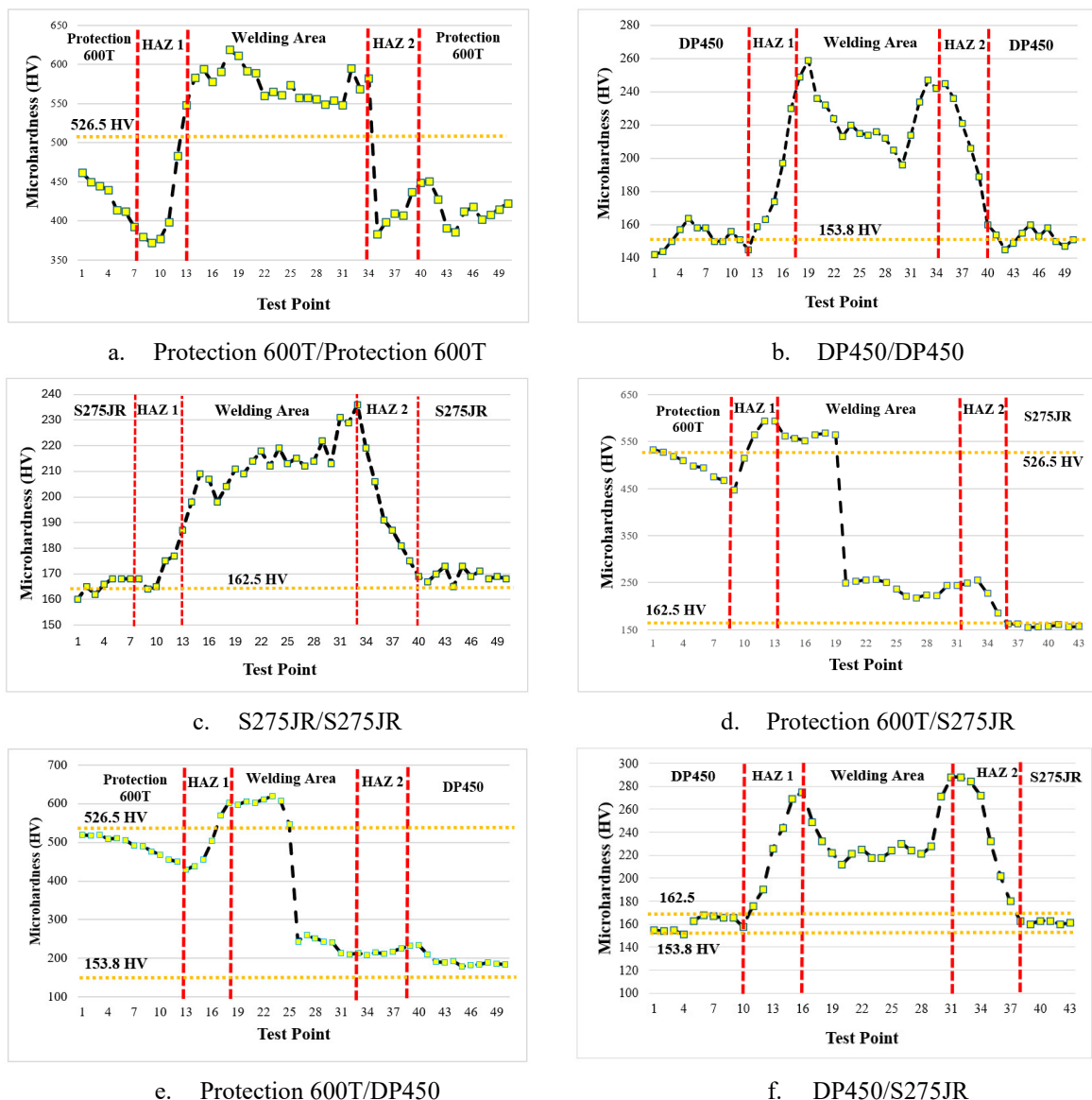


Figure 11. Post-weld microhardness measurements of Protection 600T, S275JR, and DP450 samples.

3.3.2. Tensile Test

Post-welding stress–strain graphs of Protection 600T, DP450, and S275JR materials (those close to the average value were selected) are given in Figure 11, while post-welding UTS, percentage elongation values, and welding efficiency relative to the base material are

given in Table 5. Post-welding UTS values of base materials were obtained as 1083.4 ± 3.99 , 516.5 ± 11 and 507.3 ± 5.7 MPa, respectively. When welding strengths were evaluated according to efficiency, they were determined as 49.4%, 103.05%, and 99.76%, respectively. It was determined that the weld strength of Protection 600T decreased compared to the base material UTS. It is thought that this is due to the additional welding wire.

Table 5. Mechanical properties after welding.

