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An Overview of Laser Welding of High Strength Steels for Automotive Application

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Abstract: The current study investigates the effect of processing parameters Advance High Strength Stainless steel (AHSS) in terms of weld geometry by using the Pulse Wave (PW) mode of the fibre laser. The mechanical characteristics and microstructure are discussed and studied based on the literature. This study conducted an extensive literature review and highlighted various types of steel important for automotive applications. After that, laser welding of steel and the corresponding effect of parameters and their effect on weld geometry are discussed. It can be concluded that the variation of laser welding parameters can cause high thermal distortion and greatly affect the joint's mechanical performance. Hence, an optimum parameter value should be investigated to obtain a strong joint. This study also highlighted several avenues that researchers in future must explore.

Keywords: *Laser welding, AHSS, steel, mechanical properties, dissimilar welding*

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I. INTRODUCTION

Industries nowadays are improving and looking out for a solution to improve the quality of their products at a low cost. The automotive industry is very much interested in steels that have high strength but at the same time have good ductility. There are several types of steels which have been used in the automotive industry since then, such as mild steel Dual-Phase (DP) steels, partially martensitic, and Transformation Induced Plasticity (TRIP) steels or Multiphase (MP) steels, High Strength, Low Alloy steel (HSLA), and Advance High Strength Stainless steel (AHSS) [1]. AHSS which replaces the standard High Stainless Steel (HSS) is the solution to the interest of the automotive industry. Advance high stainless steel has a strength of yield and hardenability compared to conventional high stainless steel which has been used in the manufacturing of thin components, at the same time keeping the same force bearing potentiality [2]. SS304 is Austenitic Stainless Steel (ASS). It contains chromium at 18% to 20% and nickel at 8% to 10.5%. SS304 is less thermal and electrically conductive and also not magnetic. SS304 has resistivity towards corrosion and is used widely in industries because of its easy formability. 304 stainless steel is utilized for an assortment of the family unit and modern applications, for example, nourishment taking care of and handling gear, screws, hardware parts, and

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vehicle headers. 304 stainless steel is likewise utilized in the engineering field for outside accents, for example, water, and fire highlights. It is additionally a typical curl material for vaporizers. Duplex Stainless Steel (DSS) is another example of AHSS. The development of duplex stainless steels was to enhance bonding strength and resist pitting zones and stress corrosion cracking. Duplex stainless exhibits an austenite-ferrite dual-phase structure. This can only be obtained by the appropriate composition and thermo-mechanical process [3, 4, 5, 6]. Duplex stainless steel has good corrosion resistance which is why it is widely used in shipbuilding, petrochemical, paper, and nuclear industries [7, 8].

The automotive industry requires several procedures such as hot stamping, blanking, and welding to form a component of an automobile. Each process has its advantages and disadvantages. Spot resistance welding which is the conventional welding technique used in the automotive sector is used to join two or more components together. There are many other fusion state welding processes such as Gas Metal Arc Welding (GMAW), Metal Inert Gas welding (MIG), Tungsten Inert Gas welding (TIG). Although laser welding [9] is not a recently discovered joining process, the automotive industry has given more interest to laser welding and the implementation of laser welding has skyrocketed. This is simply because of the advantages of laser welding. Laser welding has a low processing time compared to conventional spot welding [10]. The processing time is more significant in welding thicker material as resistance spot welding increases drastically. A custom shape weld can be produced via laser welding whereas this is not able to be done with resistance welding. Laser welding can also help reduce the overall weight of a vehicle. Klinger's study [11] shows that shifting from resistance spot welding to laser welding can reduce 12.2 kg in the body in white of a vehicle. Not only that, torsional rigidness is improved via laser welding by cutting off the openings which will be needed in resistance spot welding. Laser Beam Welding (LBW) has high focused and high energy density, thus minimal heat distortion can be achieved [12]. Besides that, aesthetics due to good quality laser seam welding eliminates secondary processes such as grinding and finishing.

Laser mode is one of the important features for laser output. Based on the Q-switching of laser, the power can supply in either Pulse Wave (PW) mode or Continuous Wave (CW) mode. Due to simple parameters and good quality weld, the CW mode is often favourable. But to penetrate thicker materials, PW mode is required [13]. PW mode also known as pulse seam mode has higher potentials to replace the CW mode in industry. Duplex stainless-steel exhibits good weldability because of rich nitrogen content and less carbon content. Normally, the fusion zone of duplex stainless steel contains about 15% to 20% of austenite. The quick cooling rate and fast hardening in the laser welding process give no impact to the ferrite development, however, it smothers strong state ferrite to austenite stage change. A reasonable microstructure of austenite and ferrite (50%-50%) is accomplished with post-weld heat treatment at the range of 1050°C 1100°C. This helps provide good stress corrosion properties. SS304 is known as Chromium-Nickel austenitic alloy. It has a melting point of 1399°C to 1454°C. Be that as it may, welding of materials with various substance arrangement will initiate a combination zone with intermetallic zones between the distinctive parent metals. The results have a direct impact on weld properties, microstructure, and weldability [14]. Hence, the weldability of dissimilar material remains a challenge. The weld zone properties can be controlled by precisely controlling the welding parameters. Although, CW mode is commonly used fiber laser welding with PW mode of boron steel and duplex stainless steel is not common. Currently, the most looked into source in industries is the fiber laser. It has the advantages of compact design, less starting cost, good beam quality, and less expenditure for maintenance in contrast to other lasers. Thus, this gives the desired productivity for industries. In the automotive sector, minimum heat-affected zone, deep penetration, and excellent seam welding are required. A great number of studies have been conducted for laser welding for tailor welded blank applications using boron steel [15]. The superb quality intersection is obtained by a few numbers of processing parameters associated with the CW mode. Thus, this cheaper low power laser has higher chances of replacing the CW mode laser. Before this, research in continuous LBW by using PW mode was paid more attention to parameters combination instead of specific materials weldability.

