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Microstructure and Mechanical Properties of Laser Oscillated Welded DP780 Dual Phase Steel and 5083 Aluminium Alloy: Scanning Oscillations at the Same Energy Density

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Steel and Al exhibit large differences in their physical properties and chemical compositions, making welding them together difficult. To obtain high quality steel-Al joints, three laser welding modes were used to perform lap joint experiments on two metals: DP780 dual phase steel; and 5083 Al alloy. The macroscopic morphology, microstructure and mechanical properties of the DP780 dual phase steel-5083 Al alloy joints formed with these different laser welding modes were investigated. The results show that laser oscillation welding can effectively improve the formation of the weld and reduce cracks, spatter and other defects. Laser oscillation welding through the stirring of the molten pool can distribute heat uniformly throughout the molten pool, reduce the content of ferrite in the welded joint and promote the mixing of liquid DP780 dual phase steel and 5083 Al alloy, effectively reducing the generation of an Al-rich intermetallic compound (IMC). After laser pendulum welding the microhardness of the DP780 dual phase steel-side joint was increased significantly by a factor of more than 1½ times over that of the base material (BM). The maximum shear strength of the joint reached 114 N/mm, an increase of 56% compared to that achieved with conventional laser welding.

Keywords: Disk laser, DP780 dual phase steel, 5083 Al, laser welding, laser oscillating welding, steel–Al dissimilar joints, macrostructure, microstructure, mechanical properties

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1 INTRODUCTION

Duplex steel has high strength and good toughness, and Al alloys have good corrosion resistance and weldability. Because both of these materials are commonly used in the manufacturing industry, heterogeneous welding is inevitable [1, 2]; however, the physical properties and chemical compositions of the two materials differ greatly and the small amount of solid solution is highly susceptible to reaction. The liquid steel and Al dissolve into each other and can produce a brittle intermetallic compound (IMC) after solidification. Owing to the great differences between the two metals, these IMCs can act as crack initiation points and thus affect the performance of the welded joint [3-6].

Laser welding as a welding technique with its advantages of concentrated energy, high utilization and low residual stress is often used in the welding of dissimilar materials [7, 8]. The use of laser welding of dissimilar metals implies a significant mixing of the two metals, and cracking of the IMC layer is a problem. Laser oscillation welding, a new laser welding technique, allows the use of the laser beam to stir the molten pool while controlling the heat source energy field distribution, reducing spatter and refining grain size [9], thereby effectively reducing joint defects and improving the performance of the joint. Because the energy is dispersed during swing welding, and the power per unit area is reduced, it is not possible to complete deep fusion welding of a scanned plate, and only a relatively small deep and wide weld is formed at the material joint, which avoids the transitional mixing of the material and allows a welded joint with good mechanical properties to be obtained [10, 11].

Research has been conducted on laser oscillation welding. Gao *et al.* [12] used PA66 plastic and 304 stainless steel for laser oscillation welding to study the effect of oscillation radius, oscillation frequency, and the amount of defocus on the quality of the weld. Their results demonstrated that, among the above mentioned factors, the oscillation frequency has the most significant effect on the welded joint and the shear strength of the welded joint increased from 2.90 to 7.75 MPa with the increase of the oscillation frequency. Xi *et al.* [13] investigated the effects of laser offset and oscillation frequency on weld formation and the mechanical effects on the joint using laser oscillation welding of Ti6Al4V and 6061 Al alloy. Their results showed that when the laser offset was too large and the oscillation frequency was too low, the weld exhibited defects in the form of cracks and porosity. When the laser offset was too small and the oscillation frequency was too high, the bonding of the two materials was insufficient to complete the weld. When the laser offset was 1.2 mm and the oscillation frequency was 28 Hz the Ti6Al4V and 6061 Al alloy joint formed had good mechanical properties and the tensile strength of the joint could reach 178 MPa. Dimatteo *et al.* [14] laser welded thin Cu and Al sheets of different thicknesses by laser oscillation. Comparison of the variation of tensile loads of Cu–Al joints welded at different oscillation frequencies revealed that the oscillation amplitude had a large influence on the welding results, and the best mechanical properties of the joints were achieved when the oscillation amplitude was 0.7 mm, for which the maximum fracture load could reach 120 kgf. Fetzer *et al.* [15] used two laser oscillation beams, transverse and longitudinal, to weld AlMgSi alloy and showed that either oscillation method reduced the number of bubbles within the weld. Wang *et al.* [16] used laser oscillation to weld TC31 Ti alloy and confirmed that laser oscillation welding can be beneficial in suppressing porosity by comparing the porosity obtained using different welding modes. The tensile strength of the laser oscillation welded joint was 1210 MPa, which is close to the tensile strength of the base material (BM). Most of the current research on welding with laser oscillation is focused on the mechanism of suppressing porosity so there is a need to confirm the difference between the organization and mechanical properties of laser welded joints formed in conventional welding using different pendulum welding modes.