	Material 1	Material 2	UTS	Elongation%	Weld Efficiency (%)		
					Protection 600T	DP450	S275JR
1	Protection 600T	Protection 600T	1083.4 ± 3.99	1.25 ± 0.16	49.4	-	-
2	DP450	DP450	516.5 ± 11	16.2 ± 1.46	-	103.05	-
3	S275JR	S275JR	507.3 ± 5.7	18.4 ± 0.05	-	-	99.76
4	Protection 600T	S275JR	413.6 ± 1.6	4.3 ± 0.17	19.3	-	81.34
5	Protection 600T	DP450	360.6 ± 0.4	5.3 ± 0.2	16.87	72.01	-
6	DP450	S275JR	526.3 ± 3.5	15.8 ± 1.63	-	105.5	103.5

It can be said that the welding of DP450 and S275JR materials was successful compared to the base material. In the visual inspections and penetrant tests performed for all samples, it was determined that there were no weld defects such as open weld defects or voids on the surface.

When Figure 12 is examined, it can be observed that the stress–strain diagram of welded samples (Protection 600T/Protection 600T, DP450/DP450, and S275JR/S275JR) is similar to that of the base material. The indicators given in Figure 12 correspond to the same materials as the sample numbers shown in Table 5. In the welding of dissimilar materials, the UTS values for Protection 600T/S275JR were determined to be 413.6 ± 1.6 Mpa, for Protection 600T/DP450 it was 360.6 ± 0.4 Mpa, and the percentage elongation values were determined to be $4.3\% \pm 0.17$ and $5.3\% \pm 0.2$, respectively. It is observed that the UTS and efficiency decreased when Protection 600T was welded with other materials.

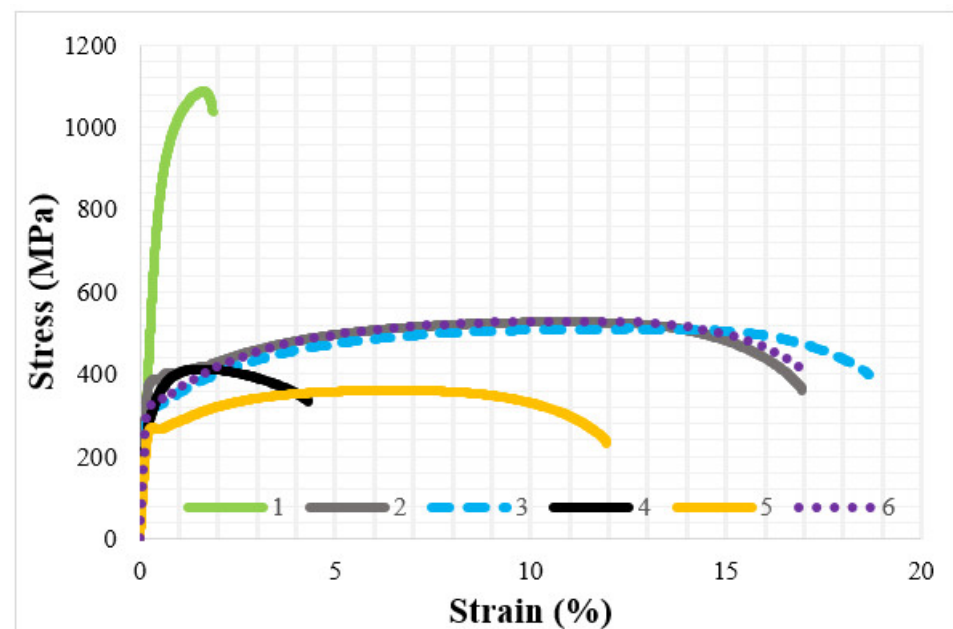


Figure 12. Post-welding stress–strain diagram.

The reason for this is likely to be the different chemical contents of the materials, the excessive coarsening of the grain structures due to the different cooling rates when passing from the base metal to the weld zone with the addition of welding wire. Similar findings are also reported in the literature. Badkoobeh et al. stated that in the joining of UNS S43000

Ferritic Stainless steel using laser welding, extremely coarse ferrite, and martensite were formed at the grain boundaries in the weld zone, and that this was responsible for the weak crystallographic texture in the zone [44].

In their study on the welding of armor steels, Çoban et al. stated that the peak temperatures and cooling rates that occur depending on the material thickness cause microstructural changes. This causes the hardness values of each zone to change. When the microstructural changes that caused this change were examined, it was stated that it caused the formation of a coarse-grained heat-affected zone in the region corresponding to the highest temperatures as well as the weld metal [21].

The welding strength of DP450/S275JR materials was determined as 526.3 ± 3.5 Mpa, the efficiency was determined as 105.5% compared to DP450 and 103.5% compared to S275JR, and the elongation was determined as 15.8 ± 1.63 . It can be said that the higher mechanical properties of DP450/S275JR compared to the base material are due to the non-homogeneous distribution of martensite phase and ferrite–perlite phases in the HAZ region and the dominance of acicular ferrite and needle-like martensites in the weld zone.