In the domain of pulsed fiber laser, the influence and significance of processing parameters are very important. The consequences of the processing parameters can be deduced based on the microstructure changes. Processing parameters influence the mechanical properties of the welded specimen. The complete parameter study is necessary for parameter optimization of continuous laser welding by using pulse waves on specific materials weldability in terms of weld geometry. Besides that, in dissimilar material welding, many defects are prone to occur. So, we will use a different approach which is using fiber laser and pulsed wave mode to overcome this issue. Although DSS has been welded by LBW and boron steel too has been joint by laser beam welding, but there is no study on joining these two materials; duplex stainless steel and boron steel together by laser beam welding. Thus, the novelty lies in successfully welding these AHSS dissimilar materials. Therefore, this review is carried out to investigate the effect of processing parameters AHSS steel in terms of weld geometry by using PW mode of the fiber laser. The mechanical characteristics and microstructure are discussed and studied based on the literature.

II. WELDING

Fusion Welding is defined as the process of joining two similar or dissimilar materials by applying heat to soften the materials and allowing them to cool down causing a fusion. Welding is now a commonly used method to join materials, as its ability to join complex structures, high strength of joint specimens, cheap and also highly reliable. Welding can be categorized into two, which are solid-state welding and fusion welding (Fig. 1). In solid-state welding, materials are not melted to form a molten pool whereas in infusion state welding, the melting of material to form a molten pool to join the materials occurs. Diffusion welding, cold welding, friction welding, and resistance welding are several types of solid-state welding. Resistance welding is the oldest and most used process in manufacturing body-in-white (BIW) in the automotive industry [16]. Some examples of fusion welding are SMAW which stands for shield metal arc welding [17], GMAW [18] abbreviated for gas metal arc welding, GTAW which means gas tungsten arc welding, and submerged arc welding. Laser welding is a type of fusion welding which is favored by many industries in 1990 [19].

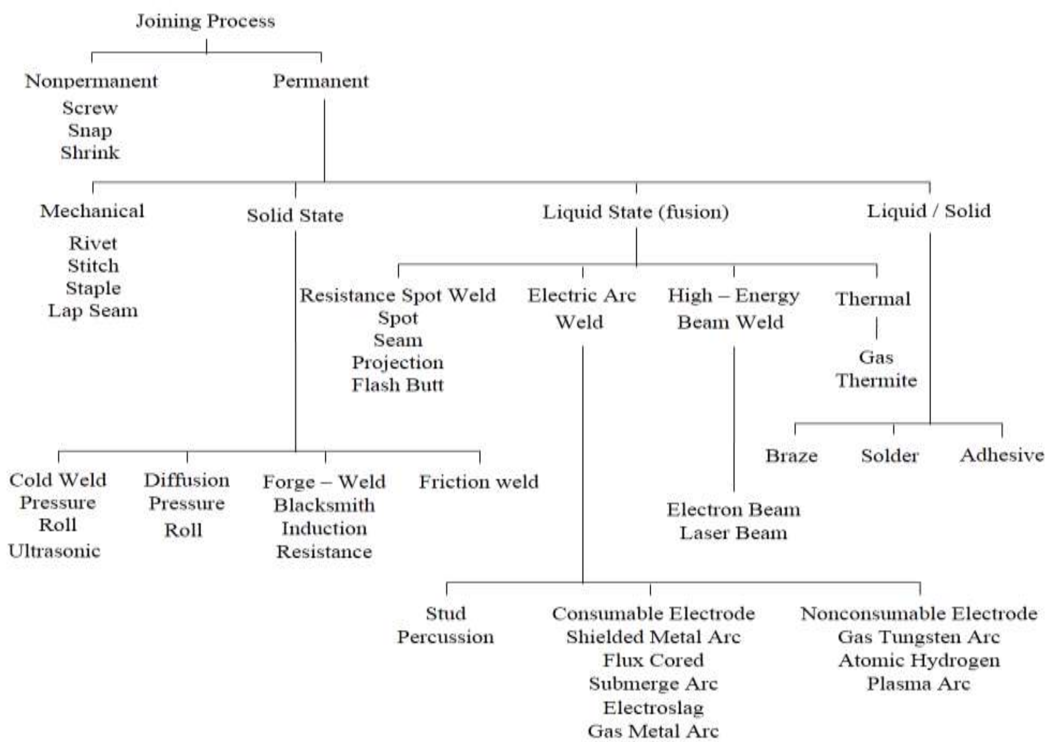

Fig. 1. An overview of the types of joining processes [20]

III. LASER WELDING

Laser welding was introduced by ThyssenKrupp in 1983. Laser welding has become a more common mode of welding due to its advantages over other types of welding processes. For example, laser welding has low processing time [10] comparing to resistance spot welding especially at times of joining thicker materials. Laser welding can weld with deep penetration and has a higher welding speed because of the sharp focus and high power of the laser beam. The keyhole method of welding requires less vitality move to the material, which results in the minimum Heat-Affected Zone (HAZ) with little warm twists and low leftover pressure. Welding with keyhole mode requires power density to begin vaporization which is gotten by concentrating the laser beam. Keyhole is in this way shaped which empowers various inside reflections of the beam along these lines bringing about productive power deposition. Fine welding seam quality and superior metallurgical bonding which is favored in the automotive industry are what laser welding is known for. This is because it helps reduce weight, improve safety, and absorb vibration [21]. The maintenance cost is not cheap for spot welding especially for welding alloys like aluminum as it needs frequent replacements of electrode tips due to deposition of aluminum alloys. Laser welding is also widely used in many industries because of its ability to produce custom shape welds. In the automotive industry, laser welding is also able to reduce the overall weight of the vehicle due to the reduction of flange widths while giving the flexibility to employ lightweight materials [22]. On the other hand, spot welding will require about 16mm of flange width to allow spot gun positioning which eventually builds on weight and increases the material cost. Converting from spot welding to laser welding in the body in white structures can reduce mass up to 12.2 kg [11]. Moreover, laser welding which has a single access feature can increase torsional rigidity. Removing the access openings which is needed for resistance welding is the way done to improve the torsional rigidity. High energy density and high focused beams result in very less thermal distortion. Not only that, ending processes like grinding and finishing is not necessarily due to the high-quality laser seam welding.

