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Influence of Laser Beam Orientation on Weld Morphology, Microstructure, and Mechanical Performance of Similar and Dissimilar Dual-Phase Steels: A Comprehensive Review

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Abstract

This review encompasses a comprehensive evaluation of the findings from various experimental works and computational data on welding dual-phase steel in similar and dissimilar configuration. It concentrates on the effect of the orientation of laser beam on geometrical features of the weld joint, microstructure, defect occurrence, and mechanical behavior of dual-phase steel. These steels, characterised by a ferritic matrix with islands of martensite, are among the most preferred Advanced High-Strength Steels due to their exceptional strength, formability, and crashworthiness. The automotive industry uses laser-based processing for dual-phase (DP) steels because of their high precision, adaptability, and suitability for lightweight design specifications. Laser incidence angle is considered as crucial factors for establishing melting pool dynamics, penetration depth, heat input and, stress field, joint strength and hardness uniformity, and fatigue lifetime. Experimental investigations prove the efficiency of the application of tilting angle in the range of 5° to 15° degrees in achieving successful results in balancing welding with the lowest number of defects. Numerical techniques, help in acquiring thermal cycle, key hole stability, and phase transformation kinetics data. This study aims to highlights some of the unresolved research areas, industrial applications, and future prospects of laser beam orientation adaptation.

Keywords: Beam Orientation; Dual Phase Steel; Laser Welding; Tilt Angle; Application in Automotive Sector; Computational Modelling.

1 Introduction

The demand for lightweight, high-strength materials in structural and automotive applications is growing, and dual-phase (DP) steels are being increasingly utilised. For components subjected to cyclic loading circumstances, these steels' exceptional qualities—such as their high strength, excellent ductility, and crash energy absorption—make them perfect. Dual-phase steels consist of soft ferritic matrices containing a hard martensitic phase. These modern steels belong to one of the more recognized high-strength advanced steels (AHAS) categories, having extraordinary properties fit for operational requirements of lightweight yet extremely high, with formability, coupled with damage resistance to impacts or heavy loads, compared to conventional steels [1][2][3][4]. The

nature of the microstructural constituents with good ductility-strength balance makes these steels very important for applications in the automotive industry for structural and safety components like B-pillars, A-pillars, reinforcements, crash boxes, or frame members [5][6][7].

Safety through lightweight vehicle construction has led to very strict regulations concerning consumption and emissions. Among the most widely applied DP steel grades, DP600, DP780, DP980 and DP1000, which have made their way into the market for use not only in tailor-welded blank sheet applications but also as blank forming pieces [8][9][10][11]. These steels have performed reasonably well in the electric vehicle environment, wherein 'safer' DP steels with enhanced resistance against impacts can be counterbalanced with reduced weight at other parts of the vehicle by the weight of the batteries [12][13].

There has been an increasing demand for welding of theses DP steels in similar and dissimilar configurations. The optimal performance of structures requires different joining techniques which should be applied to dual-phase DP steel materials. The system achieves weight savings through its design, which enables the use of multiple strength levels in a single component. Engineers can design flexibly while saving material costs because they can use lower-strength materials for non-critical areas while keeping higher-strength steels for essential load-bearing parts. The different grades of DP steels provide multiple opportunities to create dissimilar joints between different DP steels itself like DP980 and DP780 as well as between DP800 and DP600 which will enhance performance under different loading conditions [14]. Figure 1 highlights the dissimilar joints microstructures evolution which focused on characterizing the laser-welded dissimilar joints consisting of DP600 and DP980 and DP800 and DP 600 dual-phase steel materials. The SEM micrographs display the joint microstructural evolution which includes base metal microstructure with its ferrite-martensite dual-phase structure and HAZ area which developed tempered martensite and FZ area which showed mostly martensitic development. There is also an increasing trend in joining of DP steels to other lightweight materials such as DP600 and aluminum 6016 leads to better weight reduction and structural efficiency improvements for advanced engineering applications [15]. This is what is termed optimum material usage, stepping on strong materials where resistance to impacts and forming is paramount, and offsetting lighter alternatives in areas of lesser significance [12][13][16]. In short, these joinings are majorly needed for optimal functionality and design flexibility and, more importantly, are economically viable in the automotive and construction industries.

Laser or resistance spot welding are the two principal methods of joining, and both are suggested to be used mainly because of precision, high energy density, and suitability for serial production [17][18][19]. Laser welding enables designers to create more flexible designs through its ability to produce continuous joints and deeper welds and its capability to connect complex materials and different materials while creating minimal distortion. Figure 2 shows a robotic laser welding system which uses 3D scanners measures workpiece dimensions through its automatic system which simultaneously controls beam positioning and tilt and offset adjustments during the welding process. Proper beam orientation (tilt, offset, and incident angle) enables stable heat input which decreases defects and strengthens weld quality, making laser welding suitable for high-strength and lightweight applications. Furthermore, the laser beam inclination (tilt angle, incident angle, beam offset) has recently been shown to affect the fusion pool characteristics and, even more importantly, with respect to stresses, hardness, microcracking, residual stresses, and, generally, mechanical behaviour [20][21][22][23][24][25]. More oriented laser beams yield a uniform and less hardened heat-affected zone (HAZ), with increased toughness due to residual stress and even

higher fatigue toughness. However, it has been found that poorly oriented beams lead to pores, microcracking and stress concentration [26][27][28][29].

The international greenhouse gas reduction campaign is being supported by regulatory bodies who are promoting dual-phase (DP) steel as a preferred material. The European Union's 2035 ban on internal combustion engine vehicles and US regulations force manufacturers to adopt new joining techniques together with lightweight sustainable materials. The development of technology for similar and dissimilar DP steel joining needs additional research to support upcoming safety and sustainability requirements [13][30][31][32].

Thus, an important direction for future lightweight automotive structures is the effective welding of dual-phase steels. This study presents a comprehensive review of experimental and numerical investigations to evaluate how laser beam orientation and related welding parameters influence weld geometry, microstructure, defect formation, mechanical properties, and overall joint reliability in similar and dissimilar DP steels.

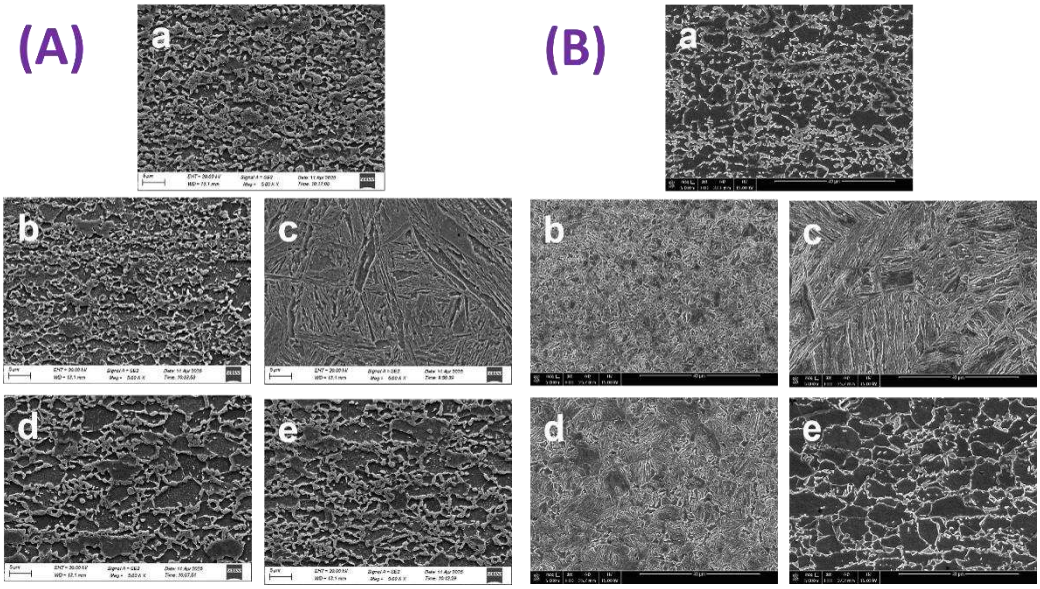


Fig. 1 The SEM micrographs display the laser-welded dissimilar joints of Dual-Phase steel which consist of (A) DP980 and DP780 materials, in which (a) DP980 base metal, (b) HAZ (DP980), (c) fusion zone (FZ), (d) HAZ(DP780), (e) DP780 base metal and (B) DP600 and DP800 materials, in which (a) DP600 base metal, (b) HAZ (DP600), (c) fusion zone, (d) HAZ(DP980), (e) DP980 base metal (where, M: martensite, TM: tempered martensite, B: bainite, F: ferrite, SPF: sideplate ferrite)

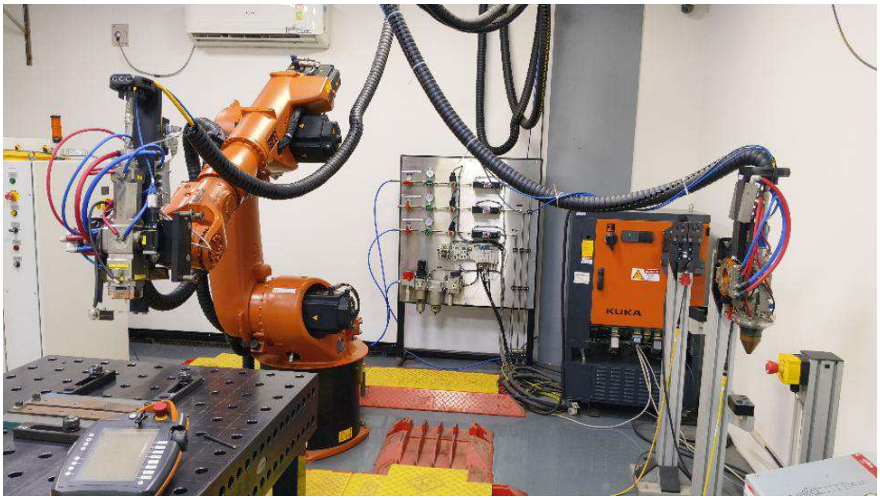


Fig. 2 The robotic laser welding system

2 Methodology

In order to obtain the relevant literature for this review, systematic searching of major scientific databases and journals was conducted from Google Scholar. ScienceDirect (Elsevier) was the main source of literature for publications associated with laser welding, effects of beam orientations, dual-phase steels and AHSS (Advanced High-Strength Steels). Additional literature was obtained from Springer Nature, MDPI, Taylor & Francis, Wiley Online Library, IEEE Xplore, Sage journals, and other online journal libraries.

In general, literature collection and reviewing for this topic included research papers on laser welding of both similar and dissimilar types of dual-phase steels like DP600, DP780, DP980, DP1000, etc., and other AHSS. Of particular interest for this literature review was the investigation of various beam orientations like tilting angle, beam offset, incidence angle, oscillation effect, weld pool characteristics, HAZ softening, residual stress, and fatigue properties.

The number of articles reviewed is estimated at around 119 and are chosen based on their years of publication between 1995 and 2026. For journal articles, the majority is sourced from Elsevier (37) while the others come from MDPI (17), Springer Nature (12), AIP Publishing (8), SAGE Journal (7), Wiley Online Library (7), IOP Science (6), Nature (5), Taylor & Francis (5), Cell Press (3), IEEE Xplore (2), J-Stage (2), , Annualreviews (1), Castman (1), EBSCOhost (1), Emerald Publishing Limited (1), Researchgate.net (1), The American Society of Mechanical Engineers (1), Trans Tech Publications Ltd (1), and SciELO Brasil (1) (Figure 3; Table 1). The methodology used for this review enabled all aspects to be critically analyzed, including current research progress, applications in the industry, limitations, and future research scope.