The fracture surfaces of the tensile test samples are given in Figure 13. It was observed that the fracture occurred as brittle fracture in the weld pairs with S275JR material. In the DP450/DP450 and Protection 600T/DP450 material pairs, the fracture was ductile and on the DP450 side. In DP450/S275JR, the breakage occurred on the DP450 material side. The rupture in the Protection 600 T/Protection 600 T welded joints occurred in the weld area. These data showed that the welded joints were made appropriately, and the rupture occurred where it was expected according to the strength of the base material.

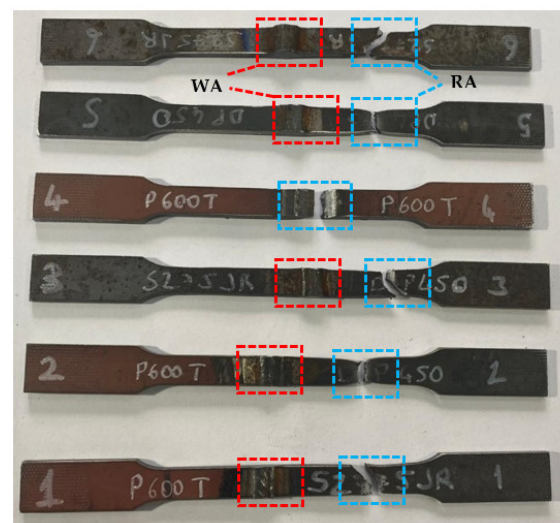


Figure 13. Tensile rupture morphologies of the welded sample (Welding Area: WA, Rapture Area: RA).

In the study, the joinability of three different materials (Protection 600T, DP450, and S275JR) was examined using ER70S-A1 welding wire. When the compatibility of the welding wire and base materials was evaluated as a result of post-welding HAZ and weld zone microstructure examinations, it was seen that the DP450/Protection 600T material pair was compatible. In the DP450/Protection 600T material pair, it was determined that while the martensite phase increased in the microstructure in the weld zone, the austenite and ferrite phases present in the structure increased the ductility relatively. However, considering the post-weld mechanical properties, the presence of phases in the material's microstructure has imparted ductility, resulting in a decrease in hardness and yield/tensile strength. In the welded samples of Protection 600T and S275JR, although tensile strength has increased, toughness has decreased, while hardness and strength have increased. When the microstructure and tensile diagrams of the DP450 and S275JR material pair are examined, it is determined that the materials and welding wire are well matched, leading to an increase in mechanical properties. In conclusion, the best results for welding the Protection 600T,

DP450, and S275JR material pairs were obtained in the following order: DP450/S275JR, Protection 600T/DP450, and Protection 600T/S275JR. There has been a significant decrease in strength after welding in the Protection 600T/Protection 600T material pair. The reason for this is the lower mechanical properties of the welding wire added to the weld zone compared to Protection 600T. In the DP450/DP450 and S275JR/S275JR material pairs, there was compatibility between the welding wire and the base materials, resulting in welding strength that was the same as or higher than the base material strength.

3.3.3. Bending Tests

To determine the deformation of the weld zones and base metals, a 90° bending test was applied after welding on similar and dissimilar Protection 600T, DP450, and S275JR materials. Bending test results are given in Table 6. The bending forces of 16.7 ± 0.4 , 11.0 ± 0.2 , and 9.3 ± 0.3 kN for the Protection 600T, DP450, and S275JR unwelded specimens and 16.8 ± 0.1 , 11.6 ± 0.9 and 10.4 ± 0.7 kN for the welded specimens, respectively, were close to each other. This indicates that the welding process was performed with high efficiency and the weld zone behaved similarly to the base material during the bend test. In dissimilar materials, however, it was determined that the bending force significantly decreased. This is likely due to the weld zone consisting of two different materials, leading to crack formation/propagation in the transition zones.

Table 6. Maximum bending test results of welded and unwelded (base material) samples.

	Material Pairs	Max. Bending Force (kN)
Base material	Protection 600T	16.7 ± 0.4
	DP450	11.0 ± 0.2
	S275JR	9.3 ± 0.3
Similar material	Protection 600 T/Protection 600T	16.8 ± 0.1
	DP450/DP450	11.6 ± 0.9
	S275JR/S275JR	10.4 ± 0.7
Dissimilar material	Protection 600 T/DP450	10.7 ± 0.1
	Protection 600 T/S275JR	9.4 ± 0.1
	DP450/S275JR	8.2 ± 0.4