The most efficient welding technique in the welding automotive steel sheet is LBW. During the late 1980's in Europe, CO_2 laser was used in tailor blank sheets for automotive parts for roof welding. In 1990's, kW-grade Nd: YAG lasers were introduced. LBW using the Nd: YAG lasers were used because of its ability to weld with the aid of articulated robots. The new laser invention of laser brazing and remote LBW has come into use as of late, and the laser-circular section has begun to be used to weld aluminum amalgams. With more advancements in lasers, the new high-controlled fiber laser and plate lasers have higher pillar accuracy, which is adequate for the LBW welding of car bodies. LBW is a mechanism by which the metal is melted by a directed radiation beam that focuses on the metal surface when two sections are joined together. The upper layer of the metal absorbs partially of the radiation which causes it to raise its melting point [23]. LBW's main process parameters are laser beam properties such as peak power, beam quality, and diameter, laser wavelength radiated, focal length, welding conditions such as focus to the material surface, workpiece movement to the laser spot, weld type, processing gas, and physical properties of welded material [24]. Parameters and combinations in LBW where the heat input is determined should be selected correctly for superb weld quality [25].

There are lots of superiority of LBW compared to the conventional method in the point of view of production due to: [26]

- The effect of low heat input results in higher HAZ and lower thermal distortion;
- Excellent quality, durability, and repeatability of welded joints and increased welding metal strength;
- Flexibility to control the laser beam through fiber optics until it reaches the fusion zone
- Strong affidavit rate and process output accordingly; Easy process management and automation

A. *Nd: YAG Laser*

CO_2, Nd: YAG and fiber laser are the three common types of LBW widely used in the industry. In solid-state laser welding, a common laser is the Nd: YAG crystal that stands for neodymium-doped yttrium aluminum garnet; Nd: Y3Al5O12. Triply ionized neodymium, Nd (III), which acts as a dopant replaces the (1%) of the yttrium ions which comes from the host crystal structure of the Yttrium Aluminum Garnet (YAG). This happens because both ions are similar in size. The neodymium ion conducts the lasing activity in the crystal. The first laser welding of Nd: YAG was carried out in the year 1964 [27]. A flash tube or laser diode is used to optically pump the Nd: YAG lasers. The Nd: YAG laser has light emission with a wavelength of 1064nm in the infrared. In PW and CW mode, laser Nd: YAG can be used. Since the Nd: YAG laser can absorb mostly in the band of 730-760 nm and 790-820 nm, the most suitable for pumping the Nd: YAG laser would be the xenon lamp. The neodymium dopant amount varies according to its usage as the doping amount is lesser in CW mode comparing to the PW mode. Nd: YAG has a wide application in several industries such as medicine, dentistry, fluid dynamics, manufacturing, automotive, and military.

B. *Carbon Dioxide Laser*

CO_2 is another form of laser used in laser welding. This device operates by allowing electricity to flow through a gas-filled tube. The end of the tube is a mirror where one end is opaque, while the other end allows some light to pass through. Carbon dioxide, nitrogen, hydrogen, and helium is the gas composition. CO_2 lasers produce invisible light. When an electric current is allowed to pass through, the nitrogen in the gas excites. Since nitrogen can store the energy or is known as an excited state for a long period without losing charge, thus it is used. These excited nitrogen molecules in return excite the carbon dioxide molecules. A state called population inversion is achieved at this state which is the point where there are more excited molecules compared to non-excited molecules. The nitrogen atom should release its excited state to produce light by energy generation in the form of photons. Thus, the excited nitrogen atom meets very cold helium resulting in the release of light. Since the tube is fully mirror, thus the light is reflected back and forth till it gains enough intensity to pass through the partially reflective mirror. Thus, the light coming out of the tube is very powerful. The light produced from a CO_2 laser is so powerful that it is used to dissect materials like cloth, wood, and paper. Machining steel and other metals are done by the most powerful CO_2. The CO_2 laser has a long wavelength which is about 10.6 micrometres.

C. Diode Laser

The diode laser is also another form of laser used in laser welding. The diode laser is just beginning to be familiarized in the welding applications. A diode laser is a physically small sized compared to other lasers. The starting cost is not as costly as other welding lasers because of its smaller number of system components. The diode laser is a little semiconductor gadget that utilizes electrical flow as its wellspring of vitality [28]. At most, a few watts of power is produced by a typical diode laser emitter. Nevertheless, a total output of 100 W can be produced by fabricating numerous emitters on a single, monolithic substrate or bar. The bars in return will be consolidated in level and vertical stacks to deliver high-control diode laser frameworks with absolute yield in a multikilowatt run. Due to the inherent optical characteristics of the diode laser, the output light is not focused upon exiting thus making it impossible for key-hole welding. To overcome this, fiber optic is used to obtain the output from each diode emitters which then delivers the necessary power for welding usage.

D. High Power Diode Laser

HPDL is known as high power diode lasers in short. Diode lasers have been used in electronic equipment and metrology for many years. The introduction of industrial HPDL was due to the improvement of materials engineering. On the surface where the laser beam is focused, the new HPDL output can deliver power up to 6kW. As shown in Fig. 2, lasers of the ROFIN DL diode are defined as rectangular or linear form with multiple delivery target beams. This form of laser power density, fired to a surface layer of after-process materials, is lower compared to the mono-mode distribution. With that being so, HPDL is suitable to modify a surface layer. Increased efficiency and the ability to control the amount of energy deposited to a material surface layer is proven empirically for steels.

