A Comparison of Tensile Properties of Single-Sided and Double-Sided Laser Welded DP600 Steel Sheets

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Dual Phase (DP) steels are the most commonly used steels in the automotive industry to reduce vehicle weight and improve car safety. DP600 steel is one of the most used steels for the automotive industry because this steel has high strength and good elongation properties. During the manufacture of automotive parts, welding is the most commonly used joining process, and especially the laser welding is getting more and more importance. This study was executed to evaluate how the welding type (single-sided and double-sided) affects the tensile properties of Nd:YAG (Neodymium-Doped Yttrium Aluminum Garnet; *Nd*:$Y_3Al_5O_{12}$) laser welded DP600 steel sheets using different pulse frequencies. The laser welded samples were investigated by the methods of tensile test and fractography. Experimental results indicated that the tensile properties varied significantly depending on the welding type and pulse frequency. The tensile properties of the double-sided laser welded joints were significantly higher than those of the single-sided laser welded joints. Tensile strength and elongation of the single-sided and the double-sided laser welded joints increased almost linearly with increasing pulse frequency. The higher pulse frequency resulted in larger fully bonded section size, which led to higher tensile properties. The maximum tensile strength and elongation (611 MPa and 10.06 %) were obtained with the double-sided laser welded joint in the pulse frequency of 8.5 Hz. The tensile strength of this joint was almost equal to that of the base metal, but its elongation value was lower that of the base metal.

Keywords: DP600 steel, Nd:YAG laser welding, pulse frequency, tensile properties, fracture surface.

1. INTRODUCTION

Ferrite-Martensite dual phase (DP) steel sheets are the one of the most common used advanced high strength steels (AHSS) for the automotive industry in order to reduce weight, improve crash performance and fuel efficiency. In the combination of martensite and ferrite phases, the body-centered-tetragonal (BCT) martensite contributes to high strength, while the body-centered-cubic (BCC) ferrite matrix provides good elongation, which can create a good combination of strength and ductility for applications requiring good formability. In DP steels, DP600 steel sheet is quite popular in automotive applications [1].

The use of DP steel sheets in the automotive industry inevitably involves welding [2–4]. In recent years, especially for the automobile manufacturing industry, the laser welding has gained importance due to its specific properties. Advantages of laser welding compared to conventional welding methods are; narrow heat affected zone (HAZ), low residual stresses and distortion, high welding speed, suitable for automation, easy controlling, ability to weld complicated shapes, economic efficiency and suitable for precision welding with very low error rate [5–8]. Currently, CO_2 and Nd: YAG (Neodymium-Doped Yttrium Aluminum Garnet; *Nd*:$Y_3Al_5O_{12}$) lasers are the two main type of laser welding methods that are of interest to the automotive industry and structural manufacturing [9, 10].

The pulsed Nd: YAG laser is advantageous over other laser sources due to its ability to control the laser parameters such as pulse duration and frequency [11]. Laser welding parameters affect the formation and resultant properties of laser seam welds. The performance of the laser welding process depends mainly on the energy absorbed by the material to be welded. Selection of the proper welding parameters is required to improve the weld quality. Main laser welding parameters are travel speed, pulse energy, pulse duration time, pulse frequency and focal spot diameter [12].

Limited studies have been carried out on the laser weldability of similar or dissimilar DP steels [13–17]. Jia et al. [13] evaluated the metallurgical changes and tensile properties of DP600-DP980 dissimilar joints after laser welding with focused and defocused beam. In their study, the joint by the defocused beam exhibited tensile behavior similar with focused beam except for slightly increase in yield strength. Farabi et al. [14] aimed at evaluating the microstructural changes, tensile and fatigue properties with an emphasis on yielding characteristics and work hardening behavior of laser welded dissimilar DP600/DP900 steel joints. Alves et al.[15] studied the laser beam weldability and the effect of the main welding parameters on the mechanical behavior of ultra-high-strength DP1000 steel. They found the optimal laser welding conditions for 2.0 kW laser power and 150 mm/s welding speed parameters. Bandyopadhyay et al.[16] investigated the quality of the laser welded similar (DP600-DP600) and dissimilar (DP600-DP980) joints. Xia et al. [17] studied the effect of heat input on HAZ softening of Nd:YAG and diode laser welded DP450, DP600, and DP890 steels. In all welds, softening has occurred in the HAZ.