3.3.4. Charpy V-Notch Tests

As a result of the CVN test, the impact energies of the base metals were found to be 75 ± 2.7 for Protection 600T, 85 ± 3.4 for DP450, and 32 ± 1.2 for S275JR. CVN test on welded samples was carried out by preparing samples from the weld zone and HAZ. Table 7 gives the impact energy values as a result of the CVN test after samples taken from HAZ 1, HAZ 2, and the welding area. While the impact energy values (87.3 ± 1.6 and 44.3 ± 1.3) for the HAZ region of Protection 600 T (1) and S275JR (3) materials were higher than the base material, the impact energy value (75.8 ± 8.4) for the HAZ region of DP450 (2) decreased. There was a decrease in the impact energy of the samples taken from the Protection 600 T, DP450, and S275JR welding area (57.0 ± 1.5 , 85 ± 3.4 , and 32 ± 1.2 , respectively). This is due to the fact that the welding wire added to the welding zone affected the microstructure. After welding different material pairs, CVN experiments were carried out in three different regions: the weld zone and the HAZ of each material. It has been determined that in the Protection 600 T/S275JR and DP450/S275JR material pairs, the impact energy in the HAZ region of S275JR increased compared to the base material. The reason for this is that the martensite phase was formed along with the ferrite and pearlite phase in the HAZ region of S275JR under the influence of heat. A decrease in the impact energies of the samples taken from the Protection 600 T and DP450 HAZ region and the welding region of all material pairs was determined. The fracture surfaces of the

selected samples after the CVN impact test are given in Figure 14. While fracture occurred in Protection 600T/Protection 600T material pair after CVN, no rupture occurred in other welded specimens. A ductile fracture was observed in all samples.

Table 7. Impact energy after HAZ 1, HAZ 2, and welding zone Charpy V-notch test.

	Material Pairs	HAZ 1	Welding Zone	HAZ 2
1	Protection 600 T/Protection 600T	87.3 ± 1.6	57.0 ± 1.5	-
2	DP450/DP450	75.8 ± 8.4	55.7 ± 0.2	-
3	S275JR/S275JR	44.3 ± 1.3	25.9 ± 2.3	-
4	Protection 600 T/DP450	47.1 ± 1.0	37.9 ± 6.2	55.1 ± 7.6
5	Protection 600 T/S275JR	69.7 ± 4.6	48.79 ± 1.7	40.4 ± 1.2
6	DP450/S275JR	60.1 ± 2.0	46.47 ± 1.8	51.0 ± 0.9

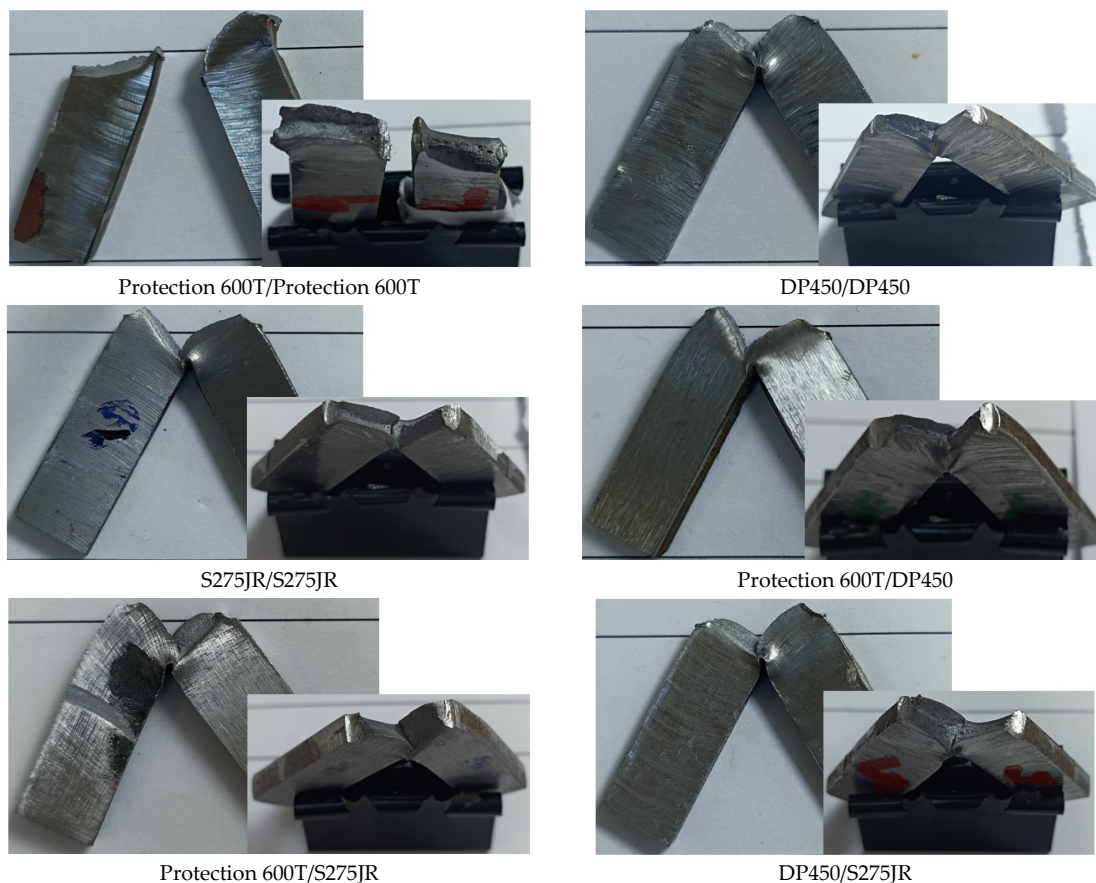


Figure 14. Fracture surfaces of selected samples after Charpy V-notch test.

