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Araştırma Makalesi / Research Article

Microstructural and Mechanical Properties of Nd:YAG Laser Welded Dissimilar DP600-DP1000 Steel Sheets

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Abstract

In this study, the DP600 and DP1000 steel sheets were joined with the pulsed Nd:YAG (Neodymium-doped Yttrium Aluminum Garnet (Y3Al5O12)) laser welding and, mechanical and microstructure properties of the dissimilar welds were experimentally investigated. As known, there is a demand in modern automotive industry for performing dissimilar weld of DP steel sheets. In the laser welding operation, the selection of welding parameters affects the final properties of welds substantially. So, the main aim of this study was determining the influence of pulse frequency on the mechanical properties of pulsed Nd:YAG laser welded DP600-DP1000 steel sheet joints. For this purpose, dissimilar (DP600-DP1000) steel sheets were double-sided welded with the butt joint. To analyze the welding performance, microstructural studies, tensile tests and microhardness measurements were carried out. The weld cross-sections of the joints revealed three main distinct macrostructural zones: Base metal and heat affected zone of both steels, and fusion zone. Moreover, a transition zone was observed between the base metal and heat affected zone on the DP1000 sides. Higher pulse frequency led to deeper penetration and larger fusion zone and heat affected zone. The laser welded joints without filler material had macro porosities in the fusion zones. The tensile strength of the joints significantly increased with increasing pulse frequency. The tensile strengths obtained in this study may be quite satisfactory for automotive industrial applications. Fusion zone had the highest microhardness values. However, the lower microhardness values than base material were measured in the transition zone on DP1000 side.

Keywords
DP steels; Nd:YAG laser welding; Dissimilar welding; Pulse Frequency; Microstructure; Mechanical properties

Nd:YAG Lazer Kaynağı ile Birleştirilen Farklı Türdeki DP600-DP1000 Çeliklerinde Mekanik ve Mikroyapı Özellikleri

Öz

Bu çalışmada DP600 ve DP1000 çelik sacları darbeli Nd:YAG (Neodymium-doped Yttrium Aluminum Garnet (Y3Al5O12)) lazer kaynağı ile birleştirilmiş ve farklı türdeki sacların kaynağında mekanik ve mikro yapı özellikleri deneysel olarak incelenmiştir. Bilindiği gibi modern otomotiv endüstrisinde farklı türdeki DP çeliklerimin birleştirilmesine talep vardır. Lazer kaynak işleminde kaynak parametrelerinin seçimi kaynak nihai özelliklerini önemli ölçüde etkiler. Bu yüzden bu çalışmanın amacı Nd:YAG lazer kaynaklı DP600-DP1000 çeliklerinde darbe frekansının mekanik özelliklere etkilerinin belirlenmesidir. Bu amaçla farklı türdeki (DP600-DP1000) çelik saclar çift taraflı olarak alın kaynağı ile birleştirilmiştir. Kaynak performansını analiz etmek için mikro yapı çalışmaları, çekme testleri ve mikro sertlik ölçümleri gerçekleştirilmiştir. Kaynak kesitinde temel malzeme, ısı tesiri altındaki bölge ve ergime bölgesinden oluşan 3 farklı makro yapısal bölge ortaya çıkmıştır. Ayrıca DP1000 tarafında ısı tesiri altındaki bölge ile temel malzeme arasında bir geçiş bölgesi gözlenmiştir. Yüksek darbe frekansı derin penetrasyon ve daha geniş ergime bölgesi ve ısı tesiri altındaki bölgeye neden olmuştur. Dolgu teli olmadan gerçekleştirilen kaynaklar ergime bölgesinde makro gözenekler içermektedir. Kaynaklı birleştirmenin mukavemeti darbe frekansındaki artışla beraber önemli ölçüde artmıştır. Bu çalışmada elde edilen çekme mukavemetleri otomotiv endüstrisi için oldukça tatmin edicidir. Ergime bölgesi en yüksek mikro sertlik özelliklerine sahiptir. Fakat DP1000 geçiş bölgesinde temel malzemeden daha düşük sertlik değerleri ölçülmüştür.