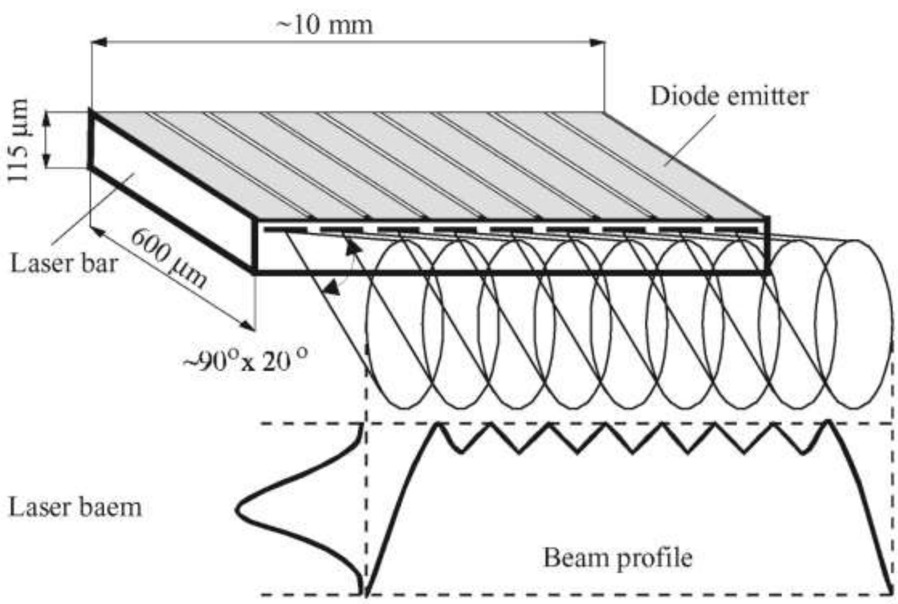

Fig. 2. Emission of laser radiation from a single laser bar in high power diode laser HPDL ROFIN DL 020 [28]

E. Fibre Laser

Fig. 2 shows that fibre lasers have the best label arrangements among the most commonly used modern lasers [13, 29].

Fibre laser gives a few favourable circumstances contrasted with the other sort of lasers, for example, high vigorous productivity, when contrasted with light or diode, siphoned bar lasers, a reduced structure which disentangles establishment, great shaft quality, the and it is likely to transmit a few kilowatts of strength and the whole lifespan that leads to low ownership support costs [30]. Fibre laser and Nd: YAG is identical in wavelengths while numerous amounts of materials could not absorb CO_2's wavelength as it possesses such wavelength. Ren studied the comparison between fiber laser and CO_2 laser welding on Inconel 617, he found that the melting efficiency of fiber laser was higher than that of CO_2 laser [31]. Thus, the heat input required to achieve full penetration of the weldment in a fiber laser is lower than the CO_2 laser. In addition, the results obtained for the cost of the use of laser equipment promoting low operational cost of fiber lasers compared with CO_2 and laser Nd: YAG are shown in Fig. 3 and Fig. 4.

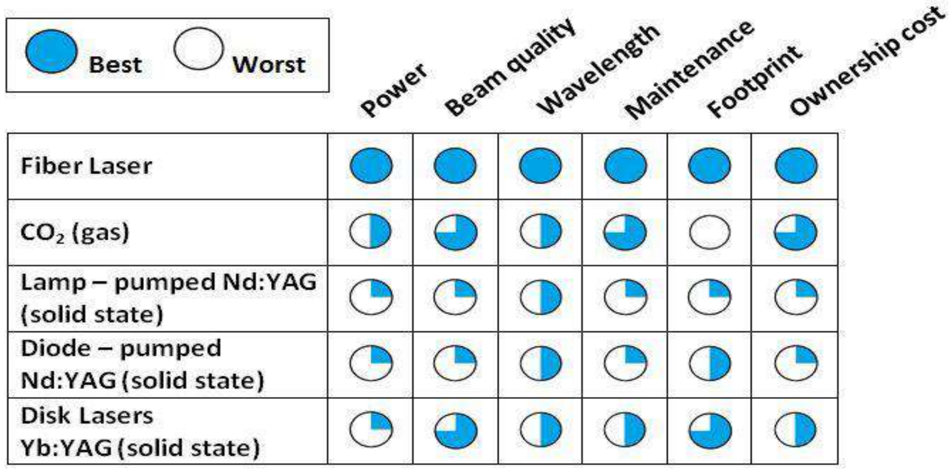

Fig. 3. Characteristic comparison between fibre, CO_2 and Nd:YAG laser [32]

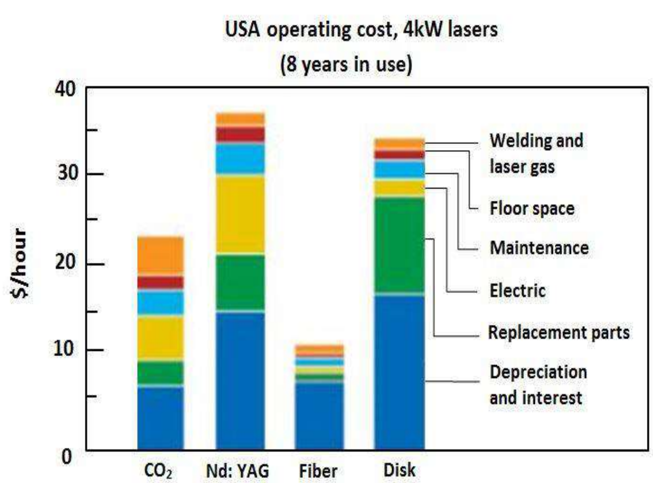

Fig. 4. Operating cost of 4 kW laser use for 8 years in industry [32]