To address the difficulties of steel and Al heterogeneous welding we used three scanning paths for lap welding of DP780 dual phase steel and 5083 Al alloy with a disk laser. The effects of different scanning paths on weld formation, metallographic organization, element diffusion within the joint, microhardness and shear strength of the joint were studied to achieve an effective connection of DP780 dual phase steel-5083 Al alloy joints and to provide a reference for the industrial application of laser pendulum welding.

2 EXPERIMENTAL DETAILS

2.1 Materials specifications and sample preparation techniques

The test materials used were DP780 dual phase steel of 1.2 mm in thickness and 5083 Al alloy of 1 mm in thickness. The sizes of the plates of both materials were 180×100 mm^2. Their chemical compositions are listed in Table 1. Before laser welding a steel brush was used to polish the surface of the DP780 dual phase steel and 5083 Al alloy plates, and then 100% industrial ethanol was used to wash the plates and remove surface impurities and grease. Finally the two materials were air blown to dry.

TABLE 1
Main chemical composition of the DP780 dual phase steel and the 5083 Al alloy (% mass fraction %).

Material	Mn	Si	Mg	C	P	S	Zn	Cr	Al	Fe
DP780	1.950	0.235	0.000	0.160	0.022	0.007	0.000	0.000	0.132	Bal.
5083	0.50	0.10	4.70	0.00	0.00	0.00	0.03	0.10	Bal.	0.30

2.2 Laser welding apparatus and procedure

Laser oscillation welding of the DP780 dual phase steel and 5083 Al alloy plates was conducted using a disk laser (TruDisk 10002; TRUMPF, GmbH). The disk laser has a maximum output power of 10 kW, a fiber core diameter of 200 μm and a wavelength of 1030 nm. It was operated in continuous wave (CW) mode and the power output stability under the rated power was ±1%. The experimental configuration is shown schematically in Figure 1. During the laser welding N_2 was used as the shielding gas, supplied at a gas flow rate of 10 l/min.

As shown in Figure 2, in this work the DP780 dual phase steel plate was lapped under the upper 5083 Al alloy plate and the lap width was 10 mm. Changing the welding mode means changing the heat input. Under horizon-

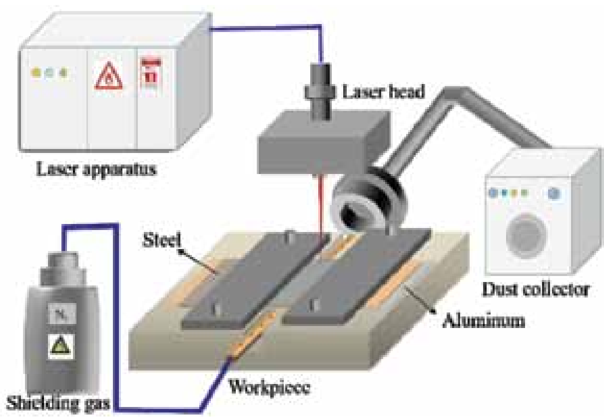

FIGURE 1
Schematic diagram of the laser oscillating welding configuration.

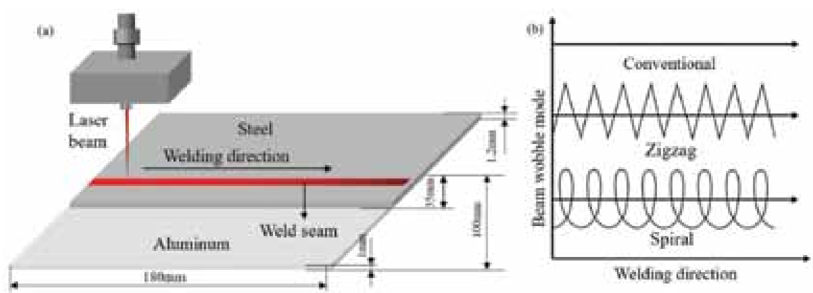

FIGURE 2
(a) Schematic diagram of the DP780 dual phase steel-5083 Al alloy laser lap welding configuration used in this work and (b) plot of the three laser scanning path.