Anahtar kelimeler
DP çelikleri; Nd:YAG lazer kaynağı; Farklı malzemelerin kaynağı; Darbe frekansı; Mikro yapı; Mekanik özellikler

1. Introduction

Advanced high-strength steels (AHSSs) are utilized to lighten vehicle body by the automotive manufacturers. Ferrite-martensite dual phase (DP) steel sheets are commonly used (AHSSs) in the automotive sector due to the high tensile strength and quite high formability. Martensite phase in the DP steels provides high strength and the ferrite matrix phase provides good elongation. These features of DP steels have attracted the attention of automotive manufacturers, especially in terms of fuel economy and environmental protection (Farabi et al. 2011)(Fillafer et al. 2017)(Aydin 2015)(Jia et al. 2017).

When DP steel sheets are used in car body components, welding is inevitably needed during the manufacturing process. Although the conventional resistance spot welding (RSW) is the most used welding method in the automotive industry, the newly popular laser welding has gained importance in the welding of DP steels because a narrower weld and heat affected zone (HAZ) can be achieved when compared to the conventional welding methods. Moreover, laser welding can minimize residual stress and distortion (Mohammadpour et al. 2018)(Sun et al. 2016)(Yuce et al. 2017). CO_2 lasers and solid state Nd:YAG or fiber lasers are commonly used technologies in welding processes [8](Dal and Fabbro 2016). The prominent benefits of laser welding are intensive laser power, high energy density, high welding speed, high precision, high productivity, flexibility and effectiveness (Iordachescu et al. 2011)(Zhao et al. 2013). In the current work, pulsed Nd: YAG laser was used. The advantage of Nd:YAG laser welding over other laser sources is that it can precisely control the laser parameters (Hekmatjou and Naffakh-Moosavy 2018). Therefore, it is crucial to choose the appropriate welding parameters because the parameters directly affect the weld quality. And, the main Nd:YAG laser welding parameters are average power rate, pulse duration time, pulse frequency and focal spot diameter (Tadamalle et al. 2014)(Pereira et al. 2019).

Various studies have been performed in the literature on laser welding of DP steels. In the studies on the welding zone of the DP steels, a soft HAZ region and fully hard martensite phase in the fusion zone (FZ) have been observed (Bandyopadhyay et al. 2017)(Xia et al. 2008). Fernandes et al. (Fernandes et al. 2017) aimed in their study to determine the weldability and optimum welding parameters of DP600 sheets combined with Nd: YAG laser welding. Nd:YAG laser welding of the DP600 steel sheets accomplished successfully with optimum parameters. Wang et al.(Wang et al. 2016) examined the effects of energy input on the microstructure and mechanical properties of Nd:YAG laser welded DP1000 steel. When the energy input was reduced, the melting zone and the soft HAZ zone were narrowed, as well as the mechanical properties improved with the reduction in energy input. Alves et al. (Alves et al. 2018) in their study showed that retained austenite and tempered martensite as the main cause of softening between intercritical and subcritical HAZs in laser beam welding of DP1000 steel. Xue et al. (Xue et al. 2017) studied the effect of Nd.YAG laser welding parameters on weld penetration and the hardness of DP steel butt joint. Their study revealed that tempering of martensite caused the hardness drop in the HAZ and lower hardness values were measured than base metal (BM). Sreenivasan et al. (Sreenivasan et al. 2008) employed two different lasers (diode and Nd:YAG) to evaluate the formability of DP980 steel. In their study heat input is substantial on HAZ softening and so, Nd:YAG laser welded DP980 steels showed higher limiting dome height than the diode laser welded DP980 steels.

The motivation of this study was the lack of studies on double-sided Nd: YAG welding of DP600 and DP1000 sheets, which are commonly used in the modern automotive industry. Therefore, this study investigated the double-sided Nd:YAG laser welding capabilities of dissimilar DP steels (DP600-DP1000), which are increasingly used in the automobile industry. In particular, the effect of pulse frequency on the mechanical properties of the dissimilar joints was investigated. Within the scope of experimental studies, tensile tests and Vickers microhardness measurements were executed to determine mechanical properties of welds. Also, weld geometry was examined by using an optical microscope for macrostructure and microstructure studies.