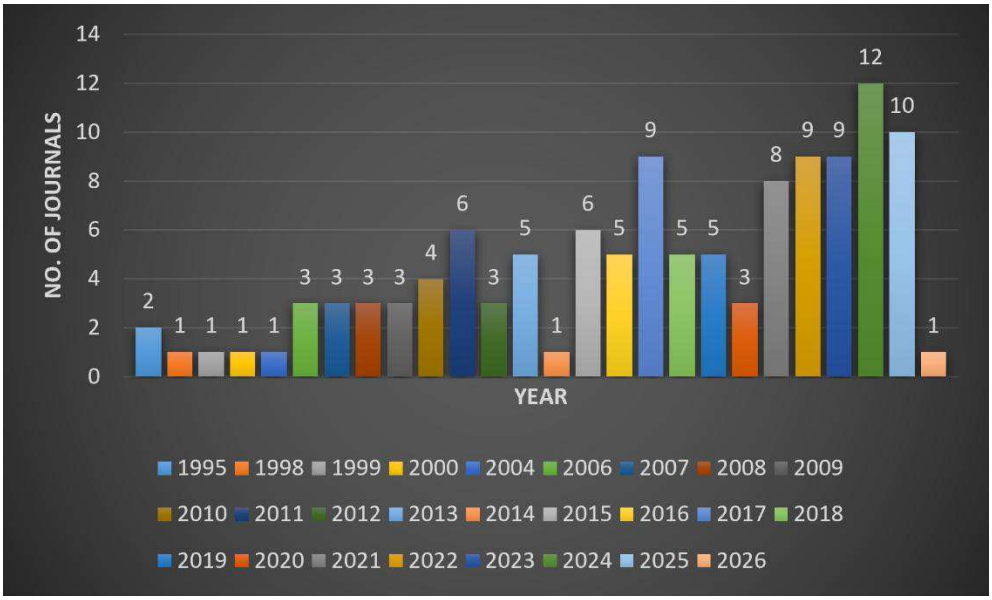


Fig. 3 Graph between Year and No. of Journals (Google Scholar)

Table 1 Details of Journal

Publication	Journal	Number of journals
Springer Nature	Archives of Civil and Mechanical Engineering	1
	Acta Metallurgica Sinica (English Letters)	1
	The International Journal of Advanced Manufacturing Technology	4
	Journal of Materials Science	1
	Production Engineering	1
	Journal of Materials Engineering and Performance	2
	Applied Physics A	1
	Advanced Manufacturing Technologies: Modern Machining, Advanced Joining, Sustainable Manufacturing	1
Wiley Online Library	Steel research international	3
	Advances in Materials Science and Engineering	2
	Materialwissensenschaft und werkstofftechnik	1
	Mathematical Problems in Engineering	1
MDPI	Metals	3
	Energies	1
	Sensors	3
	Materials	9
	Electronics	1
Cell Press	Heliyon	3

Taylor & Francis	Materials Science and Technology	2
	Computer-Aided Design and Applications	1
	Science and Technology of Welding and Joining	1
	Energy Sources, Part A: Recovery, Utilization, and Environmental Effects	1
Sage journals	Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications	1
	Journal of Reinforced Plastics and Composites	1
	Science and Technology of Welding and Joining	4
	Advances in Mechanical Engineering	1
IEEE	2013 Design, Automation & Test in Europe Conference & Exhibition (DATE)	1
	IEEE Transactions on Automation Science and Engineering	1
J-STAGE	Materials Transactions	1
	ISIJ international	1
iopscience	Journal of Physics D: Applied Physics	4
	Materials Science and Engineering	1
	Engineering Research Express	1
AIP Publishing	journal of laser applications	7
	Journal of Applied Physics	1
Elsevier	Materials & Design	5
	Transportation Engineering	1
	Journal of materials processing technology	4
	Computational materials science	1
	Advances in engineering software	1
	Optics & Laser Technology	2
	Materials Science and Engineering	3
	Journal of Manufacturing Processes	4
	Additive Manufacturing	1
	Journal of Materials Science & Technology	1
	Journal of Alloys and Compounds	2
	International Journal of Mechanical Sciences	1
	Finite elements in analysis and design	1
	Physics procedia	1
	International Journal of Thermal Sciences	3
	Applied Surface Science	1
	International Communications in Heat and Mass Transfer	1

	Micron	1
	Measurement	1
	Control Engineering Practice	1
	Engineering Failure Analysis	1
annualreviews	Annual Review of Materials Research	1
researchgate.net	Scientia Iranica	1
The American Society of Mechanical Engineers (ASME)	Journal of Pressure Vessel Technology	1
Trans Tech Publications Ltd	Key Engineering Materials	1
Emerald Publishing Limited	Multidiscipline Modeling in Materials and Structures	1
Nature	Nature communications	1
	Communications materials	1
	Scientific Reports	3
CASTMAN	Proceedings of LiM	1
EBSCOhost	Journal of Mining & Metallurgy, Section B: Metallurgy	1
SciELO Brasil	Soldagem & Inspeção	1

3 Beam Orientation Variables and Their Effects on Laser Welding of Dual-Phase Steels

Beam orientation includes several key variables in laser welding that govern energy absorption, and the trajectory of molten flow, leading to the determination of microstructure and mechanical behaviour of the welded joint. There has been extensive research into the identification of these orientation variables by many researchers studying different welding processes using Laser, arc and resistance spot welding technologies on dual-phase steels (DP) and other classes of high-strength steels (AHSS) [33].

Such work made it possible to discover the fundamentals of managing orientation towards the better quality of Laser welding under a very wide variety of material systems and processing conditions (Table 2) [34].

Table 2 Summary of Research on Beam Orientation and Angle Effects in Laser Welding Processes

Material(s)	Welding Process	Key Variable(s) Related to Beam Orientation	Main Findings Related to Beam Orientation	Performance & Optimization Insights	Reference
304 Stainless Steel (thin sheet)	Pulsed Laser Spot Welding	Beam Incident Angle (30°–75°)	- Beam incident angle significantly alters weld spot shape (elliptical) and dimensions. - Penetration Depth	- Experimental and metallographic analysis used to characterize the direct effects of	[35]

			(PD) and Bead Width (BW) increase with angle; Bead Length (BL) decreases. - Asymmetrical "tumour" formation in cross-section at high power densities due to keyhole dynamics and refraction.	beam angle on weld geometry.	
Mild Steel	High Power Direct Diode Laser (HPDDL) Welding	Tilt Angle (38° to weld direction), Beam Profile (Rectangular strip)	- Inherently asymmetric temperature field and weld pool due to angled, strip-shaped beam. - The pre-heating effect from the beam's leading edge creates a wider, "half-peach" shaped weld pool on one side.	- Numerical simulation (FDM) and experimental validation highlight the critical role of beam geometry and orientation in heat distribution.	[36]
5182 Al-Mg Alloy	Laser Welding	Beam Defocus	- Inverse modeling demonstrates that beam defocus is a key parameter, among others, that can be adjusted to achieve a target weld geometry.	- A hybrid approach (3D Heat Transfer Model + Genetic Algorithm) finds multiple parameter sets (including beam defocus) to achieve identical target weld attributes, establishing a scientific	[37]

				optimization framework.	
316L Stainless Steel	Laser Welding	Defocus Distance	- Confirms that defocus distance has a significant, non-linear impact on the Depth-to-Width Ratio (DWR).	- A hybrid metamodel ensemble (EGBM) + NSGA-II algorithm systematically optimizes beam parameters (power, defocus) and speed for conflicting objectives (energy vs. quality), providing a Pareto-optimal front for decision-making.	[38]
(Various)	(Various Laser & Welding Processes)	(Review of various parameters, including beam orientation)	- Synthesizes findings that beam orientation and related parameters are critical factors influencing weld quality and geometry across studies.	- Comprehensive review compares optimization methods (RSM, ANN, GA, Taguchi), providing a selection guide and highlighting that hybrid methods (e.g., GA+RSM) are often superior for complex, multi-objective problems involving parameters like beam orientation.	[39]

Mild Steel (implied from model parameters for iron). - The model uses optical constants for molten iron (n=3.6, k=5.0 at 1070 nm).	Fiber Laser Welding (Model)	- Beam Profile Formulation: Gaussian vs. Measured (complex) vs. Top-hat profile.	- The central, high-intensity part of the beam profile has minimal impact on keyhole shape if the focal point is near the surface, as the keyhole initiates at the beam periphery. - A top-hat profile would create a steeper keyhole entrance than a Gaussian profile.	- A Gaussian beam model is often sufficient for predicting keyhole geometry and penetration trends. - Optimization should consider the actual intensity distribution of the beam, especially for deep penetration or defocused conditions.	[40]
2219 Aluminum Alloy. - Skin: 2219-T8, 6 mm thick - Stringer: 2219-T6, 4 mm thick - Filler Wire: ER2319 (ø 1.2 mm)	Double-Sided Laser Beam Oscillation Welding (DLBOW)	- Beam Incident Angle (α): 20°, 30°, 40° - With and without beam oscillation.	- A smaller incident angle (20°) significantly reduced porosity (0.26% vs. >3.45% at 40°). - A smaller angle improved keyhole stability and molten pool flow, allowing bubbles to escape more easily. - Mechanical properties (hoop tensile strength) were highest at the 20° angle.	- For T-joint configurations, minimizing the beam incident angle is critical for defect suppression. - Combining a small incident angle with beam oscillation is a highly effective strategy for optimizing weld quality and mechanical performance in complex joints.	[41]
Dissimilar Pair: - AA6013 Aluminum Alloy	Laser Welding-Brazing with filler wire	- Laser Beam Deviation Distance: Offset from the Al sheet edge (0.5, 0.75,	- The deviation distance (effectively controlling heat distribution between steel and	- Precise beam positioning is essential for controlling heat input to the steel	[42]

- Q235 Low-Carbon Steel - Both 2.5 mm thick - Filler Wire: ER4043 (Al-Si) - Steel prepared with hot-dip galvanized zinc coating.		1.0 mm). - Beam tilted 12° (trailing).	aluminum) critically affected the formation of Fe-Al intermetallic compounds (IMCs). - An optimal distance (0.5 mm) ensured good wettability and a thin, continuous IMC layer (1.8–6.2 μm). - Excessive deviation (1.0 mm) prevented bonding.	side, which governs IMC growth. - Optimizing the beam's lateral position is a key mechanism for achieving sound dissimilar joints by managing brittle phase formation.	
Commerciall y Pure Titanium Tubes. - Dimensions: 0.8 mm outer diameter, 0.7 mm inner diameter. - Application: Capsule for Iodine-125 radioisotope seed.	Pulsed Nd:YAG La ser Welding	- Focal Position: Distance above the tube end (2.9 - 4.5 mm). - Tilt Angle: Tube angle relative to beam (5° - 28°).	- The focal position was the most critical parameter for controlling the melted length for sealing. - A specific focal position range (3.18–3.35 mm) was optimized to achieve the target melt length (1.3–1.4 mm). - A slight tube tilt was necessary for uniform melting.	- Demonstrates that the axial position of the beam focus relative to the workpiece is a fundamental aspect of "beam orientation" for micro-welding applications. - Statistical optimization (Taguchi/Regressi on) is highly effective for determining precise beam positioning parameters.	[43]

3.1 Tilt Angle Effects on Penetration, HAZ, and Weld Symmetry

One of the most influential parameters in DP steel Laser welding, the laser tilt angle, has been highlighted in most studies as shown in Figure 4. The laser beam tilt angle is an essential orientation parameter that can significantly

affect weld penetration, HAZ properties, weld symmetry, and performance of DP joints. Many studies demonstrated that moderate inclinations in the range from 5° to 15° positively influence weld penetration uniformity, stabilizing the keyhole behavior and reducing welding defects like porosity, undercutting, humping, and surface waviness [44]. These positive outcomes can be achieved by redistributing laser energy on the workpiece surface, ensuring stable fluid flow and uniform solidification of the molten metal.

When dealing with dissimilar DP steels, the choice of direction for the inclined beam is also of particular importance. It is usually tilted or shifted towards the side with higher melting point temperature, thermal conductivity, thickness or strength level. For instance, when DP780–DP980 joints are created, it is advisable to direct the laser beam at the DP980 part because the latter has higher content of martensite, which makes it harder and stronger than DP780 material [14]. Such a measure helps compensate for the thermal difference by providing extra energy necessary for melting the side with higher melting point temperature and keyhole formation.

In fact, the optimal beam tilt affects the way of moving of heat flux and minimizes thermal gradients in the welding area [45]. It allows narrowing the softening area of the HAZ, creating uniform hardness of the welded joint, and increases tensile strength. In addition, there is a variety of papers dedicated to the impact of the optimal tilt on the symmetry of the weld since it promotes the symmetrical distribution of liquid metal flow in both sides of the weld seam [46].

Penetration capability is heavily influenced by inclination angle. Optimal penetration is always observed at 0° when conducting trailing angle laser welding since the laser energy is coupled into the keyhole. On the other hand, the deeper the inclination, the lesser the penetration depth as more reflection occurs and lower energy concentration takes place at the point of interaction, specifically after exceeding 20° [47]. Inclinations above 45° may result in keyhole instability, asymmetrical joint formation, less penetration, and susceptibility to defects; thus, such inclination angles should not be used for industrial purposes [48]. As such, having an optimal inclination angle and choosing the right tilt angle towards the more thermally demanding material is highly important in ensuring optimum joint morphology and mechanical characteristics as shown in Figure 5.