TABLE 2
Laser welding parameters used in this work.

No.	Wobble Type	Laser Power (W)	Wobble Breadth (mm)	Wobble Cycle (mm)	Wobble Frequency (Hz)	Welding Speed (mm/S)
1	Conventional	1400	1	0.786	28	22
2	Conventional	1500	1	0.786	28	22
3	Conventional	1600	1	0.786	28	22
4	Horizontal8	2200	1	0.786	28	22
5	Horizontal8	2300	1	0.786	28	22
6	Horizontal8	2400	1	0.786	28	22
7	Horizontal8	2500	1	0.786	28	22
8	Vertical8	2200	1	0.786	28	22
9	Vertical8	2300	1	0.786	28	22
10	Vertical8	2400	1	0.786	28	22
11	Vertical8	2500	1	0.786	28	22

tal8 and vertical8 welding modes the laser power needs to be increased to ensure the effective connection of the weld. The laser power in the conventional mode was selected from 1400 to 1600 W, and in horizontal8 and vertical8 modes the laser power was selected from 2200 to 2500 W. The specific test parameters are listed in Table 2.

2.3 Sample analysis techniques

After laser oscillation welding the metallographic and tensile specimens were cut along the direction perpendicular to the weld seam. The metallographic specimens were polished with 600#, 1000#, 1500#, and 2000# metallographic sandpaper in turn, and then the specimens were mechanically polished with a metallographic specimen grinding and polishing machine (UniMP-202; Suzhou Fema Precision Instrument Company, Ltd.) to obtain a glossy mirror surface. The surface of each specimen was etched using a solution of $HF:HNO_3:H_2O$ in the ratio 1:2:7.

The weld morphology and microstructure were analysed using a planimetric microscope (VH1202; Huiguang Technology (Suzhou) Company, Ltd.) and a metallographic digital microscope (M2m; Ario Image). The joint morphology was observed with a scanning electron microscope (SEM) (Quanta 250; FEI Company) fitted with an energy dispersive spectroscope (EDS) so that the distribution of elements in each part of the joint could be analysed.

The microhardness of the laser welds was measured using a micro Vickers hardness tester (VH1202; Buehler, Inc.) and ASTM E384 was selected as the measurement standard, with a loading force of 500 g and a holding time of 10 seconds. Tensile testing was performed on an electronic universal tensile testing machine (CMT4202; Shanghai Jiehu Instrument Company, Ltd.). For the tensile test, 1.2 and 1.0 mm thicknesses of material were added on each side of the base material (BM) to ensure that the tensile force is parallel to the joint interface.

3 RESULTS AND DISCUSSION

3.1 Macroscopic evaluation

Figure 3 shows the laser welds obtained in conventional, horizontal8, and vertical8 welding modes. It can be seen that the DP780 dual phase steel-5083 Al alloy joints lapped by all three scanning paths were completely welded through the upper steel plate and partially melted in the lower 5083 Al alloy plate. In the conventional mode the weld surface was poorly formed, with spatter and porosity evident. With oscillation welding the weld surface formation was much improved, exhibiting a clear surface texture and reduced spatter. This is because the laser beam stirs the molten pool during the oscillation welding process, which can reduce the thermal stress concentration, stabilize the molten pool, and help discharge the gas in the meltpool.

The change in welding mode implies a change in heat input and heat dissipation. The welding results reveal that oscillation welding has a strong adaptability to the changes in welding power and heat input. In conventional laser welding, owing to the burning of alloying elements caused by the joint on both sides of the biting edge, the holes appear in the joints. When oscillation welding is used, the biting edge disappears and the number of holes is reduced [17].

FIGURE 3
Optical micrographs of weld seams obtained with different scanning paths: (a) Conventional mode weld surface and (b) cross-section; (c) horizontal8 mode weld surface and (d) cross-section; and (e) Vertical8 mode weld surface and (f) cross-section.

3.2 Microstructural characteristics

As can be seen in Figure 4, in the conventional mode a large amount of ferrite is formed in the laser welded joint because of the high temperature gradient and the influence of the meltpool cooling conditions. Pendulum welding changes the trajectory of the spot, which indirectly changes the energy distribution and flow characteristics, affecting the thermal mixing in the melt pool and resulting in a lower peak temperature in the fusion zone (FZ) of the weld; consequently, when the laser is used for oscillation welding, the amount of ferrite within the weld is reduced and the amount of martensite is increased, as shown in Figure 4(b) and Figure 4(c). The DP780 dual phase steel-5083 Al alloy joints formed *via* both horizontal8 and vertical8 laser oscillation welding methods consist primarily of martensite, with only a small amounts of ferrite at the bottom and sides of the joints.