2. Material & Method

Commercially available 1 mm thick DP600 and DP1000 steel sheets were used in this study and the chemical compositions and tensile properties of these steel sheets were listed in Table 1 and 2. DP600 and DP1000 test specimens with dimensions of 100 x 260 mm were prepared for welding (Fig. 1 a). Laser welding operations were performed without any filler metals by joining the sheets in the square butt-joint configuration using a SISMA SWA 300 Nd:YAG laser welding machine (Fig. 2). A special fixture was also manufactured to ensure complete contact between the matching surface of the butt weld samples, and this fixture was mounted onto the stand of the welding machine (Fig. 3). Pure argon gas was used for shielding. The focal length was 120 mm above the sheet metal surface. The capacity of the welding device was insufficient for single-sided welding, therefore, the welds were performed as double-sided in the pulse frequencies of 3 Hz, 4 Hz, 5 Hz, 6 Hz and 6.5 Hz and other parameters kept constant (Table 3). In the double-sided welding process, first, the front face and then the opposite side was welded, respectively.

The tensile test specimens were prepared according to ASTM E8/E8M (Fig. 1b) (American and Standard 2002). UTEST-7014 tensile device with an extensometer was used to determine tensile strength properties of welded joints. Microstructure characterization was done by using an optical microscope. Vickers microhardness tests were also conducted by applying 100 grams load for 10 seconds. The hardness values were measured spacing of 100 µm along the center of weld zone. Microhardness measurements were done from the first welding pass to see the effect of the final thermal cycle. Before the optical and microhardness studies, grounding and polishing processes were carried out, and then samples etched with a mixture of 3 ml of nitric acid and 97 ml of alcohol reagent for 10-15 seconds.

Table 1. Chemical properties of DP600 and DP1000 steels.

Steel	C	Mn	Si	Cu+Cr+Ni	Cr	Fe
DP600	0.12	1.40	0.5	1.3	-	Balance
DP1000	0.16	1.89	0.26	-	0.44	Balance

Table 2. Mechanical properties of DP600 and DP1000 steels.

Steel	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
DP600	370	630	24
DP1000	660	1020	13.5

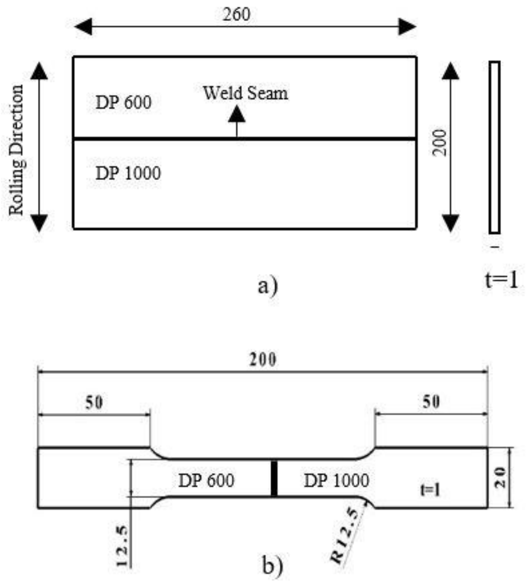


Figure 1. a) Nd:YAG laser welded DP600 steel-DP1000 steel sheets; b) The tensile test specimen.

Figure 2. The SISMA SWA 300 Nd:YAG laser welding machine.

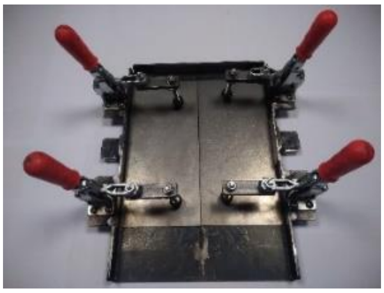


Figure 3. The fixture used in the welding operations.

Table 3. Selected Nd:YAG laser welding parameters.

Average Power Rate [%]	Pulse Duration Time [ms]	Pulse Frequency [Hz]	Focal Spot Diameter [mm]	Welding Speed [mm/s]
% 50	5	3	1.4	4
% 50	5	4	1.4	4
% 50	5	5	1.4	4
% 50	5	6	1.4	4
% 50	5	6.5	1.4	4

3. Results & Discussions

The strength of the double-sided laser welded joints determined by using tensile tests. The results of tensile tests exhibited that the pulse frequency significantly affected the tensile performance of double-sided laser welded dissimilar DP600-DP1000 steel sheet joints (Figure 4 and Figure 5).