The laser fiber is an optical fiber consisting of a silica glass doped with an unusual earth component. (REE, for example, erbium, ytterbium, neodymium, dysprosium, praseodymium, and thulium. Known as Doping, small particles of REE are mixed into the middle of the fiber. The REE function in laser fiber depends on the valuable vitality of iotas. The level of vitality assimilates the photons of a standard laser or siphon source wavelength and ultimately rotates to an expression that is comparable to the very high level of shaft regulation. The laser source requires an electrically siphoned siphon shaft or laser diode that is propelled longitudinally along the fiber length. There are different sources from the end or from the side as shown in Fig. 5. before experiencing the Bragg Grating reflector. Bragg Grating Reflector is an area of a glass with stripes where the refractive list is changed to reflect the particular wavelengths of light and passed onto others. This sector creates a laser hole in the doped tool. The inner cover absorbs the siphon light or diode for the process inside fiber doping and guides it over the fiber. The transmitted light is intensified by a heavy yield laser that passes through the middle of the inside. Light from one or several siphon lasers is finalized and collected by a couple during the final siphoning process before reaching the fiber end. Nonetheless, inside pumping, the siphoned light is coupled to the fiber sides and then promoted into a connector that links it to the external core. This is not quite like Nd: YAG laser, which is symmetrically positioned on the fiber pivot, in the side-siphoned laser bar. Upon, completion of the laser doping process, the light experiences the shaft conveyance framework. The yield optical get together in the bar conveyance comprises of a double focal point imaging framework. The main focus is a collimator focus that pulls the veered shaft from the fiber outlet, repairs it, or collimates it. This focal point is set a good way off equivalent to its central length from the fiber leave face to collimate the pillar. The subsequent focal point is a central focal point which goes about as a target and spotlights on the pillar to shape a picture of the fiber face.

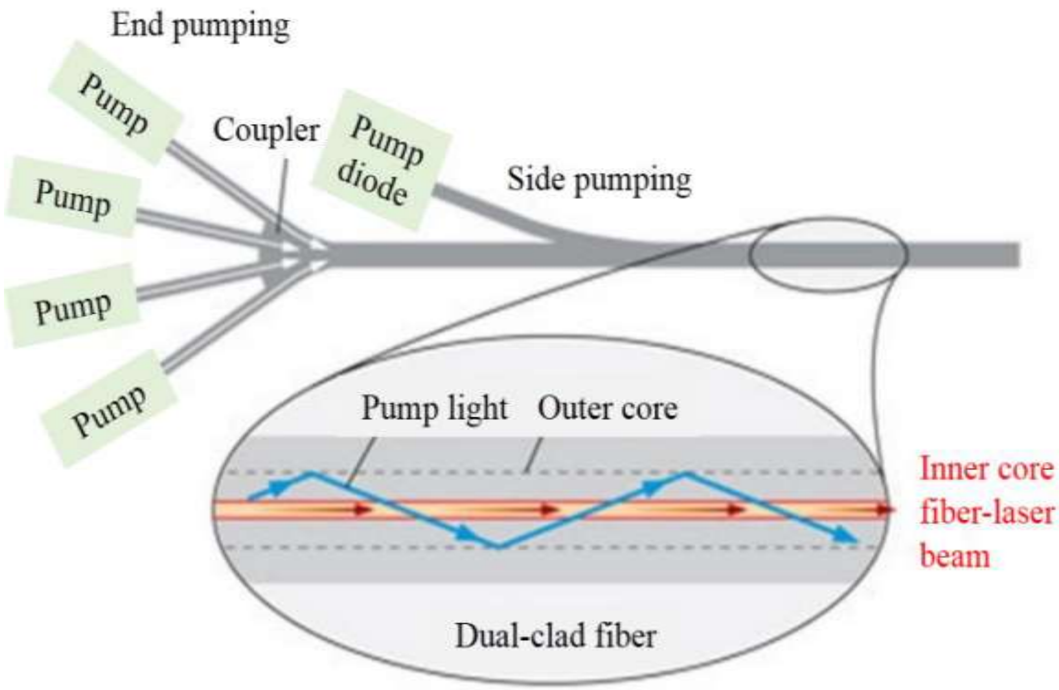

Fig. 5. The structure and configuration of multiple pump and dual clad fibre [17]

PW or CW, both can be done using a fiber laser. CW welding ensures a continuous laser beam is discharged over some time. It will deliver a steady straight weld bead and can infiltrate further in view of its persistent light discharge. CW welding has the capacity of melding a more extensive assortment of disparate metals. This applies to welding metal pieces with high thickness because of the capacity of infiltrating further into the metals. In the interim, PW mode output is made by pumped laser with quick bursts to deliver laser pulses which are controlled shortly. The pulse cycle consists of on and off periods and able to burst in precise with several pulses per second. The energy of pumped laser during no explosions and the radiation from the top properties is stored throughout the pulse cycle of PW mode. On the other hand, CW uses average power for its applications while PW mode releases the high power which is capable to create deep insight under the same average power source. The performance parameters which take into account are Peak Power Density (PPD) and energy applied. From the peak power value from PW laser output, the threshold value for both performance parameters to produce sufficient penetration can be achieved. Thus, with the only power source of 200 W, it is sufficient to give out 2 kW of peak power which is good enough for welding steel which has a thickness of 2 mm similar to CW mode condition.

CW welding has the capacity of combining a more extensive assortment of unique metals like coppers welded to treated steels. As for welding thicker metal pieces, this applies the same because of the capacity of infiltrating further into the metals. They differed in infiltration brings about huge change modes contrasted with PW that advance keyhole modes. Nevertheless, the CW laser beam runs and produces light that concentrates the tiny territories and makes the metal very hot. This welding mode is commonly used in industrial applications due to simple process parameters and versatility. However, the high-power laser source various from 2 to 10 kW is required to supply sufficient energy to produce sound weld for 2 mm-thick steel. Huge investment is required to acquire high power laser machine to perform CW mode for their application.

Continuous welding can be achieved using PW mode by overlapping each pulse also known as pulse seam welding. The sound continuous weld can be achieved by a consistent welding process and optimum parameter selection. When looking at the material association between the two modes, under comparative conditions (power density, interaction time, and beam diameter) the PW welds have higher infiltration profundity contrasted with the CW welds. It very well may be proof that welding by utilizing PW mode is conspicuous in higher entrance effectiveness [13].

Since the mechanical properties of a weld joint by laser weldings such as tensile strength and ductility depends on the microstructure of the join, it is very much important to use a perfect combination of process parameters as laser welding has no filler materials involved.