The DP780 dual phase steel-5083 Al alloy joint laser welded using the conventional mode is shown in Figure 5. Here one can see that the Fe in the DP780 dual phase steel plate is rapidly diffused into the 5083 Al alloy plate by the laser heat source, as the heat source of laser welding in the conventional mode is transferred toward the plate thickness, resulting in a greater melt depth in the welded joint. A greater melt depth means an increase in IMC content. By analysing the composition of the joint, as given in Table 3, it can be seen that the elemental Fe content within the joint gradually increases as the melting depth increases. The Fe content reaches beyond 60% at the bottom of the joint and the increase in the Fe element at the bottom of the joint has a negatively impacts the mechanical properties of the joint [18].

A DP780 dual phase steel-5083 Al alloy joint laser welded using the horizontal8 mode is shown in Figure 6. When welding in the horizontal8 mode the melt depth of the weld decreases and the melt width increases. As can be seen in Table 4, the Fe-rich phase content increases at the bottom of the welded joint, which is mainly thought of as Fe_3Al at the bottom of the joint. At the junction of the joint with the 5083 Al alloy side of the BM, the content of Fe gradually decreases and the steel–Al compounds are mainly FeAl and

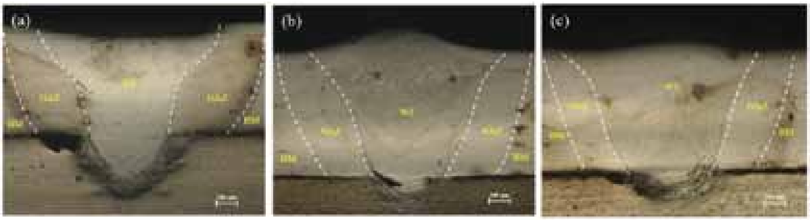

FIGURE 4
Optical micrographs for the metallographic organization of the DP780 dual phase steel-5083 Al alloy laser welded joints when using (a) conventional mode, (b) horizontal8 mode and (c) vertical8 mode.

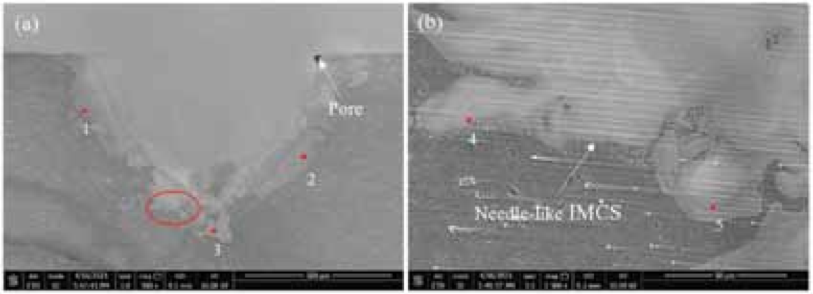

FIGURE 5
SEM micrographs showing the microstructure of a DP780 dual phase steel-5083 Al alloy laser welded joint interface formed in the conventional mode at (a) the bottom of the interface and (b) the DP780 dual phase steel-5083 Al alloy interface.

TABLE 3
Main components of the marked positions in Figure 5.

Position	Atomic Fraction (%)						Possible Phases
	Mg–K	Al–K	Si–K	Cr–K	Fe–L	Ni–L	
1	2.67	55.21	0.20	0.33	41.05	0.55	FeAl
2	7.62	77.41	0	0.22	14.44	0.31	$FeAl_3$
3	0.88	36.11	0.12	0.08	62.29	0.50	Fe_3Al
4	1.14	58.87	0	0.26	39.13	0.60	$FeAl_2$
5	0.33	8.47	0.52	0.21	90.14	0.33	Fe(Al)

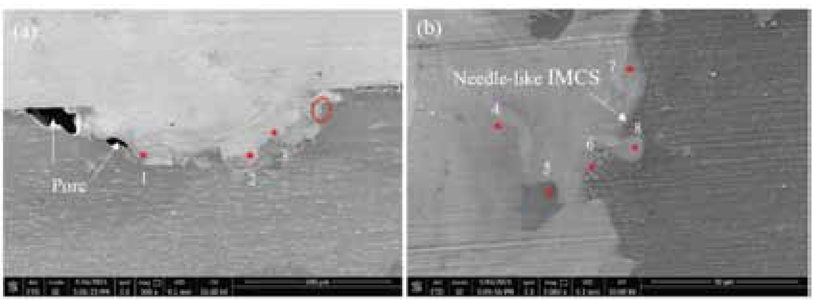

FIGURE 6
SEM micrographs showing the microstructure of a DP780 dual phase steel-5083 Al alloy laser welded joint interface formed in the horizontal8 mode at (a) the bottom of the interface and (b) the DP780 dual phase steel-5083 Al alloy interface.