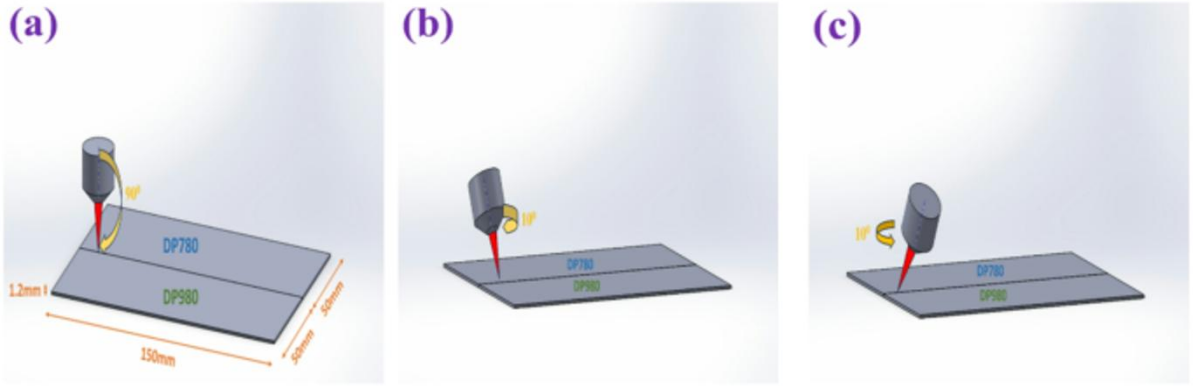


Fig. 4 Laser beam orientation: (a) no tilt, (b) a 10-degree tilt on the DP780 side, and (c) a 10-degree tilt on the DP980 side from perpendicular to the direction of welding [49]

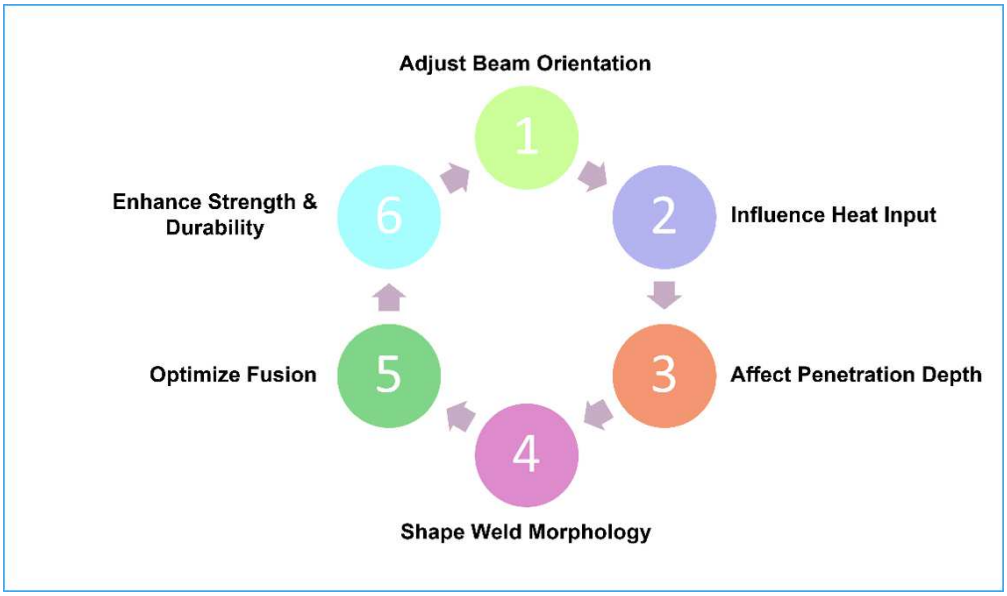


Fig. 5 Laser welding orientation effect on weld characteristics

3.2 Tilt Angle and Thermal Distribution

Tilt angle of the laser beam is important for controlling thermal distribution in laser welding since it influences the laser-material interaction, energy absorption, and heat transfer path in the work piece. While laser power and welding speed are parameters that influence the quantity of heat input, tilt angle influences mainly the distribution of heat and the process of energy transformation to the keyhole and molten pool. In several studies on experiments and numerical simulations, it has been shown that moderate tilt angles of the laser beam (usually 5° to 15°) increase the efficiency of energy transfer and contribute to forming a relatively uniform temperature distribution inside the fusion zone and the heat-affected zone (HAZ).

The effect of the tilt angle on thermal profile depends largely on the materials' properties, such as thermal conductivity, absorptivity, melting temperature, and plate thickness. In asymmetric joining of materials, the beam is usually tilted towards the side that possesses high thermal conductivity, higher melting temperature, thicker plate, or higher strength grade due to differences in their thermal dissipation rates. The tilt angle helps to make up for the differences in terms of heat dissipation. Specifically, in the joining of DP780/DP980, tilting the beam towards the DP980 material increases the symmetry of the welding operation, as DP980 usually needs relatively higher energy density to ensure fusion due to the higher degree of martensite in it. This has been proven by numerical simulations using finite element and CFD analysis techniques.

The heat input distribution during tilting of the beam will also depend on other interrelated factors, such as laser power, welding speed, focus, beam diameter, shielding gas flow rate, and leading/trailing angles of the laser welding operation. The parameters that exhibit the most pronounced interaction between themselves and the tilting angle of the beam are welding speed and laser power, since they define linear heat input, whereas the angle of inclination determines the heat distribution within the weld. Optimum inclination angles ensure improved forward heat transfer processes and stable Marangoni convection, resulting in deeper penetration and narrower HAZ formation. Nevertheless, excessive inclination angles result in increased beam reflection from the surface of the workpiece, reduced energy density at the point of interaction of the laser beam, inhomogeneous temperature field

within the weld, inadequate depth of penetration, instabilities in keyhole formation, and asymmetrical joint profiles [50]. Thus, inclination angle can also be defined as an integrated parameter of thermal control rather than an independent one.

The microstructural characteristics and weld geometry defects of fiber laser welded DP980 steel are illustrated in Figure 6. The welded joint cross-section exhibits typical weld droop along with the distinct microstructural regions, namely the base metal (BM), heat-affected zone (HAZ), and fusion zone (FZ). The base metal DP980 steel consists of a characteristic dual-phase ferrite–martensite microstructure containing approximately 56 vol.% martensite. In the HAZ, tempered martensite formation is observed due to thermal exposure during welding, resulting in significant softening and a reduction in hardness to nearly 280 HV compared to the base metal hardness. In contrast, the fusion zone exhibits a predominantly martensitic microstructure formed under rapid cooling conditions, leading to a high hardness value of approximately 480 HV. Furthermore, the adjacent regions reveal asymmetrical HAZ softening caused by the non-uniform thermal distribution during laser welding. This thermal asymmetry can be effectively minimized through optimized beam orientation, which improves heat distribution and enhances overall weld quality and mechanical performance [51].

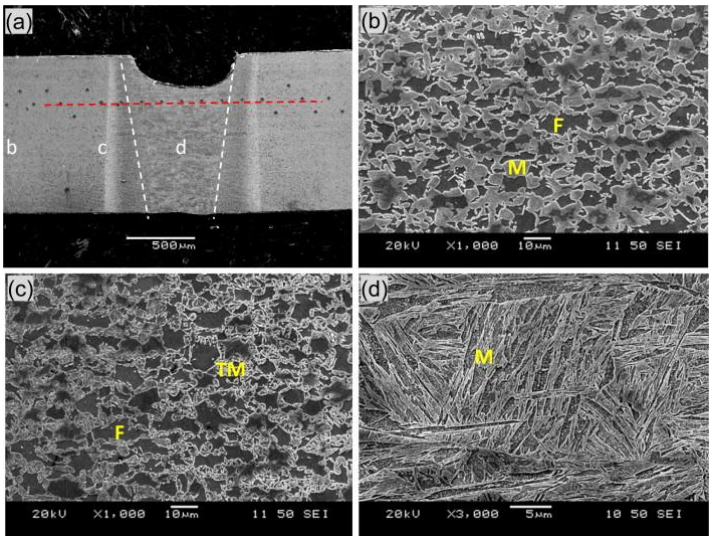


Fig. 6 Microstructural characteristics and weld geometry defects in fiber laser welded DP980 steel showing (a) complete weld cross-section with weld droop and distinct BM, HAZ, and FZ regions, (b) dual-phase ferrite–martensite microstructure of the base metal, (c) tempered martensite formation and HAZ softening, and (d) martensitic fusion zone formed under rapid cooling [51]

The tilt angle of the laser beam plays an essential role in controlling the thermal distribution during laser welding and, therefore, has a considerable effect on the fatigue fracture initiation, propagation, and morphology of dissimilar DP780-DP980 steel joints. Changes in the heat distribution resulting from tilting of the laser beam lead to changes in weld morphology, stress distribution, hardness profile, and microstructure. According to Kumar et al. [49], tilting the laser beam towards the DP980 side led to improvement of thermal distribution through shifting the heat towards the stronger component and, hence, balancing the thermal gradient and eliminating stress concentration in the weld.

The influence of laser beam inclination on fatigue crack formation behaviour was presented in Figures 7 (a) and (b).

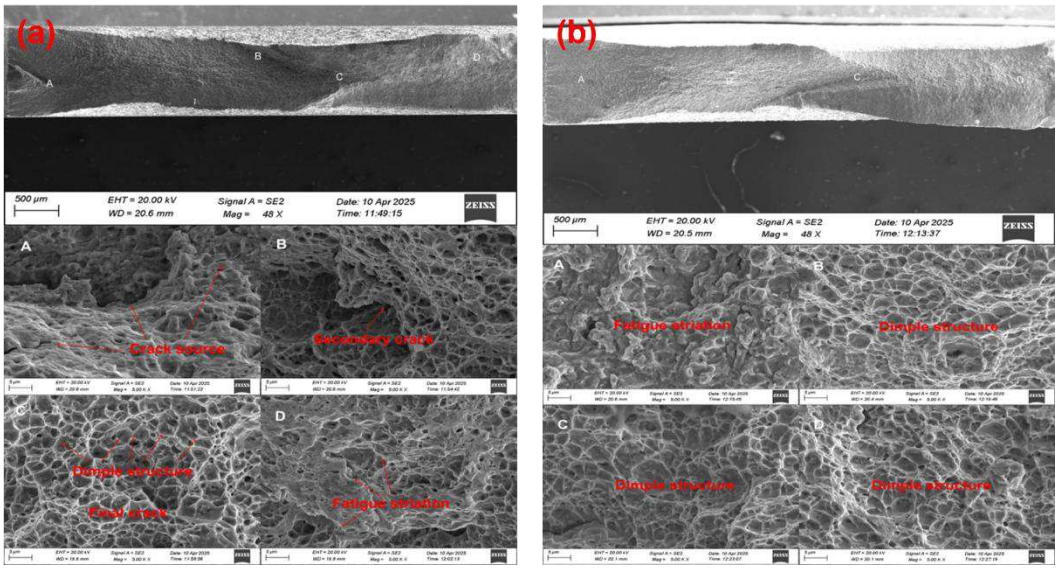


Fig. 7 SEM fatigue fracture surfaces of dissimilar DP780–DP980 laser welds under (a) no-tilt and (b) DP980-side tilt conditions [49]

In the no-tilt welding case, the appearance of fatigue cracks at higher thermal/mechanical heterogeneous areas, with the formation of local high hardness values, indicated the nucleation area for the generation of fatigue cracks. Fatigue fracture surfaces were distinguished through the existence of fatigue striations and subsequent ductile dimple rupture, which implied that fatigue cracks propagated along these areas. In sharp contrast to this, the welded joint with laser beam inclination towards DP980 steel had the fatigue fractography consisting of large areas of ductile dimples without any second crack appearance, implying enhanced fatigue properties owing to the formation of less thermal gradient and smaller residual stress concentration.

It has been previously reported that proper laser beam inclination helps reduce the residual stress and increase the symmetry of welded joints due to the reduction of thermal gradients; hence, the welding of dissimilar DP steels with beam inclination towards DP980 steel is an efficient way to control thermal distribution.

3.3 Incident Angle and Energy Absorption

This is the incidence angle that is fundamentally significant for the effective absorption of laser energy and the formation of the hole geometry. It constitutes the angle between the laser beam and the surface of the workpiece. An inclined laser incidence would trigger a whole range of events that would further be detrimental, such as losses caused during laser reflection, excessive heating, and unwarrantedly hardening by crack networks [52][53][54]. Different incidence angles using DP steel also largely affect the development of the hardness gradient at the weld joint, and that of the remaining stresses [26][52][55][56]. Advanced work indicates that the absorption coefficient of Fresnel displays maximum limits as the angle of incidence approaches the Brewster angle; furthermore, the absorption efficiency varies by a wide margin in reference to the depth of the hole being generated. These findings imply that when optimizing the angle of incidence, one must take into account not only the optical properties of

the material but also the dynamics of the penetration hole so that the coupling energy remains steady throughout the welding process [57].

The orientation of a laser beam directly impacts the efficiency and form of the energy provided to a material, rendering typical 2D heat input calculations erroneous. When a laser is tilted away from the perpendicular (normal) position, it alters the beam's footprint, reflectivity, and penetration mechanics [58]. The circular beam spot stretches into an ellipse when a laser beam strikes a surface at a certain angle, increasing the interaction area and diluting the localized power density as shown in Figure 8[59]. The mechanism is as follows: the spot area increases by a factor of 1/Cosθ , and effective power density becomes I_0 Cosθ , where I_0 is the peak intensity of a perpendicular beam and θ is the inclination angle relative to the surface normal [59]. Asymmetric heat distribution and a melt pool result from a tilted beam's skewing of the thermal profile. Equation 1 shows the heat flux absorbed by the top surface when Laser is incident on the surface at and angle θ[59].

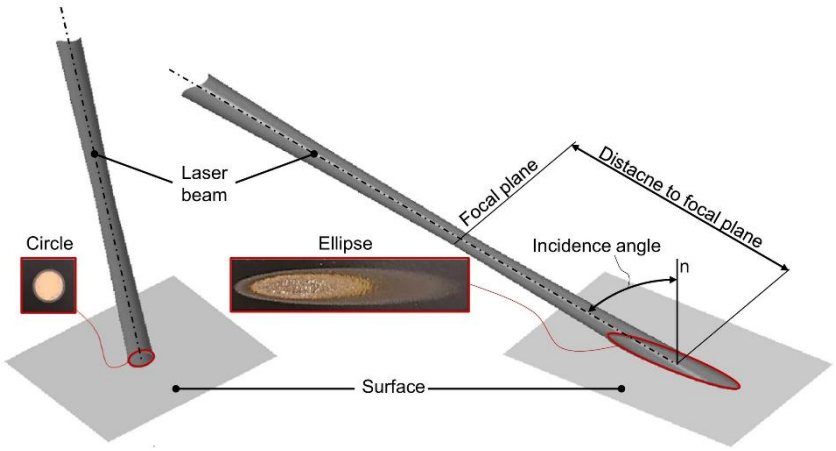


Fig. 8 Change in shape of weld bead dimension due to change in Laser beam incidence angle[59] [59]

$$q(x,y) = \frac{2P\eta}{\pi r_x r_y} \exp\left(-2\left(\frac{x^2}{r_x^2} + \frac{y^2}{r_y^2}\right)\right) \quad (1)$$

Where q is the effective heat flux distribution on the top surface, P is the Laser power, $r_x = r_o/\text{Cos}\theta$ and $r_y = r_o$ are the radius which expand as function of the incident angle θ and r_o the normal beam radius.