Double-sided laser welded dissimilar DP600-DP1000 joints tensile strength significantly increased with increasing pulse frequency (Fig. 4). The tensile strength of these joints increased approximately 2.3 times when the pulse frequency was increased from 3 Hz to 6.5 Hz. The peak tensile strength (610.5 MPa), which is approximately equal to the strength (630 MPa) of DP 600 base metal, was obtained in the joints welded with a pulse frequency of 6.5 Hz. This value is almost the highest value that can be obtained for the dissimilar DP600-DP1000 welded joints due to the lower strength of DP600 steel. The enhanced tensile strength of the laser welds is due to the deeper penetration that increases with the pulse frequency (Fig. 6). Also, the lower tensile strength in the joints with the lower pulse frequency can be associated with the possible unbonded section because of the lower heat input (Fig. 6). The effect of pulse frequency on the elongation of the double-sided laser welded joints can also be seen in Fig. 5. Similar to tensile strength values, the elongation of these joints increased with increasing pulse frequency (Fig. 5). When pulse frequency increased from 3 Hz to 6.5 Hz, the elongation value increased from 2.25% to 20.45%. For 6.5 Hz the elongation value (20.45%) is higher than that of DP1000 (13.5%) and this value is quite close to the elongation (24%) of DP600. The tensile properties of the double-sided laser welded dissimilar DP600-DP1000 joints with a pulse frequency of 6.5 Hz are quite satisfactory for the automotive industrial applications. Sun et al.(Sun et al. 2016) studied the effect of pulse frequency on mechanical properties of Nd:YAG laser welded 1 mm thick DP590 steel sheets. In their study, when pulse frequency is lower than 8 Hz shallow penetration was obtained (not full penetration). Engineering stress and engineering strain are increased with increasing pulse frequency because of higher heat input and higher penetration. The results obtained in their study support this current study.

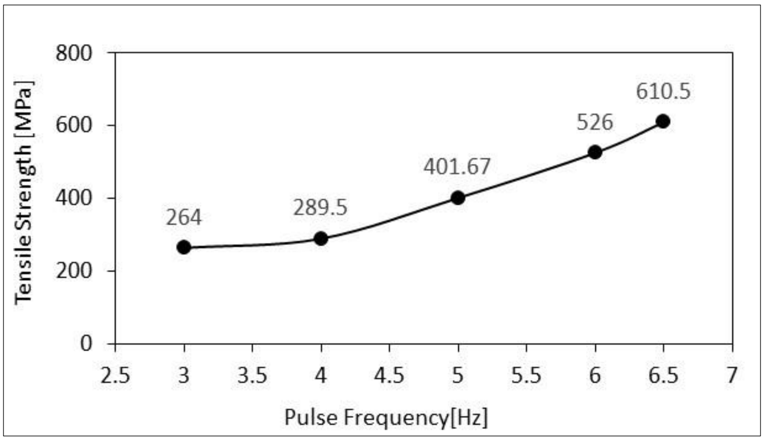


Figure 4. Tensile strength of welded DP600-DP1000 steel sheets joints versus pulse frequency.

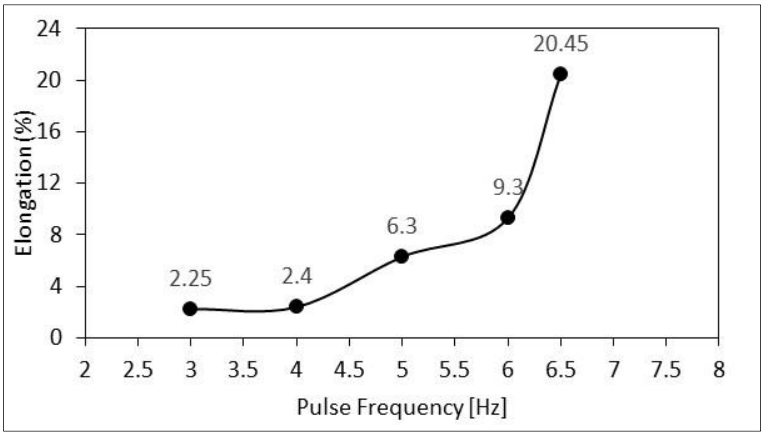


Figure 5. Elongation of welded DP600-DP1000 steel sheets joints versus pulse frequency.