TABLE 4
Main components of the marked positions in Figure 6.

Position	Atomic Fraction (%)						Possible Phases
	Mg–K	Al–K	Si–K	Cr–K	Fe–L	Ni–L	
1	4.42	28.83	0.17	0.28	67.05	1.08	Fe_3Al
2	0.14	19.84	0.42	0.17	78.76	0.52	Fe_3Al
3	0.20	18.85	0.33	0.66	79.13	0.63	Fe_3Al
4	0.54	18.49	0.60	0.26	79.81	0.30	Fe_3Al
5	1.35	56.55	0.02	0.07	41.52	0.49	FeAl
6	1.29	69.13	0.00	0.00	29.09	0.48	$FeAl_2$
7	0.84	43.28	0.08	0.18	55.10	0.54	FeAl
8	4.23	91.04	0.00	0.07	4.13	0.53	Al(Fe)

$FeAl_2$. Under welding in the horizontal8 mode the steel element diffuses better in the 5083 Al alloy plate and the steel–Al compound is mostly a steel-rich phase. Although there are holes on the left side of the joint, the better forming effect can effectively compensate for this defect.

Figure 7 shows a DP780 dual phase steel-5083 Al alloy joint laser welded in the vertical8 mode. Under welding in the vertical8 mode the IMCS layer thickness of the weld increases and 'islands' of IMCs appear at the bottom of the weld. As can be seen in Table 5, the Fe-rich phase content increases at the top of the welded joint and is dominated by Fe_2Al_5 and $FeAl_2$ at the bottom of the weld, which results from the reduced heat input *per* unit area of the weld by the Vertical8 mode and the weakened diffusion of Fe atoms in Al as the weld depth increases. At the bottom end of the DP780 dual phase steel-

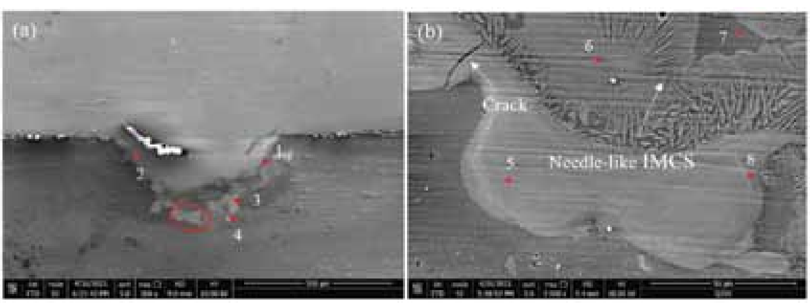

FIGURE 7
SEM micrographs showing the microstructure of a DP780 dual phase steel-5083 Al alloy laser welded joint interface formed in the vertical8 mode at (a) the bottom of the interface and (b) the DP780 dual phase steel-5083 Al alloy interface.

TABLE 5
Main components of the marked positions in Figure 7.

Position	Atomic Fraction (%)						Possible Phases
	Mg–K	Al–K	Si–K	Cr–K	Fe–L	Ni–L	
1	11.16	80.13	0.00	0.10	7.90	0.71	$FeAl_3$
2	0.38	14.58	0.37	0.37	83.78	0.53	Fe(Al)
3	1.74	22.35	0.40	0.23	74.66	0.62	Fe_3Al
4	5.32	72.96	0.11	0.11	21.13	0.36	Fe_2Al_5
5	1.48	47.26	0.05	0.19	50.28	0.73	FeAl
6	2.66	72.78	0.00	0.35	23.88	0.33	Fe_2Al_5
7	2.26	76.04	0.00	0.14	21.23	0.32	Fe_2Al_5
8	1.25	67.23	0.00	0.00	31.17	0.36	$FeAl_2$

5083 Al alloy joint, elemental Al is predominant. Cracks appear in the IMC layer of the weld and these cracks can easily become the starting point for joint failure, affecting the mechanical properties of the weld [19]. Compared to the conventional and horizontal8 welding modes, the vertical8 mode exhibits an increase in the IMCs of the joint pinning.