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The joining of components plays a critical role in determining the cost and productivity of manufacturing and the quality of final products [18]. Several studies have reported that a filler material has been used during laser welding to fill the gap existing at the joint or improved the weld bead quality [19 – 23]. However, laser welding with filler wire may lead to extra costs and some additional difficulties for industrial application, having many parameters and stringent requirements for wire positioning [19, 24, 25]. Therefore, the weld quality of laser welded joints needs to be improved without using filler metal. Thus, the effect of the welding type (single-sided and double-sided) on the tensile properties of Nd:YAG laser welded DP600 steel sheets without filler wire in different pulse frequencies was aimed at studying in this paper. In the literature, there is no study on the double-sided laser welding of DP600 steel sheets in different pulse frequencies.

2. MATERIALS AND METHOD

Commercial DP600 steel sheet with a thickness of 1 mm was used in this study. The chemical composition and tensile properties of this sheet was listed in Table 1 and Table 2, respectively.

Table 1. The chemical composition of DP600 steel sheet used in this study (wt.%)

C	Mn	P	S	Si	Al	N	Cu+Cr+Ni	Fe
0.12	1.40	0.085	0.008	0.50	0.02 – 0.06	0.009	1.3	Bal.

Table 2. Tensile properties of DP600 steel sheet used in this study

Ultimate tensile strength, MPa	0.2% proof strength, MPa	Elongation, %
630	370	24

DP600 steel sheets were cut into pieces in dimensions of 100 mm × 400 mm for welding processes (Fig. 1 a). Laser welding operations were performed by assembling the sheets in the square butt-joint configuration using a SWA 300 Nd:YAG laser welding machine. Welding was conducted perpendicular to the rolling direction (Fig. 1 a). Argon shielding gas was employed during laser welding operations. The focal length was 120 mm above the sheet surface. The welds were performed as single-sided and double-sided in the pulse frequencies of 4.5 Hz, 6.5 Hz, and 8.5 Hz while keeping the other parameters constant (Table 3). When compared with the literature, the welding parameters in this study were selected at relatively low levels to minimize the adverse effect of heat input on weld zone [2, 5, 8, 12, 17]. Also, the effect of frequency on single-sided and double-sided Nd: YAG laser welding can be detected more clearly with the welding parameters at relatively low levels.

The welded samples were machined perpendicular to the welding direction in accordance with ASTM E8/E8M (Fig. 1 b) [26]. In order to evaluate the mechanical properties of the welds, the tensile tests were carried out on a computerized UTEST-7014 tensile testing machine at room temperature with a constant crosshead displacement speed of 5 mm/min. The tensile properties were evaluated by averaging the value of five specimens under the same welding condition. An extensometer with a gauge length of 65 mm was used to measure the elongation during the tensile tests. Following the tensile tests, the fracture surfaces of the joints were examined using Zeiss EVO 40 XVP SEM.

3. RESULTS AND DISCUSSION

To determine the quality of the single-sided and double-sided laser welded joints, the tensile strength of the joints was experimentally determined using tensile tests. The tensile test results exhibited that the pulse frequency significantly affected the tensile performance of the single-sided and double-sided laser welded DP600 steel sheet joints (Table 4).

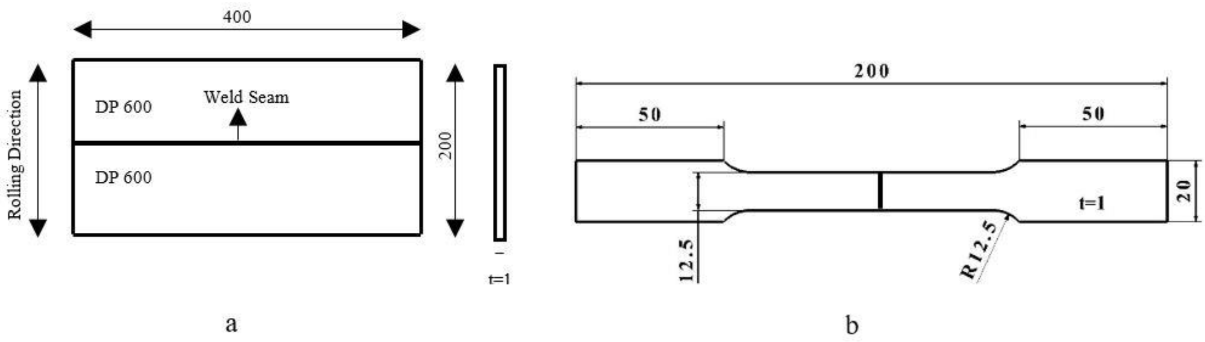


Fig. 1. a – schematic illustration of laser welded DP 600 steel sheets; b– dimensions of the tensile test specimens