The microstructure is affected due to the heat input and cooling rate of metal, thus using the right parameters for the specific welds will be able to able to give a joint with good mechanical properties. In laser welding, there are several process parameters that affect the weld quality and mechanical behavior of the joint. Among them are Peak Power (PP), Pulse Width (PW), Pulse Repetition Rate (PRR), and Beam Diameter (BD).

Peak power is the main parameter that plays an important role in obtaining a good joint. Peak decided the intensity of the laser beam focused onto the specimen. According to Assuncao and Williams et al. [13], peak power value is higher in PW mode comparing to CW mode. For a given spot size, interaction on the surface material also known as PPD can be calculated using the equation in Eq. 1 [24]. Barea resembles the laser beam spot area in this equation. By, increasing the peak power, the PPD also increases. Fig. 6 shows a steady increase in the weld depth and width with the increasing peak power [33].

$$PPD = \frac{PP}{Barea} \quad (1)$$

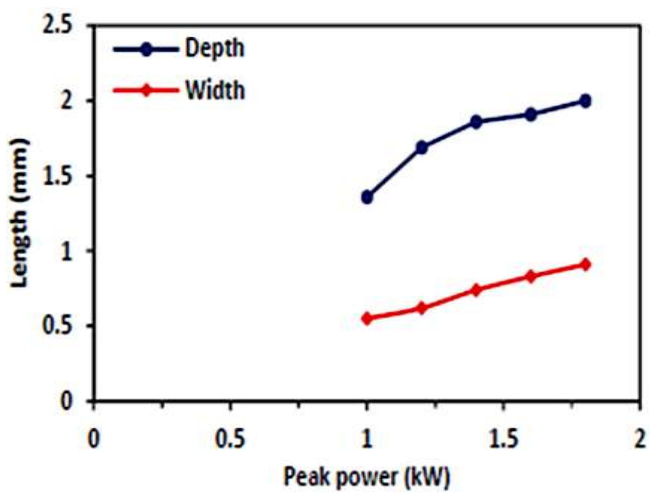

Fig. 6. The effects of peak power on laser welding [33]

PW is known as the interaction time of a particular point of a material radiated with a laser beam [13]. In short, it also means, the heat energy duration is transferred on the material surface from the beam. The expression to relate the energy is expressed in Eq. 2 [24]. Fig. 7 shows the weld depth reached maximum value as the pulse width increases and the depth decreased after exceeding the optimized value. As for the weld width, there are no significant changes [33].

$$Energy = PP \times PD \quad (2)$$

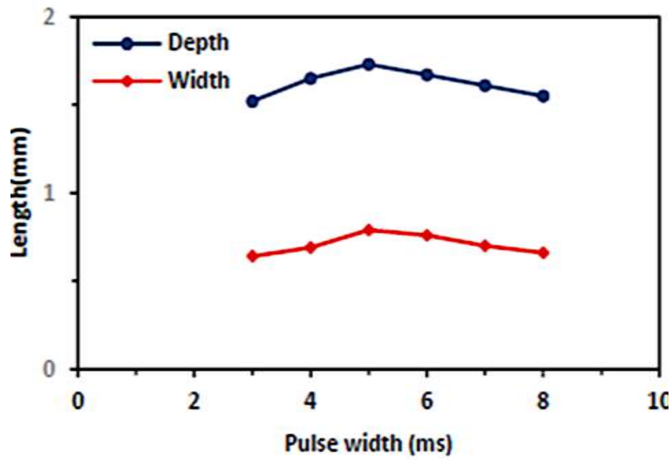

Fig. 7. Effect of pulse width on laser welding [33]

Besides that, the index for the overlap defines a pulse seam welding overlap gap. Pulse cycle time (T) is the product of PD and Pulse off time (Poff) is shown in Eq. 3. The frequency of pulse cycle time in one second is known as Pulse Repetition Rate (PRR) in Hz expressed in Eq. 4 [34]. Fig. 8 shows the increase in weld depth and width due to enhance pulse overlapping.

$$T = PD \times POFF \quad (3)$$

$$PRR = \frac{1}{T} \quad (4)$$

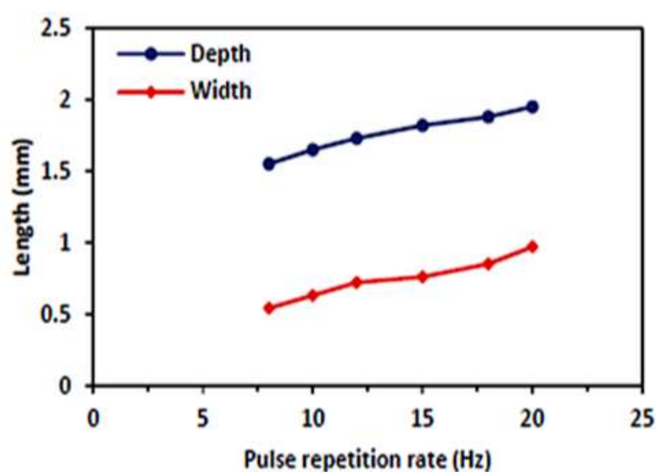

Fig. 8. Effect of pulse repetition rate [33]

Beam diameter is known as the size of the laser beam focused onto the material to be welded. Fig. 9 shows a drop-in weld depth and width as the laser beam diameter increases. This is because of the reduction in the focal point.