Because the density of liquid Fe is greater than that of Al, the top portion of the molten pool is composed of Al and the bottom portion is composed of Fe. In conventional mode laser welding the phenomenon of 'Al above and steel below' is obvious. With more Al-rich IMCs above the joint, the bottom of the weld produces a large amount of Fe(Al) solid solution and the varying weld composition of the various regions will affect the performance of the joint. When laser welding in horizontal8 and vertical8 modes the laser beam agitates the meltpool to stir the two elements of Fe and Al evenly, thereby suppressing the phenomenon of "Al above and steel below'. The laser welded DP780 dual phase steel-5083 Al alloy joints exhibit a more uniform distribution of Fe and Al compounds in all regions, producing an increase in the content of Fe-rich phase compounds at the weld interface. Swing welding can control the dispersion of Al, weakening interfacial reactions, which is conducive to improving the mechanical properties of the joint.

3.3 Mechanical properties

3.3.1 Microhardness characteristics

Figure 8 shows the microhardness of the DP780 dual phase steel-5083 Al alloy joints formed in the different laser welding modes. The DP780 dual phase steel BM microhardness was around 250 HV. The weld areas of DP780 dual phase steel-5083 Al alloy joints formed in horizontal8 and vertical8

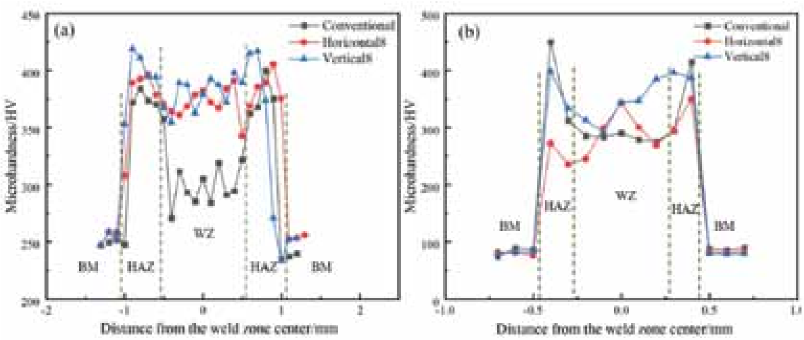

FIGURE 8
Microhardness profiles of DP780 dual phase steel-5083 Al alloy weld sections produced with the three different laser welding modes on (a) the DP780 dual phase steel side and (b) the 5083 Al alloy side.

modes exhibited significantly increased microhardness of up to 371 and 380 HV, respectively. This contrasts with the conventional mode where the microhardness of welded joints was only 303 HV. On the 5083 Al alloy side the impact of the three welding modes on the microhardness of the joint exhibited no significant differences.

When conventional mode laser welding was employed the cooling rate of the welded joint is low and the joint as a whole consists of martensite. In oscillating laser welding mode the cooling rate of the welded joint is high and the weld as a whole transforms into martensite, resulting in a higher microhardness of the welded joint in both horizontal8 and vertical8 modes than in conventional mode welded joints. Laser scanning of the material surface causes thermal cyclin, and the heat affected zone (HAZ) of the joint has a greater proportion of martensite, resulting in a higher microhardness in the HAZ of all three joints [20]. The hardness of the parent material of the 5083 Al alloy was only around 90 HV, so one can observe that the microhardness of the 5083 Al alloy side joints welded in all three modes increased significantly. This occurs because a large amount of steel is influxed into the 5083 Al alloy side joints during welding, and a large amount of steel-Al compounds with higher microhardness than the parent material is formed at the bottom.

3.3.2 Tensile strength characteristics

Figure 9 shows the variation of tensile loads obtained for the DP780 dual phase steel-5083 Al alloy laser welded joints in different welding modes. One can observe in Figure 9 that the maximum shear strength of the laser welded DP780 dual phase steel-5083 Al alloy joints welded using the conventional mode was only 73 N/mm, whilst the maximum shear strength of welded joints in both horizontal8 and vertical8 laser welding modes can reach 114 and 93 N/mm, respectively, with significant improvement in joints welded by