Table 3. Welding parameters used in this study

Sample nomenclature	Laser welding type	Pulse energy, j	Pulse duration time, ms	Pulse frequency, Hz	Focal spot diameter, mm	Welding speed, mm/s	Overlapping factor, %
SS1	Single-Sided	26.4	4	4.5	1.4	4	37.2
SS2	Single-Sided	26.4	4	6.5	1.4	4	56.5
SS3	Single-Sided	26.4	4	8.5	1.4	4	66.8
DS1	Double-Sided	26.4	4	4.5	1.4	4	37.2
DS2	Double-Sided	26.4	4	6.5	1.4	4	56.5
DS3	Double-Sided	26.4	4	8.5	1.4	4	66.8

Table 4. Tensile strength and elongation of the laser welded joints (average values)

Sample	Tensile strength, MPa	Elongation, %
Base metal	630	24
SS1	39.33	0.025
SS2	256.25	0.25
SS3	448.67	1.07
DS1	234.25	0.125
DS2	415.5	0.825
DS3	611	10.06

The tensile strength of the single-sided laser welded DP600 joints increased almost linearly with increasing pulse frequency (Fig. 2 a). The tensile strength of these joints increased approximately 12 times when the pulse frequency was increased from 4.5 Hz to 8.5 Hz. However, the highest weld strength in these joints was approximately 29 % lower than that of base metal. On the other hand, the effect of pulse frequency on the elongation of the single-sided laser welded joints can also be seen in Fig. 2 b. The elongation of these joints also increased almost linearly with increasing pulse frequency (Fig. 2 b). But, it should be emphasized that these elongation values were too low for automotive industrial applications.

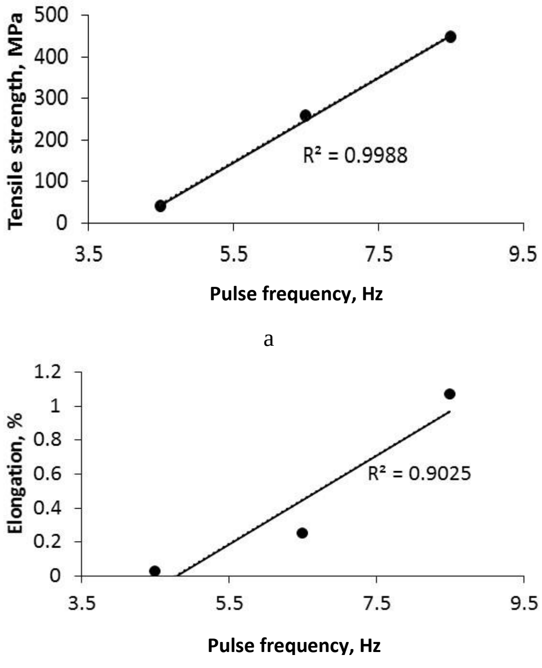


Fig. 2. a – tensile strength; b – elongation of single-sided laser welded DP600 steel sheet joints versus pulse frequency

Similarly, the tensile strength of the double-sided laser welded DP600 steel sheet joints increased linearly with increasing pulse frequency (Fig. 3 a). The tensile strength of these joints increased 2.6 times when the pulse frequency was increased from 4.5 Hz to 8.5 Hz. The highest weld strength in these joints was approximately equal to that of base metal. The effect of pulse frequency on the elongation of the double-sided welded joints can also be seen in Fig. 3 b. The elongation of these joints increased almost linearly with increasing pulse frequency. But, the coefficient of determination (R^2) for the linear correlation between the elongation and the pulse frequency was slightly lower (0.80). However, the highest elongation value (% 10) in these joints is quite satisfactory for automotive industrial applications.