4. Discussion

Joining materials with different properties is one of the significant issues in the industry since it enhances the functionality and efficiency of designs. Since dissimilar metal materials cannot be produced in the same process and do not have the same properties, they are joined using different methods. In this study, welding of three types of materials in both similar and dissimilar material combinations was aimed, and their welding capabilities were examined both mechanically and microstructurally.

The different grades of steel materials used in the experiments are Protection 600T, DP450, and S275JR general structural steel. The GMAW method was employed to join the steel materials. The thickness of the steel plates was 5 mm. Prior to welding, preparations were made by opening welding grooves (V 60° and 2 mm root gap), and welding procedures

were applied using a multi-pass technique. Pre-welding preparations and post-welding quality control procedures are given in Figure 1.

In hardness measurements, the hardness values of the base materials were determined as 526.5 HV for Protection 600T, 153.8 HV for DP450, and 162.5 HV for S275JR. In similar materials (Figure 11a–c), a decrease in hardness was observed as approaching HAZ, while an increase in hardness was identified in the weld zone due to the effect of the welding wire.

The decrease in the hardness observed in the HAZ can be explained by the grain growth in the microstructure due to the influence of heat. The microhardness values in the weld zone were determined as 619 HV for Protection 600T, 259 HV for DP450, and 236 HV for S275JR. In dissimilar materials (Figure 11d,e), an increase in hardness was observed when passing from Protection 600T to the weld zone, while a decrease in hardness occurred when transiting to the other material. This decrease is believed to be due to the relatively lower hardness of the DP450 and S275JR materials. In the DP450/S275JR material pair, microhardness values were determined as weld zone (249 HV/271 HV, respectively) and base metal (168 HV/163 HV, respectively).

Zhang et al. conducted post-weld mechanical tests in their study on laser welding of Nano-Scale Precipitation-Strengthened (NPS) steels. They noted that the highest value in microhardness measurements was in the weld zone, followed by the HAZ, and the lowest value was in the base material. The reason for this is that the elements in the new phase formed in the source region do not have time to precipitate and form the second phase due to the cooling rate. As a result, the elements remaining in the phase dissolve to a large extent in the alloy, causing the solid solution to strengthen after welding [45].

Tensile test results of DP450/DP450, S275JR/S275JR, and DP450/S275JR materials show that the welding was carried out successfully. The obtained welding strength efficiency of 100% in the tensile test demonstrates the successful joining observed in both macro and microstructures. In the welded joints of DP450 and S275JR materials, fracture occurred in the DP450 material. The strength of welding area was higher than DP450 material. In this case, it can be said that the DP450 and S275JR material pair are compatible with each other and with the welding wire, resulting in improved mechanical properties. The rupture in the welded joints of the Protection 600T/Protection 600T material pair occurred in the welding area. Although Protection 600T had higher strength (2141.98 MPa), the desired strength could not be achieved in the welding area due to the mechanical properties of the welding wire (550–670 MPa).

In the case of joining Protection 600T with DP450 and Protection 600T with S275JR materials, a similar situation has been observed. In the DP450/Protection 600T material pair, an increase in the martensitic phase in the microstructure was observed in the weld area, while the existing austenite and ferrite phases in the structure had relatively increased ductility. In the samples welded with Protection 600T and S275JR, although the tensile strength increased, the toughness decreased and an increase in hardness and strength was detected. The DP450/S275JR welded joint has shown positive results that it can be used successfully in different applications (transportation, vehicle body manufacturing, etc.). Protection 600T/DP450 welded joints (with the armor feature of Protection 600T and the formability of DP450 steel) can be used for military purposes.

Bending tests provide important information about the deformation capabilities of welded joints and the ductility and toughness of the welded joints. In the bending test, the deformation resulting from the applied force is converted into data. The curvature of the deformed samples obtained as a result of the test gives an idea about the deformation ability. Bending test results were determined as 16.7 kN, 11.0 kN, and 9.3 kN for Protection 600T, DP450, and S275JR unwelded samples and 16.8 kN, 11.6 kN, and 10.4 kN for welded samples, respectively. According to these results, it was determined that the bending strength of the welded samples was better than the base material. Welding has been conducted successfully on similar materials. In dissimilar materials, the bending force remained below the base material performance. It can be said that this is because the

welding area consists of two different materials and the transition zones cause crack formation/crack propagation.

Charpy impact tests were carried out at 21 °C room temperature, and impact strengths were compared with samples prepared from the weld zone and the HAZ. For similar materials (Protection 600 T and S275JR), the impact energy values in the HAZ increased compared to the base material, while in DP450, the impact energy value decreased in the HAZ. In these material pairs, there was a decrease in the impact energy of the samples taken from the welding area. In the Protection 600 T/S275JR and DP450/S275JR material pairs, it was determined that the impact energy in the HAZ of S275JR increased compared to the base material.