3.4 Process Integration and Industrial Relevance

When optimization of the orientation parameters is systematically carried out, it will serve greatly to improve welding quality by curbing thermal and mechanical asymmetries that encourage microstructural development and enhance overall mechanical performance. This assumption comes from pooling experimental results from various research groups [60]. In industrial applications, 10° is considered a safe value to prevent unwanted reflections and energy coupling onto the absorption surface; again, this is an excellent example of the practical utility of solutions derived from this investigation [61].

Another good example of a closed-loop control model is local monitoring of the melt pool through adaptive positioning of the laser beam to ensure that values of the orientation parameter are kept, at all times, under their optimum during welding, which has already been put into practice [62]. This, indeed, is where the interaction between fundamental research and production and quality aspects of industrial welding, in the context of DP

processes, is apparent, since solutions to problems investigated in the lab have direct transfer to adjustments in factory experimentation and process control [63].

Such systematic investigations into beam orientation in single penetration and multi-engagement welding steel would have provided the anchor point for subsequent elucidation and control of the ensuing interactions [64].

4 Review of Major Investigations on Beam Orientation Effects

Systematic investigations have been conducted to examine the effects of beam orientation variables, tilt angle, deviation position, and incidence angle on the mechanical performance, microstructural evolution, defect production, and flow dynamics of DP steels welded joints, both similar and dissimilar (Figure 9; Table 3). This review consolidates key experimental and numerical studies that highlight the importance of orientation control in achieving satisfactory and mechanically sound welded joints, considering their processing conditions, materials used, and original findings.

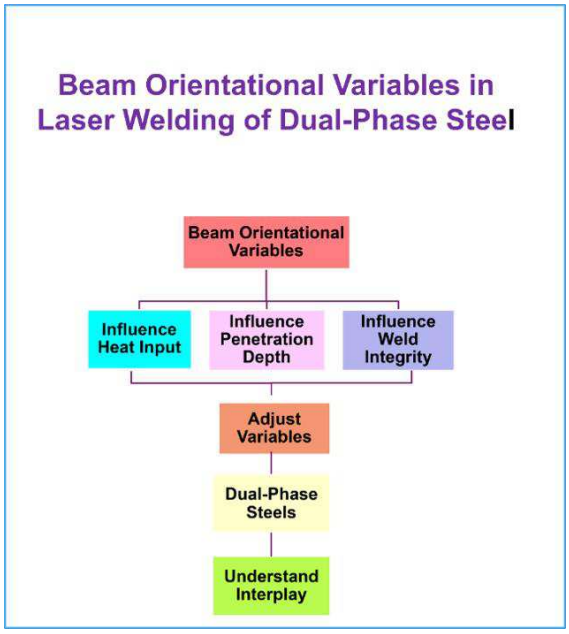


Fig. 9 Schematic illustration of beam orientational variables in laser welding of dual-phase steels, showing their influence on heat input, fusion characteristics, penetration depth, weld morphology, and mechanical performance of welded joints

Table 3 Summary of Key Studies Related to Beam Orientation Effects in Laser Welding of Similar and Dissimilar Dual-Phase Steels

Material(s), Welding Process	Key Variable(s) Related to Beam Orientation	Main Findings Related to Beam Orientation	Performance & Optimization Insights	Reference

DP600 steel, Laser Welding	Beam alignment, heat input	Symmetric beam orientation yielded uniform hardness; soft HAZ was observed due to over-tempering.	Balanced beam position avoids excessive soft zone and preserves fatigue life.	[65]
DP600–DP980, Laser Welding	Beam offset direction toward lower-strength steel	Offset toward DP600 reduces the soft zone and prevents brittle fracture.	Optimized offset improves tensile strength and fatigue resistance.	[66]
HSLA–DP980, Fiber Laser Welding	Beam offset and incident angle	Asymmetric microstructure with soft zone on DP980 side; offset affects HAZ hardness gradient.	Proper offset ensures balanced strength and ductility; improves fatigue life.	[67]
DP600, Laser Welding + FEM simulation	Beam travel orientation vs. rolling direction	Residual stresses are highest when welding parallel to the rolling direction.	Orientation-dependent residual stress control is critical for fatigue optimization.	[68]
DP600, Laser Welding + Simulation	Weld direction (0°, 45°, 90° to rolling)	The magnitude of residual stress and its relaxation depend on the welding direction.	Welding perpendicular to rolling reduces tensile stress peaks.	[69]

4.1 HAZ Softening and Tensile Performance

The effect of beam orientation on HAZ softening and subsequent tensile properties of Laser-welded dual-phase steels has been linked to the change in thermal cycle, cooling rates, and heat distributions in the weld pool. For dual-phase steels, HAZ softening results from the tempering and decomposing of martensite in the inter-critical and sub-critical HAZ. It has been shown that proper beam orientation plays an important role in minimizing thermal asymmetry and heat accumulation and consequently minimizes HAZ softening and improves performance [70]. For example, in dissimilar DP780-DP980 Laser-welded joints, Kumar et al. [49] observed that beam tilt angle influenced the HAZ hardness profile. By tilting the beam towards the DP980 side, there was a balance in the heat input in such a way that there was a narrowed, softened HAZ, and there was a more uniform gradient in hardness from fusion zone to base metal. This can be seen in Figure 10. where there is a noticeable improvement in reducing hardness loss in the softened HAZ with minimal loss of hardness in the fusion zone due to the martensitic transformation in the fast cooling region.

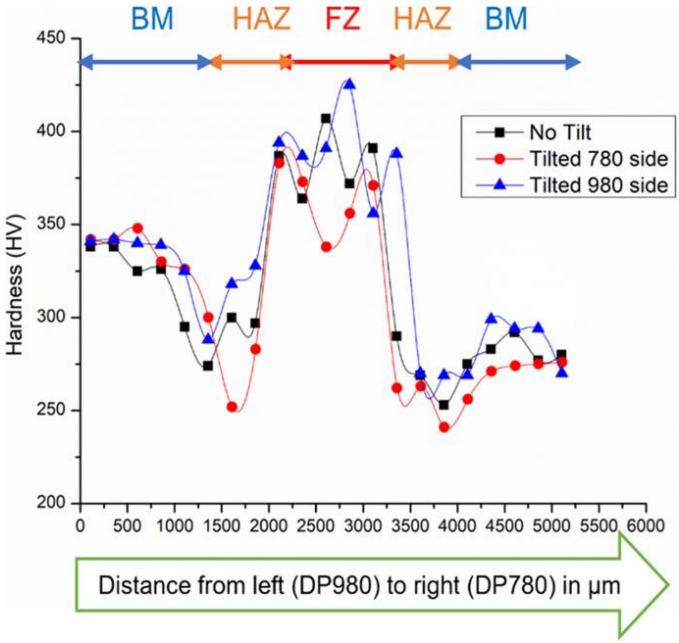


Fig. 10 Microhardness distribution across dissimilar DP780–DP980 laser-welded joints[49]

The decreased softening of the HAZ led to better tensile performance as well. According to Kumar et al. [49], welds created under optimal angles had greater tensile strength and load-carrying ability than welds created under suboptimal orientations. This is due to even distribution of stress, less hardness difference between the welds and prevention of strain localization in the softer HAZ. Farabi et al. [70] also showed similar results when they indicated that minimizing the softening of the HAZ in dissimilar DP steels improves their mechanical properties and prolongs the failure time. As a result, orientation is another effective control parameter that allows regulating HAZ characteristics and tensile performance, which helps achieve better mechanical properties for Laser-welded DP steel joints.

4.2 Fatigue Resistance and Crack Initiation

Beam orientation has been widely studied because of the role played in determining the weld profile shape, in turn influencing the fatigue behaviour, by influencing the formation of cracks and the crack initiation process. In particular, Parkes et al. [67] have investigated extensively the effects of beam positioning and orientation in dissimilar fibre laser welding of joints between HSLA and DP steels, demonstrating that weld profile geometry influences significantly the location of the crack initiation site and the fatigue life of the joint. The study showed that favourable fatigue crack initiation sites, which occur far from the areas where the stress is maximum, could be achieved by controlling the welding process conditions. This allowed the authors to report an improvement of the fatigue life of up to 40% when compared to joints with less favourable weld profiles.

In a similar study, Mansur et al. [4] studied the interaction between the laser welding parameters, microstructure, and mechanical properties of DP600 steel plates. While their study was mainly focused on the effect of welding parameters on microstructure and mechanical behavior, the result showed that thermal gradients and weld morphologies are important variables that affect performance, and these two are greatly affected by the inclination angle of the beam. It has been proven by previous researchers that the use of beam inclination in the range of about 10°-15° results in more favorable stress distribution due to reduced stress concentration factors in the weld

toe and interface. This causes a delay in the formation of plastic damage in the material, which helps increase its fatigue strength.

4.3 Penetration Uniformity and Defect Reduction

Welding quality studies using the laser welding process for DP600 steel sheets (thickness 1.2 mm) have revealed a high dependence of weld quality on beam angle as well as thermal aspects [4]. The effect of the angle of incidence has been studied in detail, where it has been found that a modest angle of inclination, usually ranging between 5° and 15°, has produced better uniformity in penetration and reduced porosity formation as compared to the vertical angle.

It was further validated that small beam displacements of ±0.5 mm resulted in a highly asymmetric thermal field distribution, shown by combining advanced finite element models with experimental validation on 1.0 mm thick DP780 steel. Their numerical investigation suggests that thermal asymmetry induced by beam offsets can be intentionally utilized to mitigate the reheating effects of the heat-affected zone (HAZ) and modify the fusion zone shape.

5 Effect of Beam Orientation on Microstructural Evolution and Mechanical Characteristics

It can be clearly seen from the reviewed literature that beam orientation is an important process parameter that affects the welding process in terms of the geometry of the weld seam, thermal characteristics, structural transformation, defect generation, and mechanical properties in laser welded dual phase steels. This has been clearly demonstrated in both empirical research work and through numerical simulation models that reveal how changes in beam orientation affect heat transfer, key hole stability, behavior of melt pool, and solidification process, leading to modification of properties in the fusion zone and heat affected zone of the weld seam.

Additionally, the high level of correspondence between experimental results and predictions from simulations serves as powerful support for the correlation between beam orientation variables and the efficiency of laser welding processes. Such a correlation has been reported in studies dealing with dissimilar as well as similar DP steels joints. In sum, it may be concluded that the effect of laser beam orientation on the performance of laser welding is quite universal. The research carried out serves as a solid basis for optimizing the welding process by means of process control variables.

5.1 Effects on Weld Morphology

Parameters, such as the angle of inclination of the beam, play a significant role in determining the efficiency of the laser welding process, which is brought about by the shift in the distribution of energy delivered by the laser at the interface of the workpieces. The variations in the angles of beam orientation affect the interactions of the laser, heat flow, and fluid mechanics of the liquid metal pool. According to results from studies conducted by Reinheimer et al. [71] and analysis done by Siva Shanmugam et al. [72], a small angle of inclination, from 5° to 15°, provided better stability of the liquid pool and weld uniformity.

Penetration studies have also shown that the penetration depth is highly sensitive to the angle of incidence of the beam. Penetration depth becomes maximum at the incidence of normal incidence angle (0°) when maximum

energy from the laser source is coupled into the work piece. As the angle of incidence gradually increases to around 20°, the penetration depth starts decreasing because of the increased losses due to reflectivity and decreased energy density at the key hole aperture [72].

The relevance of beam positioning is even further supported by findings of Bandyopadhyay et al. [73], who successfully demonstrated that process optimization can strongly influence the geometrical characteristics of the laser welds in DP980 steel. Beam positioning changes the conditions of local heat exchange and thus affects the width and depth of molten zone, determining the final shape of weld. The relevant physical processes associated with heat transfer were studied thoroughly using computer simulations. In particular, the findings of Svenungsson et al. [74] stressed the importance of keyhole dynamics and energy absorption in controlling temperature distribution and penetration process, whereas Noori Rahim Abadi et al. [75] illustrated the great impact of laser energy distribution on melt flow dynamics, heat gradients, and stability of the welding pool. Therefore, one may conclude that beam positioning is an effective process control parameter for the regulation of the above phenomena.

Penetration-hole geometry plays a critical role in governing laser energy-coupling efficiency during DP steel welding. Recent computational analyses indicate that the optimal beam incidence angle is strongly dependent on the Fresnel absorption coefficient, which reaches its maximum value near Brewster's angle, as illustrated in Figure 11. The behaviour for both 1 μm and 10 μm wavelength lasers demonstrates that maximum energy transfer occurs only within a specific range of beam incidence angles. Furthermore, the narrow 1–8° operating range along the keyhole walls indicates that even small geometric variations, such as beam inclination between 5° and 15° or slight surface waviness, can significantly alter Fresnel absorption characteristics. These variations directly influence penetration depth, weld pool stability, thermal distribution, and defect formation during laser welding of dual-phase steels. The findings highlight that beam orientation control involves complex optothermal interactions that fundamentally govern laser energy transfer and welding performance [76].