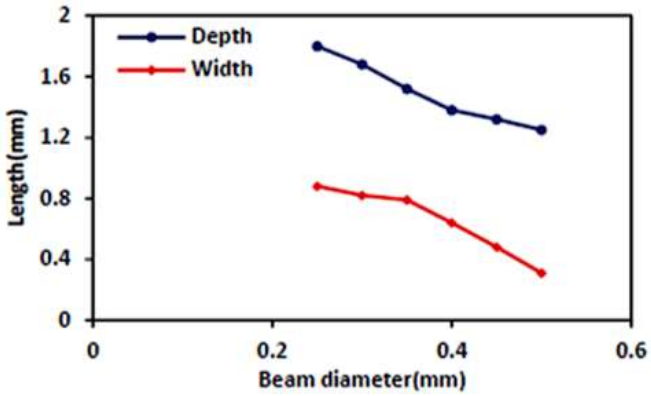

Fig. 9. Effect of beam diameter [33]

IV. ADVANCED HIGH STAINLESS STEEL

HSS is a solid solution, precipitation or grain grinding hardens, while Advance High Stainless Steel is hardened by phase-processing. The chemical compositions are carefully selected and multiphase microstructures are controlled by the heating and cooling process to form the unique combination of material and mechanical properties of AHSS grades [35]. AHSS has superior strength and more ductile in comparison to HSS. This helps to absorb energy during an impact and makes sure of safety when reducing the weight [36]. Automotive industries are very much interested in AHSS as it helps them to satisfy their requirements for manufacturing which is to have good safety, durability, quality, and manufacturability at a low cost [37]. The fuel consumption is lesser when the weight is reduced. It is able to save 3% to 7% of fuel consumption by every 10% of weight reduction [36]. AHSS also has a higher rate of hard work performance than conventional steel like mild steel. Thus, making thinner components while still being able to bear the load force is definitely made possible by AHSS [2].

A. *Duplex Stainless Steel*

Among the most favourable in industries and commonly used steel nowadays is duplex stainless steel. These steels are also known as austenitic-ferritic grades due to their metallurgical structures consisting of two phases which are austenite and ferrite in approximately equal proportions. The austenite has a face-centred cubic lattice while the ferrite has a body-centred cubic lattice. Duplex stainless steels are known for their good mechanical properties and excellent resistance to corrosion austenite and ferrite phase balance. In aggressive corrosion environments, alloy 2507 (UNS S32750) is frequently used. Pitting and stress corrosion cracking can be resisted by DSS in an excellent manner. In relative to rich nitrogen and less carbon content, duplex stainless-steel exhibits good laser weldability. Duplex stainless steels are used in oil, gas, manufacturing, chemical, wastewater, marine engineering, desalination, petroleum, and refining industries [38]. Fig. 10 shows the microstructure of the DSS of UNS 32750 which mainly consists of ferrite and austenite.

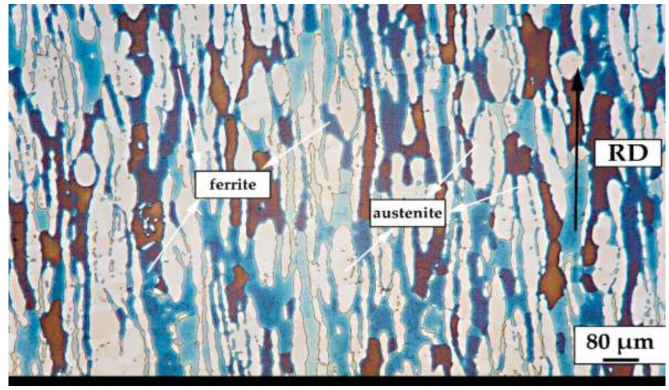

Fig. 10. Microstructure of as-received duplex stainless steel UNS 32750 [39]

B. *Boron Steel*

In hot stamping, the commonly used material is customarily boron-based or also called Boron Steel [40]. Boron alloy constitutes about 0.002 to 0.005% in steel. Boron steel has an alternate name, for example, USIBOR, BTR, and Boron which has a similar evaluation of steel with a somewhat extraordinary name contingent upon makers and the nation it originates from [41]. Saab 9000 was the first automobile invented by Saab AB in the year 1984 to utilize a hardened boron steel component. Boron alloys in boron steel will increase their hardness, preventing the heterogeneous nucleation of ferrite during fast cooling on the austenite grain surfaces. This effect is due to reduced interfacial strength since the boron isolates the grain boundaries and isolates the ferrite. Through suppressing the isolation of ferrite in this region the concentrations of bainite and martensite have increased as the boron content increases [42]. The adequacy of boron on the hardenability has been seen as emphatically based on the cooling temperature [43]. Starting with initial strength in as-received condition at 500 MPa as HSS, the strength increased up to 1500 MPa as AHSS after the heat-treatment process. Fig. 11 depicts the microstructure of boron steel 22MnB5 under an optical microscope and SEM in as-received condition. The as-received microstructure exhibit 75% ferrite and 25% pearlite.

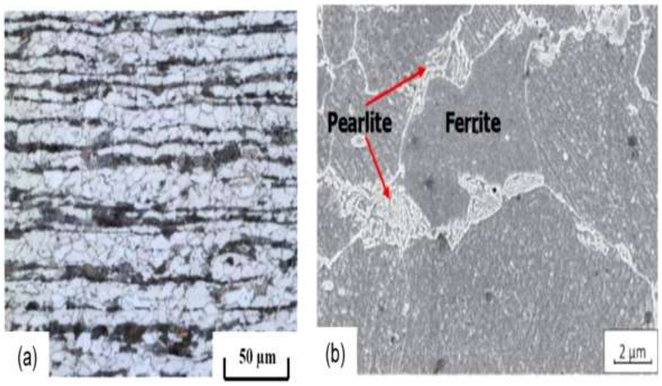

Fig. 11. As-received microstructure of 22MnB5 under (a) optical microscope and (b) SEM

C. Twin Induced Plasticity Steel

Twin Induced Plasticity (TWIP) steels offer themselves as high-quality steels with great malleability. They are utilized in the car business for sway assurance structures, for example, side effect bars, disintegrate zones, and B-pillar members [44]. Car body parts that have to be thin, lightweight, strong, and ductile could be made by TWIP steels. They depend on generating a large number of twins on deformation and the elements silicon and aluminium, alone or in combination, are needed to achieve these good characteristics. In order to obtain better ductility, a low sulphur and phosphorus content is required, approximately around 0.005%. This can be done by decreasing the volumetric fraction of sulfides. Another way to improve ductility in terms of phosphorus is by reducing the low melting point iron phosphide phase from forming. But unfortunately, TWIP is not good corrosion resistance. In the as-processed condition, TWIP steels are highly alloyed and exhibit a fully austenitic structure at room temperature because of the high manganese content in the steel. Fig. 12 shows the microstructure of the as-annealed TWIP steel.