A decrease in the impact energies of the samples taken from the HAZ of the Protection 600 T/DP450 material pair and from the weld area of all dissimilar material pairs was determined. Impact toughness is affected by many parameters. The most important factor affecting impact toughness is the irregular distribution in the microstructure in the weld area. The impact toughness value of welded joints is directly related to ferrite, bainite content and grain size [46]. Therefore, in the study, different impact strengths were measured in impact notch samples taken from different regions.

5. Conclusions

This study examined the joinability of Protection 600T, DP450, and S275JR steels, which have different mechanical and microstructural properties, using the GMAW method. Weld joints of base materials and similar/dissimilar steels were analyzed by mechanical tests and optical examination. The obtained results are presented below.

The welding efficiency of Protection 600T, DP450, and S275JR, which are similar material pairs, was determined as 49.4%, 103.05%, and 99.76%, respectively. The reason why the efficiency is relatively low in Protection 600T is that the welding strength depends on the mechanical properties of the additional welding wire. In this study, welding of similar material pairs was successfully achieved.

In dissimilar material pairs (Protection 600T/S275JR, Protection 600T/DP450, and DP450/S275JR), the welding efficiency was determined as 19.3/81.34%, 16.87/72.01%, and 105.5/103.5%, respectively. The welding of the DP450/S275JR material pair was successfully achieved.

In the DP450/DP450, S275JR/S275JR, and DP450/S275JR pairs, it was determined that there was microstructure compatibility between the welding wire and the base materials. Therefore, the strength of the base material and welded samples was the same or higher.

The microhardness of the base materials was determined as 526.5 ± 10.5 , 153.8 ± 1.8 , and 162.5 ± 5.2 HV for Protection 600T, DP450, and S275JR, respectively. An increase in hardness values in the HAZ and welded zone was determined in all welded samples. After the tensile test, it was observed that the rupture in the welded joints occurred from the side with relatively low strength in the material pairs.

As a result of the CVN test, while there was an improvement in the HAZ in the welding of similar materials, there was a decrease in the absorbed energy values in the samples taken from the welding area. In dissimilar materials, there was an increase in the HAZ and welded zone compared to the S275JR material, while there was a decrease compared to the other two materials. As a result of the bending test, the bending force in welded similar material pairs was improved compared to the base material. There was a decrease in bending force in dissimilar materials.