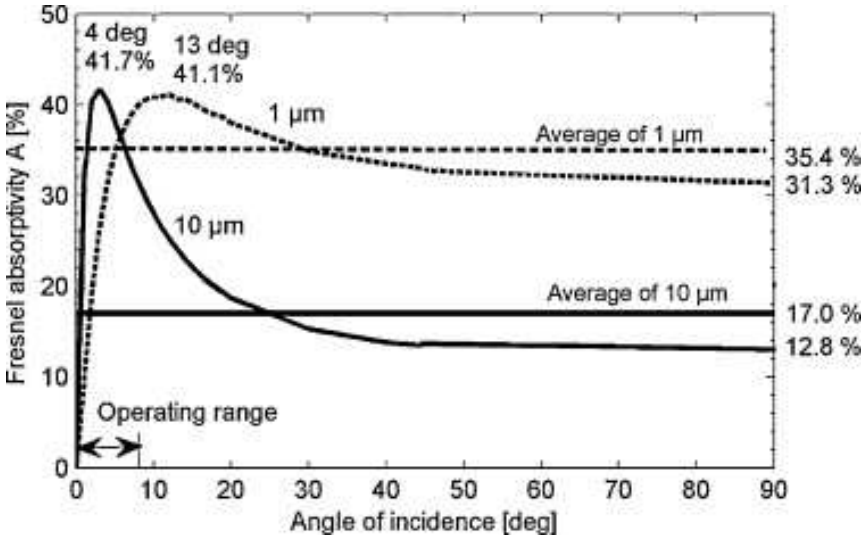


Fig. 11 Variation of Fresnel absorption coefficient with beam incidence angle during laser welding, showing maximum absorptance near Brewster's angle for 1 μm and 10 μm lasers [76]

Beam orientation significantly affects weld morphology and penetration behaviour by controlling laser energy absorption and keyhole stability. Studies reported that when the laser incidence angle approaches Brewster's angle, the Fresnel absorption coefficient increases, resulting in improved energy coupling, deeper penetration, and enhanced weld stability during laser welding [77].

5.2 Microstructural Evolution

The orientation of the beam plays an important role in determining the thermal cycle behavior and rate of cooling for laser welding, which can have an effect on the microstructure development in the FZ and HAZ regions. In the case of welding dissimilar steels like DP600-DP980 with laser, Farabi et al. [70] showed that heat input and the thermal gradient play a critical role in the softening process and hardness of the HAZ region of the weld joint. Even though the beam orientation was not considered here, it shows that the dual phase steel is sensitive to thermal asymmetry.

Some recent computations have added to knowledge about the effects of beam inclination on the formation of weld microstructure. For instance, Yu et al. [78], via their phase field simulations, have shown that the dendritic growth in weld microstructure is dependent on the local thermal gradients and solidification conditions. Also, according to CFD simulations by Hozoorbakhsh et al. [79], melt pool convection affects the modes of heat transfer and solidification in the welding process. This means that the alteration in beam inclination and its energy distribution causes changes in flow conditions, cooling, and heat transfer, consequently altering microstructure and phase formation in weld metal. It should be mentioned that all the above findings agree with the general notion that thermal asymmetry influences microstructure formation [80].

Another factor that affects the microstructure of welds has been shown by experimental investigations involving laser welding. Palanisamy et al. [81] stated that variations in the orientation of the laser beams during welding of stainless steel welds caused modifications in the geometrical form, cooling and microstructural properties of the welds. The findings suggested that the use of the beam at an angle led to variations in the solidification process and in grain formation, ultimately leading to improvements in their mechanical properties. Similar patterns have been observed for other metals subjected to laser welding processes.

The microstructure thus obtained has significant effects on mechanical properties. It has been demonstrated that optimum heat treatment using lasers could result in welding that is capable of yielding a strength near the strength of the base metal and acceptable hardness levels without any considerable microstructure inconsistency [82]. Additionally, recent coupled experimental-numerical studies have indicated that control of beam orientation together with heat and temperature gradient is a viable method to tailor weld morphology, phase composition, and mechanical properties for similar and dissimilar welds [83]. This means that beam orientation must be treated as an important process parameter for influencing the microstructure of Laser-welded DQPS components.

5.3 Defect Mitigation

The development of defects in laser welding processes depends largely on the orientation of the beam since any variations in the angle of incidence of the beam affect the stability of the keyhole, the dynamics of the melt pool, and the distribution of energy inside the melt pool. Improper selection of beam orientation leads to the creation of several welding defects, which include but are not limited to humping, porosity, lack of fusion, and surface

roughness. In a recent study conducted by Lai et al. [84], it was revealed that the development of humping instability is linked with melt pool flow behaviour and local pressure distribution during high-speed laser welding.

Formation of porosities is also strongly linked to keyhole instability and vapour trapping mechanisms. The experimental studies carried out by Börner et al. [85] and Luo et al. [86] have proved that by modifying the incidence of the beam, better melt pool mixing may be achieved along with gas escaping. This means that beam incidences can become effective methods to reduce porosities by ensuring proper keyhole stability and melt pool flow.

More advanced computational studies have also confirmed the crucial importance of beam orientation in the generation of defects. As shown by Zhao et al. [87], the dynamics of the vapor plume is strongly dependent on the welding parameters and beam movement, while plume dynamics is known to play an important part in the dynamics of keyhole and process stability. According to SaediArdahaei and Pham [88], keyhole dynamics is controlled by curvature effects, Marangoni convection, and Darcy damping forces. The imbalance of these phenomena can cause keyhole failure and the formation of defects, especially when energy distribution is unfavourable.

It has been observed that the effect of beam orientation combined with power-modulation schemes also influences the stability of the process. From numerical simulations, it was found that pulse shaping leads to significantly different stability behaviour, wherein the use of multi-pulse rectangular pulses is more prone to defect generation when compared to triangular or ramp-down pulses [88]. These results imply that the choice of orientation needs to be done in conjunction with power-modulation techniques.

The importance of these mechanisms can be seen from research into laser welding of AHSS. For instance, the findings of Alves et al. [89] showed that the quality of weldment in DP1000 steel is extremely susceptible to the thermal environment and process stability and the necessity for controlling the energy deposition and molten pool conditions was stressed. On the other hand, recent studies by Yang et al. [90] established a set of predictive numerical models that link flow asymmetry, keyhole instability, and mechanisms of defect formation. Results obtained revealed that differences in melt flow and energy distribution depending on the direction of the laser beam orientation had a substantial influence on the probability of pore formation and lack-of-fusion defects.

5.4 Mechanical Performance

The mechanical properties of Laser-welded dual-phase (DP) steels depend greatly on thermal effects, welding geometries, residual stresses, and the microstructure development of materials, all of which are dependent on beam orientations. In laser welds of dissimilar DP600-DP980 materials, Farabi et al. [70] found that variations in thermal fields and welding geometries greatly impact hardness, tensile strength, and modes of failure in specimens. While beam orientations were not studied in detail, it was found that mechanical properties depend strongly on local thermal fields and geometries, and thus, could benefit from beam optimization.

However, fatigue performance is particularly susceptible to issues related to weld shape and stress concentrations. According to the results provided by Barsoum and Jonsson [91], the influence of weld quality and geometry was shown to be an important factor in fatigue crack nucleation and growth. It is also evident from their study that the decrease in stress concentration values, caused by improvement of the weld profiles, has a positive effect on

fatigue properties. As for the application of laser welding, it has been found that optimal beam angle and placement lead to improved weld transitions and lower stress concentrations, which help prevent the initiation of fatigue cracks at high-stress points. Similar results were achieved by Xu et al. [92] when examining fatigue properties of fibre laser-welded HSLA/DP980 joints.

The generation of residual stress within a structure is yet another significant aspect that determines the overall behaviour of the joints. The extent of residual stress generation due to welding operations has been reported to depend critically upon the heat input and temperature gradients during welding processes. Qureshi et al. [93] reported that the orientation and sequence of welding had a strong influence on the pattern of residual stress formation, whereas, in their study using finite element modelling and ultrasonic technique, Javadi et al. [94] found that local thermal conditions had a direct impact on the longitudinal residual stress pattern.

Beam orientation and its effect on HAZ softening are also equally significant issues. The study conducted by Khan et al. [95] focused on HAZ softening in dual-phase steels welded using lasers, and they found that thermal history characteristics were the most significant in controlling hardness loss and the local mechanical properties. This point has already been proven by Mohandas et al. [96], who showed how overheating resulted in material softening and loss of mechanical properties. Therefore, beam orientation techniques that could ensure better thermal balance could reduce HAZ softening.

More recent investigations also confirm the positive impact of optimal beam incidence conditions on the quality of welds and their mechanical behaviour. For example, in their investigation, Wang et al. [97] found that the incidence angle of the laser beam plays a critical role in influencing the welding characteristics because of the resultant heat input distributions and behaviours of the molten pool. With optimal conditions of beam incidence, welds were observed to have better morphological structures with improved metallurgical bonding properties and mechanical properties approaching those of the base material. All in all, the results obtained show that beam incidence plays a significant role in fatigue resistance, residual stress, HAZ softening, and mechanical behaviour.

6 Gaps Recognized and Constraints Present

The weld shape, microstructure, and mechanical behavior of laser welding of similar and dissimilar dual-phase steels are well studied; however, most research focuses on power, speed, focus, oscillation, or offset rather than the entire 3D beam orientation. For complex or tilted incidence cases, particularly in automotive joints, this leaves significant gaps. Thus, much remains to be accomplished it can be successfully applied to its uncompromising industrial realization. An enormous barrier to the widespread acceptance of any of the commonly used DP grades (DP600, DP780, DP980, and DP1000) is that none of them has nearly applicable ideal tilt [98].

Even so, computational approaches today can be understood at the basic mechanisms involved; however, they have limitations on multiphysics coupling, which still describes the plumes of vapour that will be resultant from the interaction of these phenomena and the turbulence consequences associated with the complexities of solidification behaviour for a range of orientations employed [99].

The very limited availability of industrial certifications, coupled with the majority of these studies on orientation being conducted mostly in small, laboratory-controlled conditions using thin-gauge materials, makes them less applicable in the most important practical production cases: thick sections with multi-pass welds and very complex

3D geometries. More importantly, the saturation of knowledge regarding measurements for orientation effects at industrial welding speeds, multi-pass welding, and very complicated joint geometries brings a considerable degree of confusion to making the transition from research conditions to production ones.

7 Strategic Directions for Future Research

7.1 Integrated Simulation-Experiment Frameworks

Future research should invest more in developing integrated simulation-experiment frameworks that can predict the orientation effect in real-world automotive and structural applications [100]. These frameworks must include advanced multiphysics coupling covering an entire spectrum of orientation-sensitive operations, for example, keyhole dynamics, vapour plume behaviour, solidification patterning, and residual stress generation [101].

7.2 Adaptive Real-Time Control Systems

An advanced technological breakthrough, an adaptive beam orientation control system, has now been developed and requires urgent attention [102]. These systems should regulate tilt and offset settings in real time during welding operations, depending on a feedback loop from advanced sensors and machine learning algorithms, and continually optimizing process parameters [103]. There is evidence, however, that future welding parameters will be predicted by analyzing production data in real time with predictive algorithms that will adjust welding schedules to minimize the cost-per-unit and improve quality.

7.3 The Combination of Artificial Intelligence and Machine Learning

The collaboration between artificial intelligence and machine learning with huge experimental data is an unmatched opportunity for the prediction of the optimal orientation strategies of various materials and thicknesses [104]. Among the possible means for automated defect detection and improvement of the process, deep learning has probably the most potential value, in particular through convolutional neural networks [105]. Machine learning techniques significantly increase the level of performance and effectiveness of welding processes, whereas industrial robots using such AI techniques seem to deliver even better results [106].

7.4 Studies of Multi-material and Hybrid Joints

Orientation effects are undoubtedly perceived among multi-material and hybrid joints in a number of voids, particularly with metals such as dual-phase steels commonly associated with aluminium alloys or transformation-induced plasticity steels, as lightweight car researchers have now pointed in their future direction. However, the orientation study requirements in such heterogeneous systems are not very clear[30]. One needs to consider the orientation effect on a multi-material joint for all proven advanced high-strength steels relevant to the architecture of next-generation vehicles [107].

7.5 Industrial Validation and Scale-Up

Industrial validation has to be strongly emphasized, whereby such nozzles will undergo large-scale welding trials to verify orientation-controlled processes in compliance with crashworthiness, durability, and manufacturability performance indicators [108]. Industrial validations will be carried out in environments truly representative of

production processes, where high welding speeds, fully automated handling systems, and stringent quality control specifications are utilized.

7.6 Advanced Monitoring and Process Regulation

Controlled with high precision, a laser beam combined with real-time monitoring systems should minimize thermal damage while ensuring the weld accuracy through beam orientation management [109]. Monitoring systems equipped with a camera for real-time control of seam tracking enable welding torches to guide themselves to the correct spot along the welding seam while continuously modulating the parameters [110]. This will be further ensured in the connected advanced monitoring system for full optimization through linking with orientation control algorithms [111].