The weld cross-sections of the Nd:YAG laser welded dissimilar DP600-DP1000 steel joints revealed three main distinct macrostructural zones: Base metal (BM) and heat affected zone (HAZ) of both steels, and fusion zone (FZ) as shown in Fig.6a,b. There was also a transition zone (TZ) between the BM and the HAZ on the DP1000 sides of the weld cross-section. By contrast, the TZ was not detected on the DP600 side of the cross-section. Higher pulse frequency concluded deeper penetration and larger FZ and HAZ size because of the higher heat input (Fig. 6). Increasing the pulse frequency increases the overlapping factor and weld penetration (Xue et al. 2017). The joints had macro porosities in the FZs resulting from the gaps at the interface of the square butt-joint configuration. Lower pulse frequency resulted in possible unbonded section in the interface of the joints to the lower heat input (Fig.6a). The microstructures of the DP600 and DP1000 BMs are composed of martensite islands (dark color) within a-ferrite matrix (light color) (Fig.7a,b). However, a fairly higher volume fraction of martensite was seen in the DP1000 BM. The FZs were characterized by mostly dendritic martensitic structure due to the nature of the high cooling rate of thin sheets (Fig.8a,b). HAZ on DP600 side had martensite and bainite in near FZ and tempered martensite, iron carbides and ferrite in near BM (Fig.9). HAZ on DP600 side of the joints with a pulse frequency of 6.5 Hz was relatively wider due and has more bainite, tempered martensite and iron carbides due to higher heat input (Fig.9a,c). HAZ on DP1000 side had mainly martensitic and bainitic structures, and also consist of some retained austenite and ferrite (Fig.10). HAZ on DP1000 side of the joints with a pulse frequency of 6.5 Hz was relatively wider and has more martensite and bainite (Fig.10c,d). TZ on DP1000 side, which is formed by excessive tempering of the BM, had mainly polygonal ferrite (PF) and iron carbides, and also consists of tempered martensite (Fig.11). Yang et al. (Yang et al. 2019) Nd:YAG lazer welded dissimilar DP780-DP980 steels and they showed the detailed microstructure of DP980 side’s TZ in their study. In the TZ peak temperature was lower than Ac_1 and which resulted in the formation of tempered martensite along with granular carbides formed by martensite decomposition. Alves et al. (Alves et al. 2018) laser welded DP1000 steel sheets in a bead-on-plate configuration. And, they found retained austenite in all weld zones but retained austenite was more abundant in the TZ.

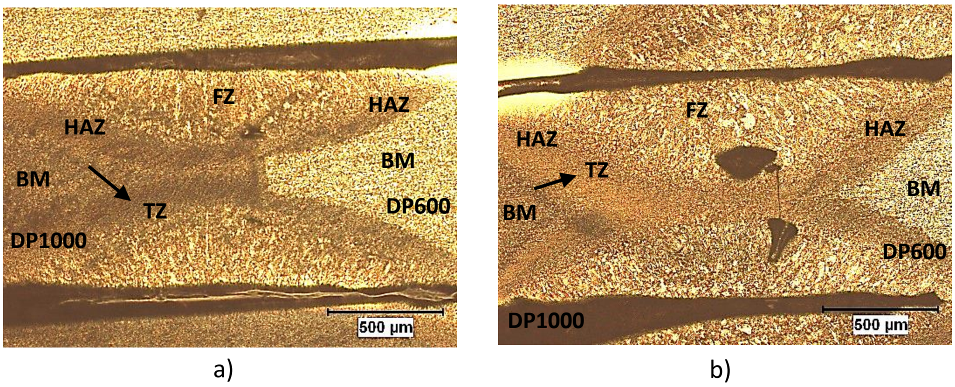


Figure 6. Typical macro images of welded joints: a) 4 Hz; b) 6.5 Hz (FZ: Fusion Zone; HAZ: Heat Affected Zone; BM: Base Metal; TZ: Transition Zone).