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References

- Kocadağıstan, M.E.; Çınar, O. Investigation of the weldability of AISI 430 and HARDON 500 steels by CMT method. *Pamukkale Univ. J. Eng. Sci.* **2023**, *30*, 1–9.
- Kılıç, S.; Öztürk, F. Comparison of Performances of Commercial TWIP900 and DP600 Advanced High Strength Steels in Automotive Industry. *J. Fac. Eng. Archit. Gazi Univ.* **2016**, *31*, 567–578.
- Májlinger, K.; Kalácska, E.; Spena, P.R. Gas metal arc welding of dissimilar AHSS sheets. *Mater. Des.* **2016**, *109*, 615–621. [\[CrossRef\]](#)
- Hanninen, H.; Aaltonen, P.; Brederholm, A.; Ehrnsten, U.; Gripenberg, H.; Toivonen, A.; Jorma, P.; Virkkunen, I. Dissimilar metal weld joints and their performance in nuclear power plant and oil refinery conditions. *VTT TIEDOTTEITA* **2006**, *2347*, 208.
- Derya, A.; Anil, İ.; Kırık, İ. Investigation of the microstructural and mechanical properties of AISI 1020/RAMOR 500 steel couple joined by friction welding. *Dicle Univ. J. Eng.* **2022**, *13*, 51–56.
- Rončák, J.; Adam, O.; Zobač, M. Electron beam welding of AlCoCrFeNi2. 1 high entropy alloy to EN 1.4301 austenitic steel. *J. Phys. Conf. Ser.* **2023**, *2443*, 012009. [\[CrossRef\]](#)
- Abioye, T.; Olugbade, T.; Ogedengbe, T. Welding of dissimilar metals using gas metal arc and laser welding techniques: A review. *J. Emerg. Trends Eng. Appl. Sci.* **2017**, *8*, 225–228.
- Kaçar, R.; Emre, H.E. Effects of welding methods on the mechanical properties of joining dissimilar steel couple. *J. Fac. Eng. Archit. Gazi Univ.* **2018**, *33*, 255–265.
- Özturan, A.B.; İrsel, G.; Güzey, B.N. Study of the microstructure and mechanical property relationships of gas metal arc welded dissimilar Hardox 450 and S355J2C+ N steel joints. *Mater. Sci. Eng. A* **2022**, *856*, 143486. [\[CrossRef\]](#)
- Mvola, B.; Kah, P.; Martikainen, J. Dissimilar Ferrous Metal Welding Using Advanced Gas Metal Arc Welding Processes. *Rev. Adv. Mater. Sci.* **2014**, *38*, 125–137.
- Devaraj, J.; Ziout, A.; Qudeiri, J.E.A. Grey-based taguchi multiobjective optimization and artificial intelligence-based prediction of dissimilar gas metal arc welding process performance. *Metals* **2021**, *11*, 1858. [\[CrossRef\]](#)
- Chaudhari, R.; Loharkar, P.; Ingle, A. Applications and challenges of arc welding methods in dissimilar metal joining. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *810*, 012006. [\[CrossRef\]](#)
- Erhard, A.; Munikoti, V.; Brekow, G.; Tessaro, U.; Tscharncke, D. Modeling for the improvement of dissimilar weld inspection. In Proceedings of the 16th World Conference on NDT, Montreal, QC, Canada, 30 August–3 September 2004.
- Bayock, F.N.; Kah, P.; Mvola, B.; Layus, P. Experimental review of thermal analysis of dissimilar welds of High-Strength Steel. *Rev. Adv. Mater. Sci.* **2019**, *58*, 38–49. [\[CrossRef\]](#)
- Maurya, B.K.; Pretap, B.; Kumar, A.; Rana, G. Experimental analysis of dissimilar metal welds of mild steel and stainless steel. *Int. Res. J. Eng. Technol.* **2017**, *4*, 1744–1748.
- Bajpei, T.; Chelladurai, H.; Ansari, M.Z. Experimental investigation and numerical analyses of residual stresses and distortions in GMA welding of thin dissimilar AA5052-AA6061 plates. *J. Manuf. Process.* **2017**, *25*, 340–350. [\[CrossRef\]](#)
- Singh, S.; Kumar, V.; Kumar, S.; Kumar, A. Variant of MIG welding of similar and dissimilar metals: A review. *Mater. Today Proc.* **2022**, *56*, 3550–3555. [\[CrossRef\]](#)
- Saxena, A.; Kumaraswamy, A.; Reddy, G.M.; Madhu, V. Influence of welding consumables on tensile and impact properties of multi-pass SMAW ArmoX 500T steel joints vis-a-vis base metal. *Def. Technol.* **2018**, *14*, 188–195. [\[CrossRef\]](#)
- Kumar, S.N.; Balasubramanian, V.; Malarvizhi, S.; Rahman, A.H.; Balaguru, V. Effect of failure modes on ballistic performance of Gas Metal Arc welded dissimilar armour steel joints. *CIRP J. Manuf. Sci. Technol.* **2022**, *37*, 570–583. [\[CrossRef\]](#)
- Magudeeswaran, G.; Balasubramanian, V.; Reddy, G.M. Metallurgical characteristics of armour steel welded joints used for combat vehicle construction. *Def. Technol.* **2018**, *14*, 590–606. [\[CrossRef\]](#)
- Çoban, O.; Gürol, U.; Erdöl, S.; Koçak, M. Effect of Plate Thickness on The Microstructure and Hardness of Robotic Fillet Welded Armour Steels. In Proceedings of the 6th International Conference on Welding Technologies and Exhibition (ICWET'21), Hatay, Turkey, 13–15 October 2021.
- Kaçar, R.; Emre, H.E. Determination of the Mechanical Properties of Gas Metal Arc Welded ArmoX Steels. *AKU J. Eng. Appl. Sci.* **2018**, *1*, 15–23.
- Günen, A.; Bayar, S.; Karakaş, M.S. Effect of different arc welding processes on the metallurgical and mechanical properties of Ramor 500 armor steel. *J. Eng. Mater. Technol.* **2020**, *142*, 021007. [\[CrossRef\]](#)
- Wang, Q.; Kai, G.; Zhang, X.; Long, X.; Wei, Y. Microstructure and Properties of ZGMn13Mo/A514 Dissimilar Steel Multi-pass Welding. *Trans. Indian Inst. Met.* **2024**, *77*, 1117–1126. [\[CrossRef\]](#)
- Ranji, A.R.; Gishanim, S.N.; Alirezaee, S. Fatigue assessment of welded joints and crack growth considering residual stress. *Eng. Res. Express* **2023**, *5*, 045001. [\[CrossRef\]](#)