7.7 Scale-up Strategy for Industry

The latest model tools must be used to create orientation-controlled welding, while advanced instrumentation measures the execution quality. They will incorporate in-situ experimental diagnostics methods such as high-speed imaging, thermography, and real-time fault-detection systems [112]. The above industrialization efforts should aim to standardize defined orientation parameters for different DP steel grades, thus enabling wide-spectrum design in the automobile and structural applications.

For instance, it is convenient and worthwhile to control orientation very well in terms of minimizing welding error rates and improving welding quality and by providing high-speed productive parameter optimization through the application of AI [113]. These real-time monitoring and control systems adjust these conditions in an adaptive manner so that welding conditions are maintained not only stable but also optimal, thus minimizing material wastage and reworking costs [114].

Beam orientation control is a process variable characterized by its relationship towards the performance and reliability of welded dual-phase steels under scientific optimization [115]. Strong orientation-based guidelines for improving productive manufacturing processes and enhancing structural safety in automotive and engineering applications can be derived from the experimental results, well-coupled with advanced computational modelling and rigorous industrial validation [83].

The outlook for DP steel welding shall define an integrated scheme of active orientation control with AI techniques and real-time process monitoring to be on unprecedented benchmarks of weld quality, productivity, and reliability [116]. As knowledge gaps will be filled by joint experimental, computational, and industrial approaches, the design of even lighter, more efficient, and sustainable engineering structures that meet the stringent performance requirements of next-generation transportation and structural systems will be possible [117].

8 Conclusion

The present literature review has tried to consolidate the range of experimentation and simulation studies under one umbrella where beam orientation emerges as one of the important aspects that influence the welding behavior of similar and dissimilar dual-phase steel plates. It is evident from the research that even minor variations in tilt angles, beam positions, and beam incidence can significantly affect the properties of the thermal cycle, thereby affecting the softening effect of the HAZ region, porosity formation, residual stress build-up, and fatigue resistance

[118]. In summary, the beam orientation should not be viewed as insignificant in the quest for perfect welds, rather it is crucial for obtaining the perfect welding [119].

1. Some important findings from this review include.The angles at which the beams are tilted moderately at 5° to 15° improve the uniformity of penetration while reducing defects.
2. The offsets at 0.1mm to 0.3mm optimize thermal conditions and improve the uniformity of hardness.
3. The laser orientation has an impact on how the heat-affected zone softening occurs, residual stresses, and the fatigue characteristics of welding.
4. CFD simulations and FE analyses are effective in finding sensitivities related to the effect on the flow and thermal conditions.

Author Contributions

S. Kumar: Conceptualization, literature review, analysis, and manuscript preparation. M. Baruah and K. S. Arora: Supervision, critical review, and revision of the manuscript. All authors have read and approved the final manuscript.

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References

1. Nanda, Tarun, Vishal Singh, Gurpreet Singh, Manpreet Singh, and B. Ravi Kumar. 2021. Processing routes, resulting microstructures, and strain rate dependent deformation behaviour of advanced high strength steels for automotive applications. *Archives of Civil and Mechanical Engineering* 21. Springer London: 1–24. https://doi.org/10.1007/s43452-020-00149-4.

2. Bleck, Wolfgang, Spyros Papaefthymiou, and Andreas Frehn. 2004. Microstructure and tensile properties in dual phase and trip steels. *Steel Research International* 75: 704–710. https://doi.org/10.1002/srin.200405831.

3. Badkoobeh, Farzad, Hossein Mostaan, Mahdi Rafiei, Hamid Reza Bakhsheshi-Rad, and Filippo Berto. 2022. Microstructural Characteristics and Strengthening Mechanisms of Ferritic–Martensitic Dual-Phase Steels: A Review. *Metals* 12. https://doi.org/10.3390/met12010101.

4. Mansur, Vinicius Machado, Raquel Alvim de Figueiredo Mansur, Sheila Medeiros de Carvalho, Rafael

Humberto Mota de Siqueira, and Milton Sergio Fernandes de Lima. 2021. Effect of laser welding on microstructure and mechanical behaviour of dual phase 600 steel sheets. *Heliyon* 7: e08601. https://doi.org/10.1016/j.heliyon.2021.e08601.

5. Hu, Shufen, Zhibin Zheng, Weiping Yang, and Haokun Yang. 2022. Fe–Mn–C–Al Low-Density Steel for Structural Materials: A Review of Alloying, Heat Treatment, Microstructure, and Mechanical Properties. *Steel Research International* 93: 1–13. https://doi.org/10.1002/srin.202200191.

6. Elrefaey, Ahmed, and Nigel G. Ross. 2015. Microstructure and mechanical properties of cold metal transfer welding similar and dissimilar aluminum alloys. *Acta Metallurgica Sinica (English Letters)* 28. The Chinese Society for Metals: 715–724. https://doi.org/10.1007/s40195-015-0252-6.

7. Oliver, S., T. B. Jones, and G. Fourlaris. 2007. Dual phase versus TRIP strip steels: Comparison of dynamic properties for automotive crash performance. *Materials Science and Technology* 23: 423–431. https://doi.org/10.1179/174328407X168937.

8. Banea, M. D., and L. F.M. Da Silva. 2010. The effect of temperature on the mechanical properties of adhesives for the automotive industry. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 224: 51–62. https://doi.org/10.1243/14644207JMDA283.

9. Hank, Peter, Ovidiu Vermesan, Steffen Müller, and Jeroen Van Den Keybus. 2013. Automotive ethernet: In-vehicle networking and smart mobility. *Proceedings -Design, Automation and Test in Europe, DATE*: 1735–1739. https://doi.org/10.7873/date.2013.349.

10. Hirz, Mario, Patrick Rossbacher, and Jana Gulanová. 2017. Future trends in CAD–from the perspective of automotive industry. *Computer-Aided Design and Applications* 14: 734–741. https://doi.org/10.1080/16864360.2017.1287675.

11. Ravishankar, B., Sanjay K. Nayak, and M. Abdul Kader. 2019. Hybrid composites for automotive applications – A review. *Journal of Reinforced Plastics and Composites* 38: 835–845. https://doi.org/10.1177/0731684419849708.

12. Chombo, Pius Victor, Yossapong Laoonual, and Somchai Wongwises. 2021. Lessons from the electric vehicle crashworthiness leading to battery fire. *Energies* 14: 1–21. https://doi.org/10.3390/en14164802.

13. Tsipouridis, Prodromos, Ewald Werner, C. Krempaszky, and E. Tragl. 2006. Formability of high strength DP steels. *Steel Research International* 77: 654–667.

14. Di, Hongshuang, Qian Sun, Xiaonan Wang, and Jianping Li. 2017. Microstructure and properties in dissimilar/similar weld joints between DP780 and DP980 steels processed by fiber laser welding. *Journal of Materials Science and Technology* 33. The editorial office of Journal of Materials Science & Technology: 1561–1571. https://doi.org/10.1016/j.jmst.2017.09.001.

15. Thomä, M., A. Gester, G. Wagner, B. Straß, B. Wolter, S. Benfer, D. K. Gowda, and W. Fürbeth. 2019. Application of the hybrid process ultrasound enhanced friction stir welding on dissimilar

aluminum/dual-phase steel and aluminum/magnesium joints. *Materialwissenschaft und Werkstofftechnik* 50: 893–912. https://doi.org/10.1002/mawe.201900028.

16. Khan, M. I., M. L. Kuntz, P. Su, A. Gerlich, T. North, and Y. Zhou. 2007. Resistance and friction stir spot welding of DP600: A comparative study. *Science and Technology of Welding and Joining* 12: 175–182. https://doi.org/10.1179/174329307X159801.

17. Khan, M. I., M. L. Kuntz, E. Biro, and Y. Zhou. 2008. Microstructure and mechanical properties of resistance spot welded advanced high strength steels. *Materials Transactions* 49: 1629–1637. https://doi.org/10.2320/matertrans.MRA2008031.

18. Vignesh, K., A. Elaya Perumal, and P. Velmurugan. 2017. Optimization of resistance spot welding process parameters and microstructural examination for dissimilar welding of AISI 316L austenitic stainless steel and 2205 duplex stainless steel. *International Journal of Advanced Manufacturing Technology* 93. The International Journal of Advanced Manufacturing Technology: 455–465. https://doi.org/10.1007/s00170-017-0089-4.

19. Sun, Z., and J. C. Ion. 1995. Laser welding of dissimilar metal combinations. *Journal of Materials Science* 30: 4205–4214. https://doi.org/10.1007/BF00361499.

20. Pang, Shengyong, Liliang Chen, Jianxin Zhou, Yajun Yin, and Tao Chen. 2011. A three-dimensional sharp interface model for self-consistent keyhole and weld pool dynamics in deep penetration laser welding. *Journal of Physics D: Applied Physics* 44. https://doi.org/10.1088/0022-3727/44/2/025301.

21. Semak, V. V., J. A. Hopkins, M. H. McCay, and T. D. McCay. 1995. Melt pool dynamics during laser welding. *Journal of Physics D: Applied Physics* 28: 2443–2450. https://doi.org/10.1088/0022-3727/28/12/008.

22. Matsunawa, Akira, Jong-Do Kim, Naoki Seto, Masami Mizutani, and Seiji Katayama. 1998. Dynamics of keyhole and molten pool in laser welding. *Journal of Laser Applications* 10: 247–254. https://doi.org/10.2351/1.521858.

23. Sudnik, W., D. Radaj, S. Breitschwerdt, and W. Erofeew. 2000. Numerical simulation of weld pool geometry in laser beam welding. *Journal of Physics D: Applied Physics* 33: 662–671. https://doi.org/10.1088/0022-3727/33/6/312.

24. Fotovvati, Behzad, Steven F. Wayne, Gladius Lewis, and Ebrahim Asadi. 2018. A Review on Melt-Pool Characteristics in Laser Welding of Metals. *Advances in Materials Science and Engineering* 2018. https://doi.org/10.1155/2018/4920718.

25. Lambiase, F., V. Grossi, and A. Paoletti. 2020. Effect of tilt angle in FSW of polycarbonate sheets in butt configuration. *International Journal of Advanced Manufacturing Technology* 107. The International Journal of Advanced Manufacturing Technology: 489–501. https://doi.org/10.1007/s00170-020-05106-2.

26. Zhao, Y. Y., Y. S. Zhang, and W. Hu. 2013. Effect of welding speed on microstructure, hardness and

tensile properties in laser welding of advanced high strength steel. *Science and Technology of Welding and Joining* 18: 581–590. https://doi.org/10.1179/1362171813Y.0000000140.

27. Tamizi, M., M. Pouranvari, and M. Movahedi. 2017. Welding metallurgy of martensitic advanced high strength steels during resistance spot welding. *Science and Technology of Welding and Joining* 22. Taylor & Francis: 327–335. https://doi.org/10.1080/13621718.2016.1240979.

28. Liu, Dezheng, Yan Li, Haisheng Liu, Zhongren Wang, and Yu Wang. 2018. Numerical investigations on residual stress in laser penetration welding process of ultrafine-grained steel. *Advances in Materials Science and Engineering* 2018. https://doi.org/10.1155/2018/8609325.

29. Perka, Ashok Kumar, Merbin John, Udaya Bhat Kuruveri, and Pradeep L. Menezes. 2022. Advanced High-Strength Steels for Automotive Applications: Arc and Laser Welding Process, Properties, and Challenges. *Metals* 12. https://doi.org/10.3390/met12061051.

30. Zhang, Wen, and Jun Xu. 2022. Advanced lightweight materials for Automobiles: A review. *Materials and Design* 221. https://doi.org/10.1016/j.matdes.2022.110994.

31. Tasan, C. C., M. Diehl, D. Yan, M. Bechtold, F. Roters, L. Schemmann, C. Zheng, et al. 2015. An Overview of Dual-Phase Steels: Advances in Microstructure-Oriented Processing and Micromechanically Guided Design. *Annual Review of Materials Research* 45: 391–431. https://doi.org/10.1146/annurev-matsci-070214-021103.

32. Conway, Graham, Ameya Joshi, Felix Leach, Antonio García, and Peter Kelly Senecal. 2021. A review of current and future powertrain technologies and trends in 2020. *Transportation Engineering* 5. Elsevier Ltd: 100080. https://doi.org/10.1016/j.treng.2021.100080.

33. Kalhor, Alireza, Ali Karimi Taheri, Hamed Mirzadeh, and Vitoon Uthaisangsuk. 2021. Processing, microstructure adjustments, and mechanical properties of dual phase steels: a review. *Materials Science and Technology (United Kingdom)* 37. Routledge: 561–591. https://doi.org/10.1080/02670836.2021.1944524.

34. Huang, Wei, and Radovan Kovacevic. 2011. A laser-based vision system for weld quality inspection. *Sensors* 11: 506–521. https://doi.org/10.3390/s110100506.

35. Liao, Yi Chun, and Ming Huei Yu. 2007. Effects of laser beam energy and incident angle on the pulse laser welding of stainless steel thin sheet. *Journal of Materials Processing Technology* 190: 102–108. https://doi.org/10.1016/j.jmatprotec.2007.03.102.

36. Wu, C. S., H. L. Wang, and Y. M. Zhang. 2009. Numerical analysis of the temperature profiles and weld dimension in high power direct-diode laser welding. *Computational Materials Science* 46. Elsevier B.V.: 49–56. https://doi.org/10.1016/j.commatsci.2009.02.005.