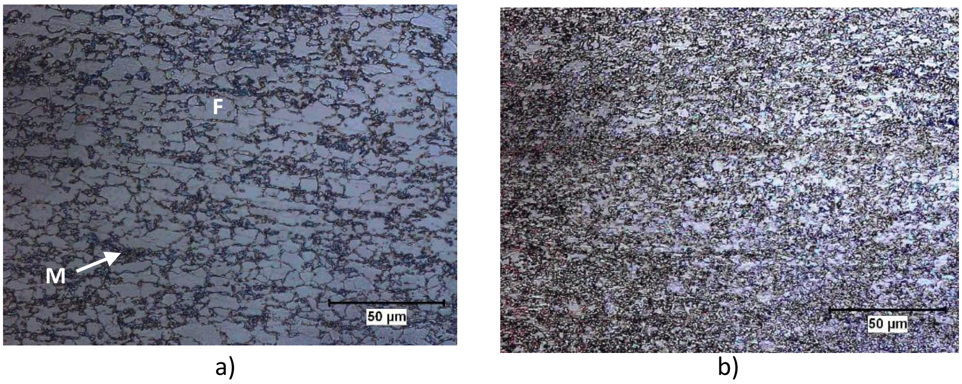


Figure 7. Microstructures of base metal used in the study: a) DP600; b) DP1000 (F: Ferrite; M: Martensite).

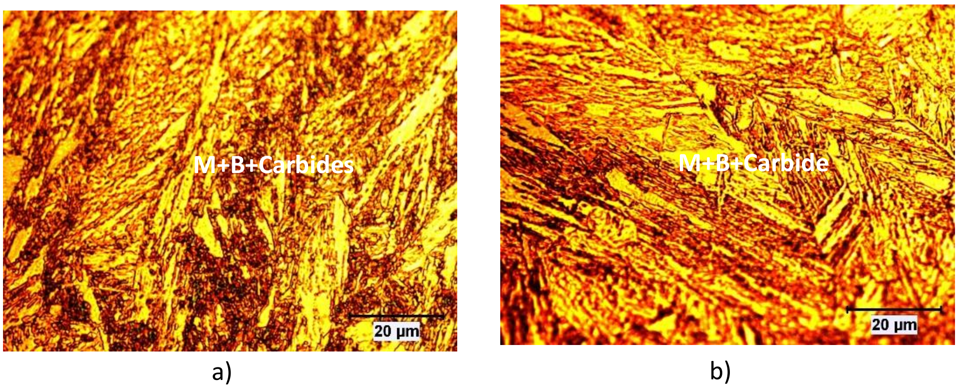
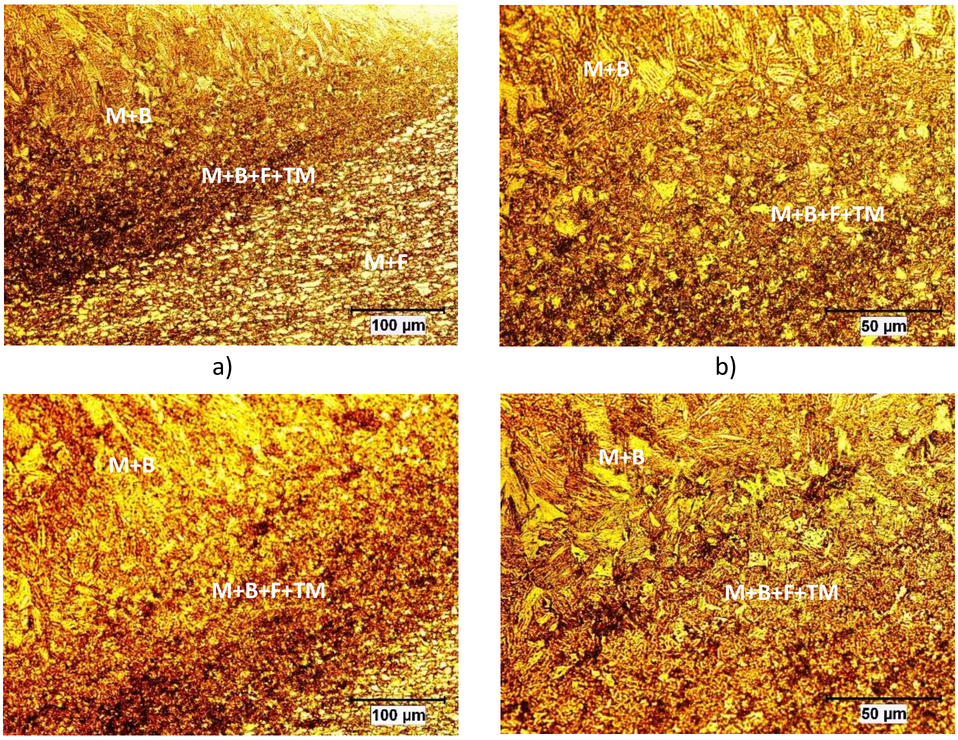