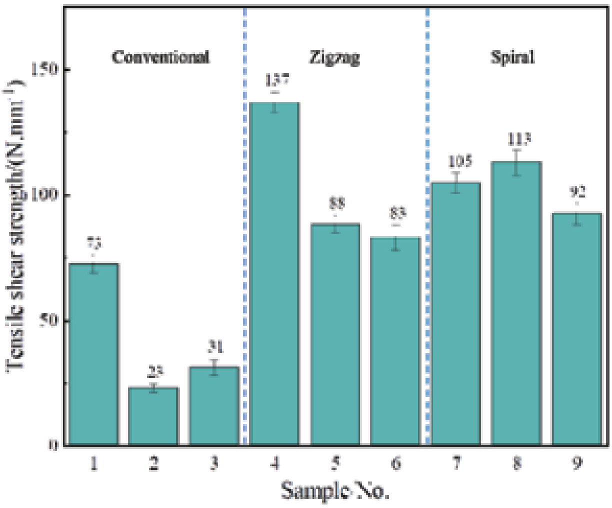

FIGURE 9
Bar chart of the tensile shear strength *per* unit length of the DP780 dual phase steel-5083 Al alloy joints laser welded with the three scanning paths.

laser oscillation. Non-swing welding in the conventional mode leads to inadequate diffusion of Fe and Al atoms in the joint. During welding, too low a power leads to insufficient fusion of the steel-side joint with the 5083 Al alloy plate to obtain a greater melt depth. But when high power is used, the melt depth increases but defects such as brittle IMCs, spatter and porosity in the weld also increase, affecting the mechanical properties of the weld and resulting in welded joints prone to fracture at the joint.

When oscillating laser welding in both horizontal8 and vertical8 modes is employed, the laser beam disturbs the meltpool and facilitates metal vapour discharge, which helps gas escape from the weld and reduces porosity in the weld. At the same time, oscillation laser welding can facilitate diffusion and fusion of Fe and Al atoms, and the DP780 dual phase steel-5083 Al alloy joint becomes more integrated. Under laser oscillation welding the contact area between the laser beam and the BM increases, and the contact area of the DP780 dual phase steel-5083 Al alloy welded joint increases [21]. Because the contact area of oscillation welding to the material surface increases and the power decreases, the weld depth of fusion decreases, effectively reducing the generation of brittle material in the weld and increasing the tensile strength of the welded joint.

4 CONCLUSIONS

Heterogeneous lap welding tests were performed on DP780 dual phase steel and 5083 Al alloy using a disk laser. The effects of conventional, horizontal8 and vertical8 scan paths on the macroscopic morphology, microstructure and mechanical properties of DP780 dual phase steel-5083 Al alloy joints were compared.

Laser pendulum welding of the DP780 dual phase steel-5083 Al alloy joints can reduce the number of weld defects and improve weld formation by increasing the flow of the meltpool and helping to remove gas from the molten pool through laser beam disturbance of the meltpool.

The microstructure of the DP780 dual phase steel-5083 Al alloy joints obtained by conventional laser welding and pendulum welding is basically the same. The weld is composed of martensite and ferrite, but because of the beam stirring in laser pendulum welding the meltpool is uniformly heated in all parts, so the martensite content of the joint is higher and the ferrite content is lower than that of conventionally laser welded DP780 dual phase steel-5083 Al alloy joints. At the same time, laser oscillation welding increases the amount of the needle-like intermetallic compound (IMC) in the DP780 dual phase steel-5083 Al alloy joint, but these IMCs have no adverse effect on the joint. Pendulum welding promotes the mixing of both DP780 dual phase steel and 5083 Al alloy in fluid form because of the disturbed meltpool of the laser beam, which reduces the generation of Al-rich-phase IMCs and helps to improve the mechanical properties of the joint.

Laser pendulum welding can effectively improve the mechanical properties of the welded joint. After welding, the microhardness of both DP780 dual phase steel-5083 Al alloy joints are higher than that of the base material (BM). The steel-side microhardness of the joint obtained in laser pendulum welding was 380 HV, a factor of 1½ times greater than that of the BM and a factor of 1¼ greater than that of the joint formed using conventional laser welding. Under laser oscillation laser welding the weld shear strength is also significantly improved with a maximum shear strength reaching 114 N/mm, an increase of 56% compared to that achieved with conventional laser welding.

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REFERENCES

[1] Marrapu B., Barnwal V.K., Chakrabarty S., Tewari A. and Mishra S.K. Experimental and numerical analysis on dual phase steel (DP780) sheet forming limit and effect of microstructure evolution on formability. *Journal of Materials Engineering and Performance* **29**(12) (2020), 8247-8260.

[2] She X., Jiang X.Q., Wang P.Q., Tang B.B., Chen K., Liu Y.J. and Cao W.N. Relationship between microstructure and mechanical properties of 5083 aluminum alloy thick plate. *Transactions of Nonferrous Metals Society of China* **30**(7) (2020), 1780-1789.