37. Rai, R., and T. Debroy. 2006. Tailoring weld geometry during keyhole mode laser welding using a genetic algorithm and a heat transfer model. *Journal of Physics D: Applied Physics* 39: 1257–1266. https://doi.org/10.1088/0022-3727/39/6/037.

38. Wu, Jianzhao, Kunlei Lian, Yelin Deng, Ping Jiang, and Chaoyong Zhang. 2022. Multi-Objective Parameter Optimization of Fiber Laser Welding Considering Energy Consumption and Bead Geometry. *IEEE Transactions on Automation Science and Engineering* 19. IEEE: 3561–3574. https://doi.org/10.1109/TASE.2021.3126077.

39. Benyounis, K. Y., and A. G. Olabi. 2008. Optimization of different welding processes using statistical and numerical approaches - A reference guide. *Advances in Engineering Software* 39: 483–496. https://doi.org/10.1016/j.advengsoft.2007.03.012.

40. H. Kaplan, Alexander F. 2011. Influence of the beam profile formulation when modeling fiber-guided laser welding. *Journal of Laser Applications* 23. https://doi.org/10.2351/1.3633221.

41. Xia, Peiyun, Lingda Xiong, Yiyang Hu, Xiaosong Feng, and Chunming Wang. 2023. Effect of laser oscillation and beam incident angle on porosity in double-sided filler welding of 2219 aluminum alloy T joint. *Optics and Laser Technology* 166. Elsevier Ltd: 109581. https://doi.org/10.1016/j.optlastec.2023.109581.

42. Sun, Junhao, Qi Yan, Wei Gao, and Jian Huang. 2015. Investigation of laser welding on butt joints of Al/steel dissimilar materials. *Materials and Design* 83. Elsevier Ltd: 120–128. https://doi.org/10.1016/j.matdes.2015.05.069.

43. Lee, Hyoung Keun, Hyon Soo Han, Kwang Jae Son, and Soon Bog Hong. 2006. Optimization of Nd:YAG laser welding parameters for sealing small titanium tube ends. *Materials Science and Engineering: A* 415: 149–155. https://doi.org/10.1016/j.msea.2005.09.059.

44. Hayat, Qamar, Pasquale Franciosa, Giovanni Chianese, Anand Mohan, Dariusz Ceglarek, Alexander Griffiths, and Christopher Harris. 2023. Elucidating the effect of circular and tailing laser beam shapes on keyhole necking and porosity formation during laser beam welding of aluminum 1060 using a multiphysics computational fluid dynamics approach. *Journal of Laser Applications* 35. Laser Institute of America. https://doi.org/10.2351/7.0001150.

45. Winczek, Jerzy, Marek Gucwa, Miloš Mičian, and Krzysztof Makles. 2019. Numerical analysis of the influence of electrode inclination on temperature distribution during GMAW overlaying. *Mathematical Problems in Engineering* 2019. https://doi.org/10.1155/2019/9048025.

46. Greebmalai, Jukkapun, Kazuyuki Matsumoto, Keita Marumoto, and Motomichi Yamamoto. 2025. Effect of Hardness Distribution on Strength of Narrow-Gap Hot-Wire Laser-Welded Joint for High-Tensile Strength Steel. *Materials* 18. https://doi.org/10.3390/ma18020297.

47. Saternus, Zbigniew, Wiesława Piekarska, Marcin Kubiak, and Tomasz Domański. 2021. The influence of welding heat source inclination on the melted zone shape, deformations and stress state of laser welded t-joints. *Materials* 14. https://doi.org/10.3390/ma14185303.

48. Tang, Fengye, Kai Guo, Xiangbo Liu, Yanhong Wei, and Jicheng Chen. 2024. The role of asymmetric metal flow on weld formation and solidification characteristics during pulsed laser butt welding with assembly tolerance. *International Journal of Thermal Sciences* 196. Elsevier Masson SAS: 108721.

https://doi.org/10.1016/j.ijthermalsci.2023.108721.

49. Kumar, Sumit, Mayuri Baruah, Kanwer Singh Arora, and Brajesh Asati. 2026. Effect of laser beam tilt angle on the weld quality of dissimilar joints of DP780 & DP980 steels. *International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-025-17324-7.

50. Volpp, Jörg, and Frank Vollertsen. 2016. Keyhole stability during laser welding—part I: modeling and evaluation. *Production Engineering* 10: 443–457. https://doi.org/10.1007/s11740-016-0694-3.

51. Xu, W., D. Westerbaan, S. S. Nayak, D. L. Chen, F. Goodwin, E. Biro, and Y. Zhou. 2012. Microstructure and fatigue performance of single and multiple linear fiber laser welded DP980 dual-phase steel. *Materials Science and Engineering: A* 553: 51–58. https://doi.org/10.1016/j.msea.2012.05.091.

52. Xia, Mingsheng, Elliot Biro, Zhiling Tian, and Y. Norman Zhou. 2008. Effects of Heat Input and Martensite on HAZ Softening in Laser Welding of Dual Phase Steels. *ISIJ International*. https://doi.org/10.2355/isijinternational.48.809.

53. Shen, Xianfeng, Lin Li, Wei Guo, Wenhua Teng, and Wenpei He. 2016. Comparison of processing window and porosity distribution in laser welding of 10 mm thick 30CrMnSiA ultrahigh strength between flat (1G) and horizontal (2G) positions. *Journal of Laser Applications* 28. https://doi.org/10.2351/1.4943992.

54. Bakir, Nasim, Antoni Artinov, Andrey Gumenyuk, Marcel Bachmann, and Michael Rethmeier. 2018. Numerical simulation on the origin of solidification cracking in laser welded thick-walled structures. *Metals* 8: 1–15. https://doi.org/10.3390/met8060406.

55. Hu, Xiaodong, Hao Yong Jiang, Yun Luo, Qiang Jin, Wei Peng, and Chun Mei Yi. 2020. A study on microstructure, residual stresses and stress corrosion cracking of repair welding on 304 stainless steel: Part II-Effects of reinforcement height. *Materials* 13. https://doi.org/10.3390/ma13112434.

56. Jiang, Wenchun, Yun Luo, J. H. Li, and Wanchuck Woo. 2017. Residual Stress Distribution in a Dissimilar Weld Joint by Experimental and Simulation Study. *Journal of Pressure Vessel Technology, Transactions of the ASME* 139: 1–10. https://doi.org/10.1115/1.4033532.

57. Shi, Lin, Xin Li, Laihege Jiang, and Ming Gao. 2021. Numerical study of keyhole-induced porosity suppression mechanism in laser welding with beam oscillation. *Science and Technology of Welding and Joining* 26: 349–355. https://doi.org/10.1080/13621718.2021.1913562.

58. Fathi-Hafshejani, Parvin, Arash Soltani-Tehrani, Nima Shamsaei, and Masoud Mahjouri-Samani. 2022. Laser incidence angle influence on energy density variations, surface roughness, and porosity of additively manufactured parts. *Additive Manufacturing* 50. Elsevier B.V.: 102572. https://doi.org/10.1016/j.addma.2021.102572.

59. Evdokimov, Anton, Filip Jasiewicz, Nikolay Doynov, Ralf Ossenbrink, and Vesselin Michailov. 2022. Simulation of surface heat treatment with inclined laser beam. *Journal of Manufacturing Processes* 81:

107–114. https://doi.org/10.1016/j.jmapro.2022.06.051.

60. Seighalani, K. Reshad, M. K.Besharati Givi, A. M. Nasiri, and P. Bahemmat. 2010. Investigations on the effects of the tool material, geometry, and tilt angle on friction stir welding of pure titanium. *Journal of Materials Engineering and Performance* 19: 955–962. https://doi.org/10.1007/s11665-009-9582-8.

61. Khatib, T., A. Mohamed, M. Mahmoud, and K. Sopian. 2015. Optimization of the tilt angle of solar panels for Malaysia. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 37: 606–613. https://doi.org/10.1080/15567036.2011.588680.

62. Mehta, Kush. 2017. *Advanced Joining and Welding Techniques: An Overview*. https://doi.org/10.1007/978-3-319-56099-1_5.

63. Wu, Ziheng, Guannan Tang, Samuel J. Clark, Andrey Meshkov, Subhrajit Roychowdhury, Benjamin Gould, Victor Ostroverkhov, et al. 2023. High frequency beam oscillation keyhole dynamics in laser melting revealed by in-situ x-ray imaging. *Communications Materials* 4. Springer US: 1–10. https://doi.org/10.1038/s43246-023-00332-z.

64. Wei, S. T., D. Lv, R. D. Liu, L. Lin, R. J. Xu, J. Y. Guo, and K. Q. Wang. 2014. Similar and dissimilar resistance spot welding of advanced high strength steels: Welding and heat treatment procedures, structure and mechanical properties. *Science and Technology of Welding and Joining* 19: 427–435. https://doi.org/10.1179/1362171814Y.0000000211.

65. Farabi, N., D. L. Chen, J. Li, Y. Zhou, and S. J. Dong. 2010. Microstructure and mechanical properties of laser welded DP600 steel joints. *Materials Science and Engineering: A* 527: 1215–1222. https://doi.org/10.1016/j.msea.2009.09.051.

66. Farabi, N., D.L. Chen, and Y. Zhou. 2011. Microstructure and mechanical properties of laser welded dissimilar DP600/DP980 dual-phase steel joints. *Journal of Alloys and Compounds* 509: 982–989. https://doi.org/10.1016/j.jallcom.2010.08.158.

67. Parkes, D., W. Xu, D. Westerbaan, S. S. Nayak, Y. Zhou, F. Goodwin, S. Bhole, and D. L. Chen. 2013. Microstructure and fatigue properties of fiber laser welded dissimilar joints between high strength low alloy and dual-phase steels. *Materials and Design* 51: 665–675. https://doi.org/10.1016/j.matdes.2013.04.076.

68. Liu, S., A. Kouadri-Henni, and A. Gavrus. 2017. Numerical simulation and experimental investigation on the residual stresses in a laser beam welded dual phase DP600 steel plate: Thermo-mechanical material plasticity model. *International Journal of Mechanical Sciences* 122. Elsevier Ltd: 235–243. https://doi.org/10.1016/j.ijmecsci.2017.01.006.

69. Liu, Miaoran, Afia Kouadri-Henni, and Benoit Malard. 2022. Influence of the Laser Welding Direction of Thin DP600 and the Residual Stresses Relaxation Obtained by Simulation and Neutron Diffraction. *Key Engineering Materials* 926 KEM: 1762–1769. https://doi.org/10.4028/p-l23f52.

70. Farabi, N., D. L. Chen, and Y. Zhou. 2011. Microstructure and mechanical properties of laser welded

dissimilar DP600/DP980 dual-phase steel joints. *Journal of Alloys and Compounds* 509. Elsevier B.V.: 982–989. https://doi.org/10.1016/j.jallcom.2010.08.158.

71. Reinheimer, Eveline N., Rudolf Weber, and Thomas Graf. 2022. Process limit imposed by the occurrence of undercuts during high-speed laser welding. *Journal of Laser Applications* 34. Laser Institute of America. https://doi.org/10.2351/7.0000621.

72. Siva Shanmugam, N, G Buvanashekaran, K Sankaranarayanasamy, and K Manonmani. 2009. Influence of Beam Incidence Angle in Laser Welding of Austenitic Stainless Steel using Finite Element Analysis. *Multidiscipline Modeling in Materials and Structures* 5. Emerald Group Publishing Limited: 257–262. https://doi.org/10.1163/157361109789017069.

73. Bandyopadhyay, K., S. K. Panda, and P. Saha. 2016. Optimization of Fiber Laser Welding of DP980 Steels Using RSM to Improve Weld Properties for Formability. *Journal of Materials Engineering and Performance* 25. Springer US: 2462–2477. https://doi.org/10.1007/s11665-016-2071-y.

74. Svenungsson, Josefine, Isabelle Choquet, and Alexander F.H. Kaplan. 2015. Laser Welding Process - A Review of Keyhole Welding Modelling. *Physics Procedia* 78. Elsevier B.V.: 182–191. https://doi.org/10.1016/j.phpro.2015.11.042.

75. Noori Rahim Abadi, S. M.A., Y. Mi, F. Sikström, A. Ancona, and I. Choquet. 2021. Effect of shaped laser beam profiles on melt flow dynamics in conduction mode welding. *International Journal of Thermal Sciences* 166. https://doi.org/10.1016/j.ijthermalsci.2021.106957.

76. Kaplan, Alexander F.H. 2012. Fresnel absorption of 1 μm- and 10 μm-laser beams at the keyhole wall during laser beam welding: Comparison between smooth and wavy surfaces. *Applied Surface Science* 258. Elsevier B.V.: 3354–3363. https://doi.org/10.1016/j.apsusc.2011.08.086.

77. Zhu, Baoqi, Jianglin Zou, Shun Xie, Tao Liu, and Wuxiong Yang. 2025. The calculation of keyhole depth based on the primary absorption of front keyhole wall in laser deep-penetration welding. *Journal of Applied Physics* 137. AIP Publishing LLC. https://doi.org/10.1063/5.0233981.

78. Yu, Fengyi, Yanhong Wei, Yanzhou Ji, and Long Qing Chen. 2018. Phase field modeling of solidification microstructure evolution during welding. *Journal of Materials Processing Technology* 255: 285–293. https://doi.org/10.1016/j.jmatprotec.2017.12.007.