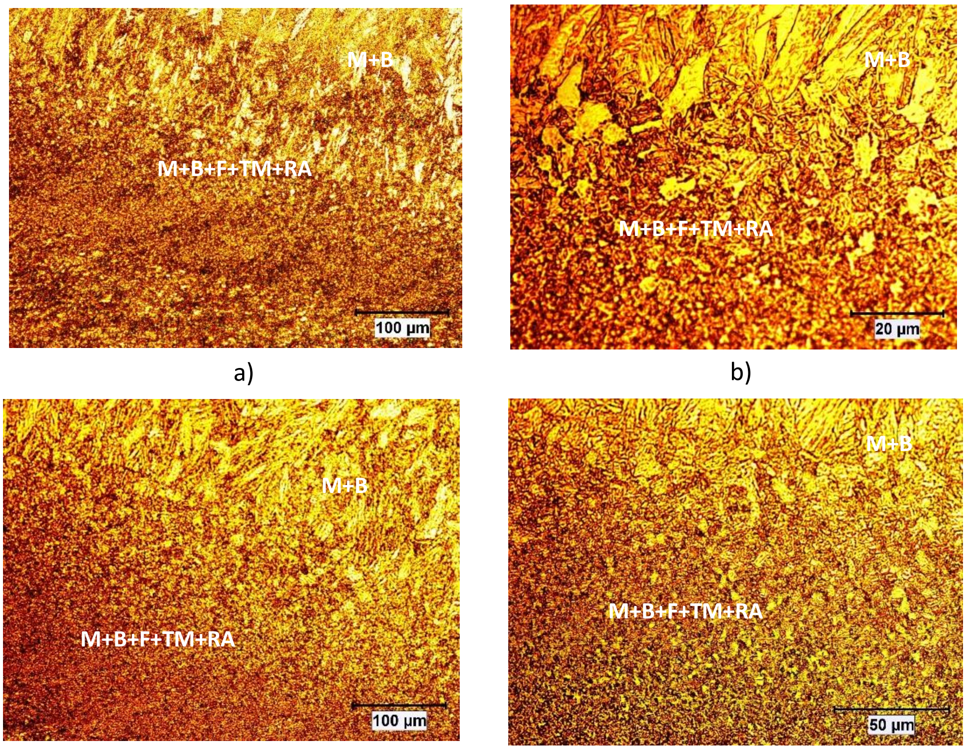
Figure 8. FZ microstructures of joints: a) 4 Hz; b) 6.5 Hz (M: Martensite; B: Bainite).



a) b)

c) d)

Figure 9. HAZ microstructures on DP600 side: a) and b) 4 Hz; c) and d) 6.5 Hz (F: Ferrite; M: Martensite; B: Bainite; TM: Tempered Martensite).



a) b)

c) d)

Figure 10. HAZ microstructures on DP1000 side: a) and b) 4 Hz; c) and d) 6.5 Hz (F: Ferrite; M: Martensite; B: Bainite; TM: Tempered Martensite; RA: Retained Austenite).

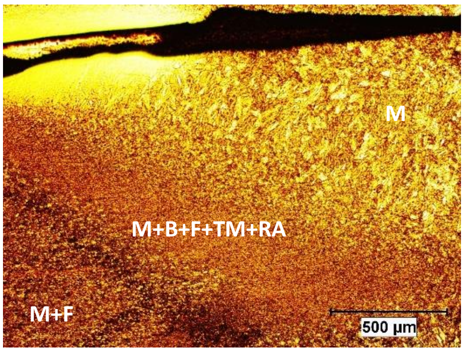


Figure 11. TZ on DP1000 side of joint with a pulse frequency of 6.5 Hz (F: Ferrite; M: Martensite; B: Bainite; TM: Tempered Martensite; RA: Retained Austenite).