26. Mukherjee, K.; Ramazani, A.; Yang, L.; Prahiet, U.; Bleck, W.; Reisgen, U.; Schleser, M.; Abdurakhmanov, A. Characterization of gas metal arc welded hot rolled DP600 steel. *Steel Res. Int.* **2011**, *82*, 1408–1416. [CrossRef]
27. Kuril, A.A.; Ram, G.J.; Bakshi, S.R. Microstructure and mechanical properties of keyhole plasma arc welded dual phase steel DP600. *J. Mater. Process. Technol.* **2019**, *270*, 28–36. [CrossRef]
28. Burns, T. *Weldability of a Dual-Phase Sheet Steel by the Gas Metal Arc Welding Process*; University of Waterloo: Waterloo, ON, Canada, 2010.
29. Ghadbeigi, H.; Pinna, C.; Celotto, S. Failure mechanisms in DP600 steel: Initiation, evolution and fracture. *Mater. Sci. Eng. A* **2013**, *588*, 420–431. [CrossRef]
30. Brnic, J.; Turkalj, G.; Niu, J.; Canadija, M.; Lanc, D. Analysis of experimental data on the behavior of steel S275JR—Reliability of modern design. *Mater. Des.* **2013**, *47*, 497–504. [CrossRef]
31. Çevik, B. Effect of welding processes on mechanical and microstructural properties of S275 structural steel joints. *Mater. Test.* **2018**, *60*, 863–868. [CrossRef]
32. Wu, W.; Zhang, T.; Chen, H.; Peng, J.; Yang, K.; Lin, S.; Wen, P.; Li, Z.; Yang, S.; Kou, S. Effect of Heat Input on Microstructure and Mechanical Properties of Deposited Metal of E120C-K4 High Strength Steel Flux-Cored Wire. *Materials* **2023**, *16*, 3239. [CrossRef]
33. Evci, C.; Işık, H.; Macar, M. Effect of welding wire and groove angle on mechanical properties of high strength steel welded joints: Einfluss von Schweißzusatzdraht und Fugenwinkel auf die mechanischen Eigenschaften von Schweißverbindungen aus hochfestem Stahl. *Mater. Und Werkst.* **2017**, *48*, 912–921. [CrossRef]
34. Mahlalela, S.S.; Pistorius, P.G.H. Influence of alloying elements and cooling rate on the presence of delta ferrite in modified 9Cr–1Mo as-welded microstructure produced by gas–metal arc welding. *Weld. World* **2023**, *67*, 1169–1180. [CrossRef]
35. EN ISO 9016:2012; Destructive Tests on Welds in Metallic Materials—Impact Tests—Test Specimen Location, Notch Orientation and Examination. ISO: Geneva, Switzerland. Available online: <https://www.iso.org/standard/81122.html> (accessed on 14 May 2024).
36. Yakup, K.; Atar, F. An Investigation of Joinability of Stainless Steel and The Low Carbon Steel Materials by Mig Welding Method. *Eng. Sci.* **2020**, *15*, 89–99.
37. Sirohi, S.; Gupta, A.; Pandey, C.; Vidyarthi, R.S.; Guguloth, K.; Natu, H. Investigation of the microstructure and mechanical properties of the laser welded joint of P22 and P91 steel. *Opt. Laser Technol.* **2022**, *147*, 107610. [CrossRef]
38. Metin, M.; Mehmet, Ü.; Gören, H.A. Comparison of the Hardness, Tensile and Notch Impact Properties of C95200 and C95300 Al Bronze Alloys. *Sinop Univ. J. Nat. Sci.* **2023**, *8*, 216–228.
39. Senčič, B.; Šolić, S.; Leskovšek, V. Fracture toughness—Charpy impact test—Rockwell hardness regression based model for 51CrV4 spring steel. *Mater. Sci. Technol.* **2014**, *30*, 1500–1505. [CrossRef]
40. Al-Qawabehe, U.F. Effect of heat treatment on the mechanical properties, Micro hardness, and impact energy of H13 alloy steel. *Int. J. Sci. Eng. Res.* **2017**, *8*, 100–104.
41. Gürol, U.; Karahanet, T.; Erdöl, S.; Coban, O.; Baykal, H.; Koçak, M. Characterization of Armour Steel Welds Using Austenitic and Ferritic Filler Metals. *Trans. Indian Inst. Met.* **2022**, *75*, 757–770. [CrossRef]
42. Indhu, R.; Divyaet, S.; Tak, M.; Soundarapandian, S. Microstructure development in pulsed laser welding of dual phase steel to aluminium alloy. *Procedia Manuf.* **2018**, *26*, 495–502. [CrossRef]
43. Çetinkaya, C.; Akay, A.; Arabacı, U.; Findık, T. Effect of Primer Coating Applied To S235JR Material on Submerged Arc Weldability. *J. Polytech.* **2022**, *25*, 1335–1348.
44. Badkoobeh, F.; Mostaan, H.; Sonboli, A. On the Microstructural Transformations and Mechanical Performance of Laser Beam Welded UNS S43000 Ferritic Stainless Steel. *J. Mater. Eng. Perform.* **2024**, 1–13. [CrossRef]
45. Zhang, M.; Wang, X.; Zhu, G.; Chen, C.; Hou, J.; Zhang, S.; Jing, H. Effect of laser welding process parameters on microstructure and mechanical properties on butt joint of new hot-rolled nano-scale precipitation-strengthened steel. *Acta Metall. Sin. (Engl. Lett.)* **2014**, *27*, 521–529. [CrossRef]
46. Sirohi, S.; Pandey, S.M.; Tiwari, V.; Bhatt, D.; Fydrych, D.; Pandey, C. Impact of laser beam welding on mechanical behaviour of 2.25Cr–1Mo (P22) steel. *Int. J. Press. Vessel. Pip.* **2023**, *201*, 104867. [CrossRef]

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