79. Hozoorbakhsh, Asghar, M. Hamdi, Ahmed Aly Diaa Mohammed Sarhan, Mohd Idris Shah Ismail, Chak Yin Tang, and Gary Chi Pong Tsui. 2019. CFD modelling of weld pool formation and solidification in a laser micro-welding process. *International Communications in Heat and Mass Transfer* 101. Elsevier: 58–69. https://doi.org/10.1016/j.icheatmasstransfer.2019.01.001.

80. Borukhovich, Efim, Guanxing Du, Matthias Stratmann, Martin Boeff, Oleg Shchyglo, Alexander Hartmaier, and Ingo Steinbach. 2016. Microstructure design of tempered martensite by atomistically informed full-field simulation: From quenching to fracture. *Materials* 9: 1–18. https://doi.org/10.3390/ma9080673.

81. Palanisamy, S., R. Rajendran, and S. Shashi Kumar. 2023. Effect of incident angle on weld microstructure and mechanical properties of laser beam welded nitronic −50 austenitic stainless steel joints. *Micron* 169. Elsevier Ltd: 103457. https://doi.org/10.1016/j.micron.2023.103457.

82. Anufriyev, Dmitriy Andreevich, Vladimir Georgievich Protsenko, Maksim Vasilievich Larin, Mikhail Valerievich Kuznetsov, Aleksey Alekseevich Mukhin, Maksim Nikolaevich Sviridenko, Sergey Vyacheslavovich Kuryntsev, Oleg Ivanovich Grinin, and Yakov Borisovich Pevzner. 2024. Influence of Laser Welding Modes along a Curved Path on the Mechanical Properties and Heterogeneity of the Microstructure of 316L Steel Plates. *Materials* 17. https://doi.org/10.3390/ma17153744.

83. Botlani Esfahani, Mohammad Behzad, Arash Karimipour, Mohammad Akbari, Ali Abdollahi, and Mohammad Najafi. 2024. Experimental and numerical investigation of dissimilar weld characterization in laser welding of duplex 2205 and AISI 1060 steel: Microstructure, mechanical properties and weld geometry. *Heliyon* 10. Elsevier Ltd: e40899. https://doi.org/10.1016/j.heliyon.2024.e40899.

84. Lai, Zen Hao, Siguang Xu, Samuel J. Clark, Kamel Fezzaa, and Jingjing Li. 2024. Unveiling mechanisms and onset threshold of humping in high-speed laser welding. *Nature Communications* 15. Springer US: 1–9. https://doi.org/10.1038/s41467-024-53888-w.

85. Börner, Stephan, Dirk Dittrich, Joseph Barrios Larrañaga, Andreas Wetzig, Michael Sawannia, Eveline N Reinheimer, Andreas Heider, and Reiner Ramsayer. 2023. Enhanced process understanding for laser welding of copper and aluminum alloys with dynamic beam oscillation.

86. Luo, Can, WeiPing Peng, and Chen Zhang. 2024. Effects of beam oscillation on porosity and microstructure of laser welded TC11 titanium alloy. *Journal of Laser Applications* 36. Laser Institute of America. https://doi.org/10.2351/7.0001262.

87. Zhao, Xu, Weihua Zhang, Hui Chen, and Yong Chen. 2023. Analysis of dynamic characteristics of vapor plume of oscillating laser welding of SUS301L-HT stainless steel. *Optics and Laser Technology* 159. Elsevier Ltd: 108947. https://doi.org/10.1016/j.optlastec.2022.108947.

88. SaediArdahaei, Saeid, and Xuan Tan Pham. 2024. Toward Stabilizing the Keyhole in Laser Spot Welding of Aluminum: Numerical Analysis. *Materials* 17. https://doi.org/10.3390/ma17194741.

89. Alves, P. H.O.M., M. S.F. Lima, D. Raabe, and H. R.Z. Sandim. 2018. Laser beam welding of dual-phase DP1000 steel. *Journal of Materials Processing Technology* 252. Elsevier: 498–510. https://doi.org/10.1016/j.jmatprotec.2017.10.008.

90. Yang, Xuan, Yazhi Li, and Biao Li. 2023. Formation mechanisms of lack of fusion and keyhole-induced pore defects in laser powder bed fusion process: A numerical study. *International Journal of Thermal Sciences* 188. Elsevier Masson SAS: 108221. https://doi.org/10.1016/j.ijthermalsci.2023.108221.

91. Barsoum, Z., and B. Jonsson. 2011. Influence of weld quality on the fatigue strength in seam welds. *Engineering Failure Analysis* 18. Elsevier Ltd: 971–979. https://doi.org/10.1016/j.engfailanal.2010.12.001.

92. Xu, W., D. Westerbaan, S. S. Nayak, D. L. Chen, F. Goodwin, and Y. Zhou. 2013. Tensile and fatigue properties of fiber laser welded high strength low alloy and DP980 dual-phase steel joints. *Materials and Design* 43: 373–383. https://doi.org/10.1016/j.matdes.2012.07.017.

93. Qureshi, E. M., A. M. Malik, and N. U. Dar. 2009. Residual stress fields due to varying tack welds orientation in circumferentially welded thin-walled cylinders. *Advances in Mechanical Engineering* 2009. https://doi.org/10.1155/2009/351369.

94. Javadi, Yashar, Mehdi Akhlaghi, and Mehdi Ahmadi Najafabadi. 2013. Using finite element and ultrasonic method to evaluate welding longitudinal residual stress through the thickness in austenitic stainless steel plates. *Materials and Design* 45. Elsevier Ltd: 628–642. https://doi.org/10.1016/j.matdes.2012.09.038.

95. Khan, Muhammad Shehryar, Maryam Soleimani, Abdelbaset R.H. Midawi, Isiaka Aderibigbe, Y. Norman Zhou, and Elliot Biro. 2023. A review on heat affected zone softening of dual-phase steels during laser welding. *Journal of Manufacturing Processes* 102. Elsevier Ltd: 663–684. https://doi.org/10.1016/j.jmapro.2023.07.059.

96. Mohandas, T., G. Madhusudan Reddy, and B. Satish Kumar. 1999. Heat-affected zone softening in high-strength low-alloy steels. *Journal of Materials Processing Technology* 88: 284–294. https://doi.org/10.1016/S0924-0136(98)00404-X.

97. Wang, Yubo, Wei Liu, Heng Cui, and Guipeng Lu. 2024. Effect of laser beam incidence angle on weld formation mechanism and corrosion resistance of T2 copper/304 stainless steel. *Scientific Reports* 14. Nature Publishing Group UK: 1–10. https://doi.org/10.1038/s41598-024-57316-3.

98. Akela, A. K., H. Shashikumar, J. N. Mohapatra, R. Singh, D. S. Kumar, and G. Balachandran. 2023. Weldability Study of Dual Phase and Transformation Induced Plasticity Automotive Steels. *Journal of Mining and Metallurgy, Section B: Metallurgy* 59: 155–167. https://doi.org/10.2298/JMMB220712014A.

99. Pang, Shengyong, Xinyu Shao, Wen Li, Xin Chen, and Shuili Gong. 2016. Dynamic characteristics and mechanisms of compressible metallic vapor plume behaviors in transient keyhole during deep penetration fiber laser welding. *Applied Physics A: Materials Science and Processing* 122. Springer Berlin Heidelberg. https://doi.org/10.1007/s00339-016-0230-5.

100. Xu, Tianqiu, Davide Concordia, Francesco Galbusera, and Ali Gökhan Demir. 2025. Development of a mid-fidelity modelling approach for laser welding with novel beam shapes for electric mobility materials. *Journal of Manufacturing Processes* 151: 772–787. https://doi.org/10.1016/j.jmapro.2025.07.030.

101. Huang, Hui, Seiichiro Tsutsumi, Jiandong Wang, Liqun Li, and Hidekazu Murakawa. 2017. High performance computation of residual stress and distortion in laser welded 301L stainless sheets. *Finite Elements in Analysis and Design* 135. Elsevier B.V.: 1–10. https://doi.org/10.1016/j.finel.2017.07.004.

102. Zhang, Yi, Shaojie Wu, and Fangjie Cheng. 2025. Automatic Adaptive Weld Seam Width Control

Method for Long-Distance Pipeline Ring Welds. *Sensors* 25: 1–16. https://doi.org/10.3390/s25082483.

103. Tong, Ying, Guo Zheng Quan, Hai Tao Wang, and Wei Xiong. 2025. Optimization of Welding Parameters Using an Improved Hill-Climbing Algorithm Based on BP Neural Network for Multi-Bead Weld Smoothness Control. *Materials* 18: 1–27. https://doi.org/10.3390/ma18174084.

104. Nagendra, J., K. S. Prashanth, Kavadiki Veerabhadrappa, K. D. Bopanna, M. Vinutha, E. Naresh, and Din Bandhu. 2025. AI-powered predictive framework for crack detection in steel–copper laser welding. *Scientific Reports*: 1–29. https://doi.org/10.1038/s41598-025-29977-1.

105. Palma-Ramírez, Dayana, Bárbara D. Ross-Veitía, Pablo Font-Ariosa, Alejandro Espinel-Hernández, Angel Sanchez-Roca, Hipólito Carvajal-Fals, José R. Nuñez-Alvarez, and Hernan Hernández-Herrera. 2024. Deep convolutional neural network for weld defect classification in radiographic images. *Heliyon* 10: 1–11. https://doi.org/10.1016/j.heliyon.2024.e30590.

106. Sathick, Javubar, and A. Abdul Azeez Khan. 2025. A smart manufacturing paradigm for robotic welding process optimization through machine learning. *Scientific Reports* 15: 1–12. https://doi.org/10.1038/s41598-024-82590-6.

107. Sezgin, Cihangir Tevfik, and Fatih Hayat. 2020. The microstructure and mechanical behavior of trip 800 and dp 1000 steels welded by electron beam welding method. *Soldagem e Inspecao* 25: 1–12. https://doi.org/10.1590/0104-9224/SI25.26.

108. Antal, Gabriel, Valentino Razza, Pasquale Russo Spena, and Manuela De Maddis. 2025. Quality monitoring framework for friction element welding. *Journal of Manufacturing Processes* 156. Elsevier Ltd: 17–28. https://doi.org/10.1016/j.jmapro.2025.10.083.

109. Klimpel, Andrzej. 2024. Review and Analysis of Modern Laser Beam Welding Processes. *Materials* 17. https://doi.org/10.3390/ma17184657.

110. Huang, Wei, and Radovan Kovacevic. 2012. Development of a real-time laser-based machine vision system to monitor and control welding processes. *International Journal of Advanced Manufacturing Technology* 63: 235–248. https://doi.org/10.1007/s00170-012-3902-0.

111. de Graaf, Menno, Ronald Aarts, Ben Jonker, and Johan Meijer. 2010. Real-time seam tracking for robotic laser welding using trajectory-based control. *Control Engineering Practice* 18. Elsevier: 944–953. https://doi.org/10.1016/j.conengprac.2010.04.001.

112. Liang, Yu, Bojian Yu, Mengyu Ding, Wenchen Hu, Yuchang Jin, and Yuefeng Yuan. 2025. WELD-DETR: A Real-Time Welding Defect Detection Framework with Multi-Scale Feature Fusion and Multi-Kernel Perception Optimization. *Sensors* 25: 1–30. https://doi.org/10.3390/s25227024.

113. Jatavallabhula, Jagadesh Kumar, Flavia Masubelele, Steadyman Chikumba, and Vasudeva Rao Veeredhi. 2025. Artificial intelligence for quality assurance in friction stir welding - a review on opportunities and challenges. *Engineering Research Express* 7. IOP Publishing. https://doi.org/10.1088/2631-8695/adc877.

114. De Bono, Paola, Chris Allen, Giuseppe D'Angelo, and Alessandro Cisi. 2017. Investigation of optical sensor approaches for real-time monitoring during fibre laser welding. *Journal of Laser Applications* 29. https://doi.org/10.2351/1.4983253.

115. Altay, Meryem, and Hakan Aydin. 2024. Parameter optimization, microstructural and mechanical properties of fiber laser lap welds of DP1200 steel sheets. *Measurement: Journal of the International Measurement Confederation* 235. Elsevier Ltd: 114822. https://doi.org/10.1016/j.measurement.2024.114822.

116. Küçükömeroğlu, T., S. M. Aktarer, and G. Çam. 2019. Investigation of mechanical and microstructural properties of friction stir welded dual phase (DP) steel. *IOP Conference Series: Materials Science and Engineering* 629. https://doi.org/10.1088/1757-899X/629/1/012010.

117. Naeem, Muhammad Ali, Sushank Chaudhary, and Yahui Meng. 2024. Road to Efficiency: V2V Enabled Intelligent Transportation System. *Electronics (Switzerland)* 13: 1–21. https://doi.org/10.3390/electronics13132673.

118. Lee, Hyoungwook, Cheolhee Kim, and Jung Han Song. 2015. An evaluation of global and local tensile properties of friction-stirwelded DP980 dual-phase steel joints using a digital image correlation method. *Materials* 8: 8424–8436. https://doi.org/10.3390/ma8125467.

119. Deepati, Anil Kumar. 2024. The Influence of Tool Tilt Angle on the Friction Stir Welding Characteristics of Wrought Magnesium Alloy Plates. *Scientia Iranica* 0: 0–0. https://doi.org/10.24200/sci.2024.62246.7728.