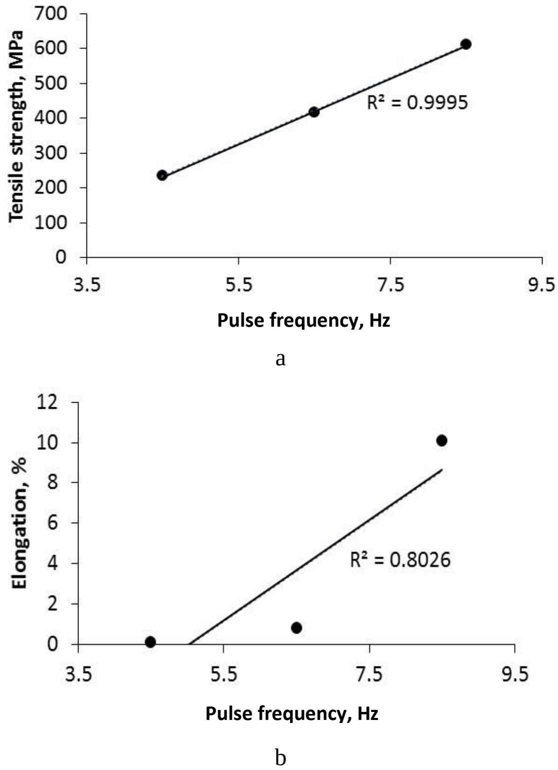


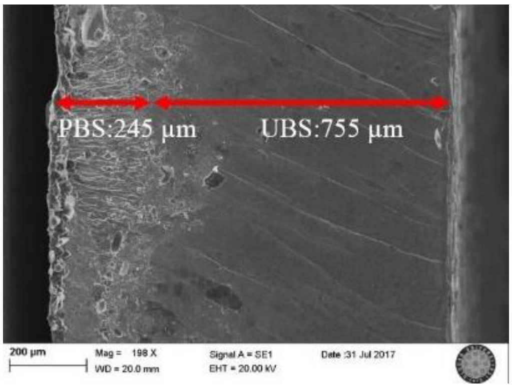
Fig. 3. a – tensile strength; b – elongation of double-sided laser welded DP600 steel sheet joints versus pulse frequency

Torkamany et al. [27] have shown keyhole formation in pulsed Nd:YAG laser welding of 0.7 mm thickness St14 metal plates. They have formulated the overlapping factor (OF) in their study and shown that the frequency increased the OF. With this increase in the OF, the conical weld zone has become cylindrical and more uniform. In our work, the increased welding strength with frequency can be attributed to more uniform welds at higher frequency values. In this study, the OF was calculated as [8]:

$$OF = [1 - (S/F)/(D + ST)] \text{ x } 100 , \quad (1)$$

where *S* is the welding speed (mm/s), *F* is pulse frequency (Hz), *D* is the laser spot diameter on the interface (mm) and *T* refers to pulse duration (ms). The calculated *OF*s according to Eq. 1. were shown in Table 3.

SEM images for the fracture surfaces of single-sided and double-sided laser welded DP600 steel sheet joints are shown in Fig. 4 and Fig. 5, respectively. Unbonded section (UBS), partially bonded section (PBS), fully bonded section (FBS) sizes of the joints in different pulse frequencies are listed in Table 5. As seen in this table, the higher pulse frequency resulted in larger FBS size due to higher heat input. The single-sided laser welded DP600 steel sheet joint having the lowest weld strength had just PBS and the double-sided joint having the highest weld strength had the largest FBS.



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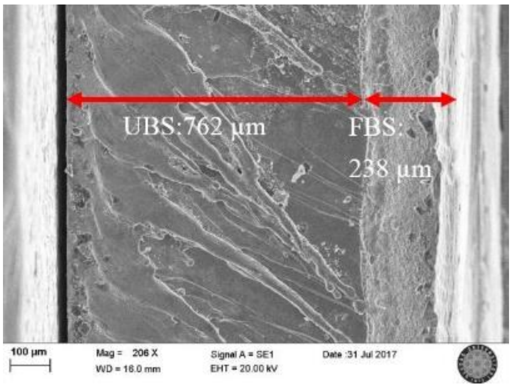

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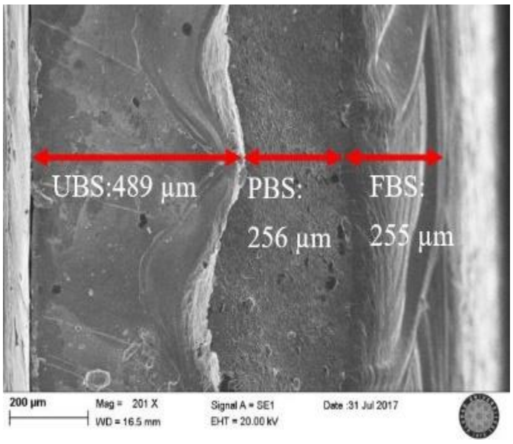