[3] Atabaki M.M., Nikodinovski M., Chenier P., Ma J., Harooni M. and Kovacevic R. Welding of aluminum alloys to steels: An overview. *Journal for Manufacturing Science & Production* **14**(2) (2014), 59-78.

[4] Kshirsagar R., Jones S., Lawrence J. and Tabor J. Measurement of ferrite content of stainless steel sheet welds using a new ferrite density number scale. *Journal of Materials Processing Technology* **274** (2019), 116278.

[5] Wallerstein D., Salminen A., Lusquios F., Comesaa R. and Pou J. Recent developments in laser welding of aluminum alloys to steel. *Metals* **11**(4) (2021), 622.

[6] Kshirsagar R., Jones S., Lawrence J. and Kanfoud J. Effect of addition of nitrogen through shielding gas on welds made homogenously and heterogeneously on 300 series austenitic stainless steels. *Journal of Manufacturing and Materials Processing* **5**(3) (2021), 72.

[7] Chen L., Wang C.M., Zhang X. and Mi G.Y. Effect of parameters on microstructure and mechanical property of dissimilar joints between 316L stainless steel and GH909 alloy by laser welding. *Journal of Manufacturing Processes* **65** (2021), 60-69.

[8] Iqbal N., Nath S., Coleman A.E. and Lawrence J. Parametric study of pulse arc welding (PAW) and laser beam welding (LBW) techniques for electrical vehicle battery cells. *Materials Science Forum* **1016** (2021), 611-617.

[9] Makoto S. and Junichi I. Laser welding of metal materials of different types. *Journal of the Japan Society for Abrasive Technology* **55**(6) (2011), 348-353.

[10] Galun R., Bordfeld H., Gattermann S. and Mordike B. Processing and influence on mechanical properties of precision laser beam welding of dissimilar material combination of stainless steel and brass. *Lasers in Engineering* **12**(3) (2002), 191-200

[11] Kraetzsch M., Standfuss J., Klotzbach A., Kaspar J., Brenner B. and Beyer E. Laser beam welding with high-frequency beam oscillation: Welding of dissimilar materials with brilliant fiber lasers. *Physics Procedia* **12** (2011), 142-149.

[12] Gao M., Liao W. and Chen C. Improving the interfacial bonding strength of dissimilar PA66 plastic and 304 stainless steel by oscillating laser beam. *Optics & Laser Technology* **138** (2021), 106869.

[13] Xi C., Zheng L.L., Yan B.C., Yu H., Meng J., Ze T., Jiang B., San B.L. and Nan J. Effect of laser beam oscillation on laser welding–brazing of Ti/Al dissimilar metals. *Materials* **12**(24) (2019), 4165.

[14] Dimatteo V., Ascari A. and Fortunato A. Continuous laser welding with spatial beam oscillation of dissimilar thin sheet materials (Al-Cu and Cu-Al): Process optimization and characterization. *Journal of Manufacturing Processes* **44** (2019), 158-165.

[15] Fetzer F., Sommer M., Weber R., Weberpals J-P. and Graf T. Reduction of pores by means of laser beam oscillation during remote welding of AlMgSi. *Optics and Lasers in Engineering* **108** (2018), 68-77.

[16] Wang Z.M., Sun L.L., Ke W.C., Zeng Z., Yao W. and Wang C.M. Laser oscillating welding of TC31 high-temperature titanium alloy. *Metals* **10**(9) (2020), 1185.

[17] Hugger F., Hofmann K., Kohl S., Dobler M. and Schmidt M. Spatter formation in laser beam welding using laser beam oscillation. *Welding in the World* **59**(2) (2015), 165-172.

[18] Shankar S. and Apelian D. Die soldering: Mechanism of the interface reaction between molten aluminum alloy and tool steel. *Metallurgical & Materials Transactions B: Process Metallurgy and Materials Processing Science* **33**(3) (2002), 465-476.

[19] Sheng J.D., Rui Y., Xin H.T. and Feng G.L. Migration behavior of IMC layer in twin-spot laser welding-brazing of aluminum to steel. *Materials & Design* **188** (2020), 108489.

[20] Yang J., Li Y.L. and Zhang H. Microstructure and mechanical properties of pulsed laser welded Al/steel dissimilar joint. *Transactions of Nonferrous Metals Society of China* **26**(4) (2016), 994-1002.

[21] Shi Y., Zhang H., Takehiro W. and Tang J.G. CW/PW dual-beam YAG laser welding of steel/aluminum alloy sheets. *Optics and Lasers in Engineering* **48**(7) (2010), 732-736.