Figures 12 show the hardness measurements of the laser welded joints with pulse frequencies of 4 Hz and 6.5 Hz, respectively. The highest hardness values were obtained in the FZs due to the effective martensite formation in this zone. And, the hardness values in the HAZ were lower compared to the FZ and this region is limited to a very narrow region about 200-300 microns wide. In the TZ on the DP 1000 side, the hardness values were lower than the BM (310 $HV_{0.1}$). The measured lowest hardness value for a pulse frequency of 4 Hz on DP1000 side was 296.7 $HV_{0.1}$ and the lowest hardness value for a pulse frequency of 6.5 Hz on DP1000 side was 284.1 $HV_{0.1}$. Bandyopadhyay et al.(Bandyopadhyay et al. 2017) laser welded dissimilar DP600-DP980 steel sheets. In their study like this study a hardness drop was also observed in the outer HAZ region of DP980 side. Bandyopadhyay et al. explained the reason for softening with decomposition of the existing martensitic phase in the BM. In the soft zone revealing the carbide precipitation confirmed the tempering of martensite because of the subcritical heating.

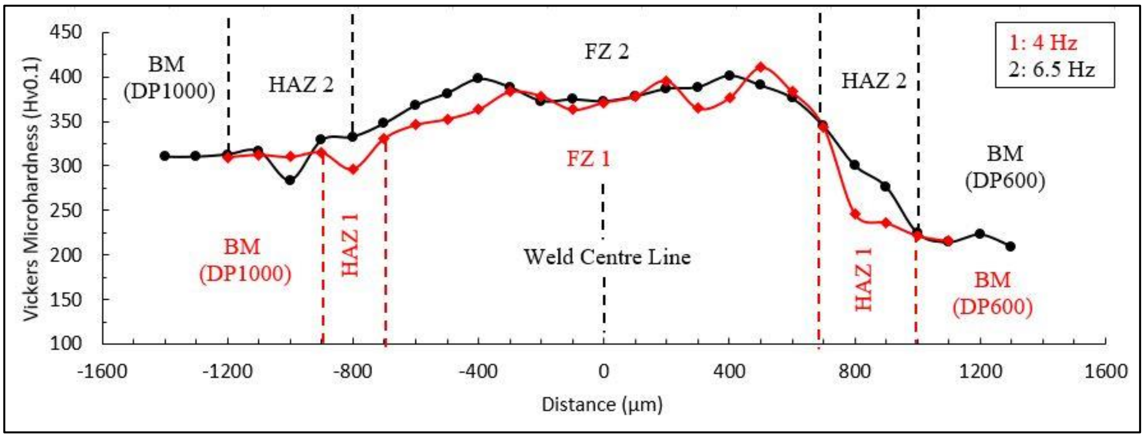


Figure 12. Hardness variation of the weld zone in the sample produced with frequencies of 4 Hz and 6.5 Hz.

4. Conclusions

The mechanical and microstructure properties of double-sided Nd:YAG laser welded dissimilar DP600-DP1000 steel sheets in different frequencies were experimentally investigated in this study. From this experiments, the following major results can be concluded:

1. The weld cross-sections of the joints revealed three main distinct macrostructural zones: Base metal and heat affected zone of both steels, and fusion zone. Also, there was a transition zone between BM and HAZ on the DP1000 side.
2. Higher pulse frequency led to deeper penetration and larger fusion zone and heat affected zone.
3. The joints welded without any filler wires had macro porosities in the fusion zones.
4. The tensile properties of the joints significantly increased with increasing pulse frequency. The parameter combination at average power rate of %50, pulse duration time of 5 ms, pulse frequency of 6.5 Hz and focal spot diameter of 1.4 mm led to the highest weld strength (610.5 MPa) and elongation (20.45%) for the welded joints. These tensile properties may be clearly quite satisfactory for automotive industrial applications.
5. Fusion zones had the highest microhardness values. But in the DP 1000 side the lowest

microhardness values were determined in the transition zone.

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