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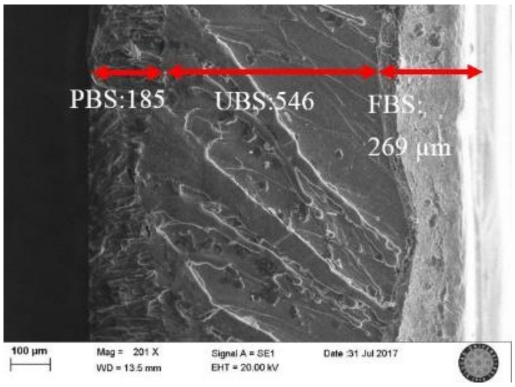
Fig. 4. SEM images for the fracture surfaces of single-sided laser welded DP600 steel sheet joints: a – SS1 sample; b – SS2 sample; c – SS3 sample

Table 5. UBS, PBS and FBS sizes for the single-sided, and double-sided laser welded DP600 steel sheet joints

Sample	UBS, µm	PBS, µm	FBS, µm
SS1	755	245	0
SS2	762	0	238
SS3	489	256	255
DS1	546	185	269
DS2	510	0	490
DS3	326	0	673

In single-sided laser welded samples, the lower *OF* (37.2 %) led to the PBS due to the lower heat input and the higher *OF*s (56.5 % and 66.8 %) resulted in larger FBS owing to the higher heat input (Fig. 4).



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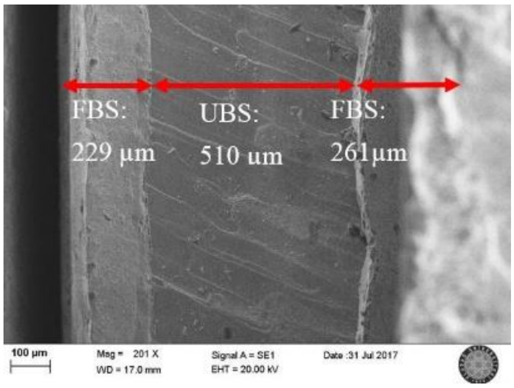

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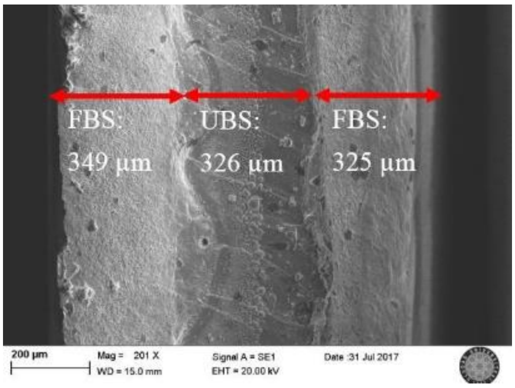

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Fig. 5. SEM images for the fracture surfaces of double-sided laser welded DP600 steel sheet joints: a – DS1 sample; b – DS2 sample; c – DS3 sample

As in single-sided laser welded samples, the lower *OF* (37.2 %) in DS1 sample led to the PBS on the side, where the first weld was made. Despite the lower OF (37.2 %), the other side of DS1 sample, where the second weld was made, had FBS (Fig. 5). This may be attributed to relatively reduced gap tolerance in the square butt-joint configuration on this side after first welding on the other side. When compared the single-sided and the double-sided laser welded joints, it was observed that the double-sided welded joints had the larger FBS size than the single-sided welded joints. Akbari Mousavi and Sufizadeh [28] have demonstrated that the increase in pulse frequency at the Nd: YAG laser welded low carbon steels triggered the overlapping of pulses and resulted in the increased weld depth and weld width. The FBS size in this study was particularly related to weld depth

4. CONCLUSIONS

This work focused on improving weld quality without extra cost and some additional difficulties for industrial application resulting from the filler wire used. So, the tensile properties of single-sided and double-sided laser welded DP600 steel sheets in different pulse frequencies were experimentally investigated in this study. From this investigation, the following major conclusions can be derived:

1. The higher pulse frequency results in a larger fully bonded section size, which leads to higher tensile properties. Additionally, the tensile strength and elongation increase almost linearly with increasing pulse frequency for single-sided and double-sided laser welded joints.
2. The parameter combination at pulse energy of 26.4 J, overlapping factor of 66.8 %, pulse duration time of 4 ms, pulse frequency of 8.5 Hz and focal spot diameter of 1.4 mm leads to the highest weld strength (611 MPa) for the double-sided laser welded joints without filler wire, which is approximately equal to the tensile strength of base metal. The elongation value of this joint is 10 %, which is lower than the elongation of base metal. Nevertheless, this value may be quite satisfactory for automotive industrial applications.

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