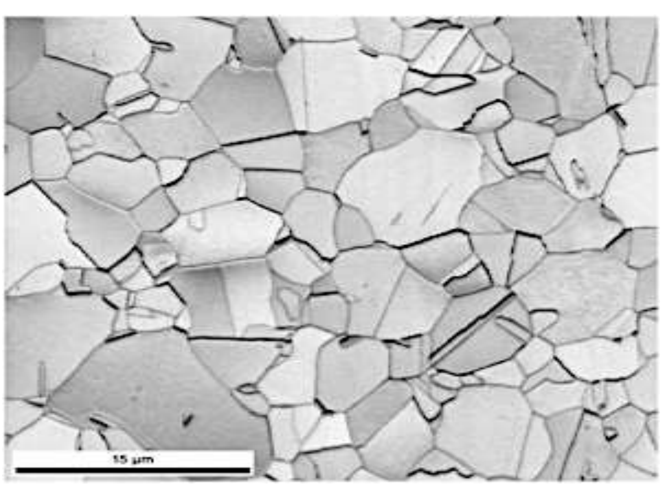

Fig. 12. Microstructure of TWIP steel as annealed [45]

D. SS304 Stainless Steel

ASS account for about 70% of stainless-steel groups. They have a face-centered cubic structure, with individual characteristics, such as weldability, toughness, and ductility [46]. This austenitic Cr-Ni stainless steel has far superior corrosion resistance compared with other types such as 302 grade. It possesses a high ductility and therefore, can be utilized for applications in which forming, excellent drawing, and spinning are of major significance. This steel does not have magnetic properties however, it becomes slightly magnetic when treated by strain hardening. One of the main advantages of SS 304 L, is the low content of carbon element which brings about less carbide precipitation in the heat-affected zone during the welding process which decreases its susceptibility against intergranular corrosion. Due to its distinct properties, it has been utilized in numerous applications such as evaporators, pressure vessels, valves, shipping drums and etc. in all of which the corrosion impact is considerable. Fig. 13 shows the weld geometry of SS304 stainless steel as received.

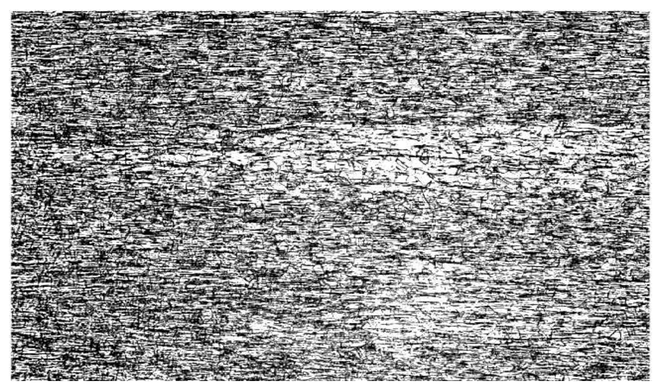
Fig. 13. Microstructure of SS304 as received

V. LASER WELDING OF AUTOMOTIVE STEELS

A. Microstructure of Laser Welded Steels

The microstructure of steel is what determines the mechanical characteristics of that particular steel. In laser welding, the microstructure of the welded steels changes accordingly to the heat transferred and cooling rate. The heat input and cooling rate are influenced by the welding parameters [33]. The furthest region from the weld bead is the base metal zone. The base metal zone does not undergo phase transformation as it is in the unaffected region. In boron steel, the base metal is outlined of two morphologies which are ferrite and pearlite phase [47]. Pearlite is a lamellar structure made out of exchange portions of ferrite and cementite. In the fusion zone of the laser-welded boron steel, thermally induced martensite is present. Martensite is shaped when fast cooling of austenite causes constrained time being accessible for molecules to diffuse out of the crystal structure to form pearlite. The results of rapid cooling can be seen in the continuous cooling transformation in Fig. 14. As for the HAZ in boron steel, it depends on the diffusivity. The temperature in the HAZ zone near the FZ exceeded the ferrite transition to austenite temperature. The microstructure was anticipated to totally change into austenite. Because of fast cooling to the encompassing temperature, the temperature inclination from the welded zone to the base metal may deliver different microstructure blends comprising of pearlite and ferrite as shown in Fig. 15. According to Moon [48], the boron component in the austenite grain limit is reached by boron steel by isolation, and the recrystallization of austenite at high temperatures is forbidden.

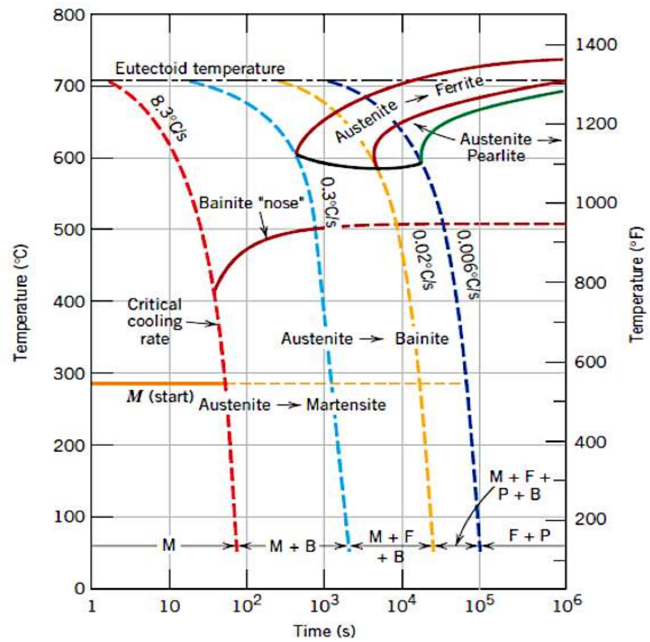

Fig. 14. Continuous cooling transformation

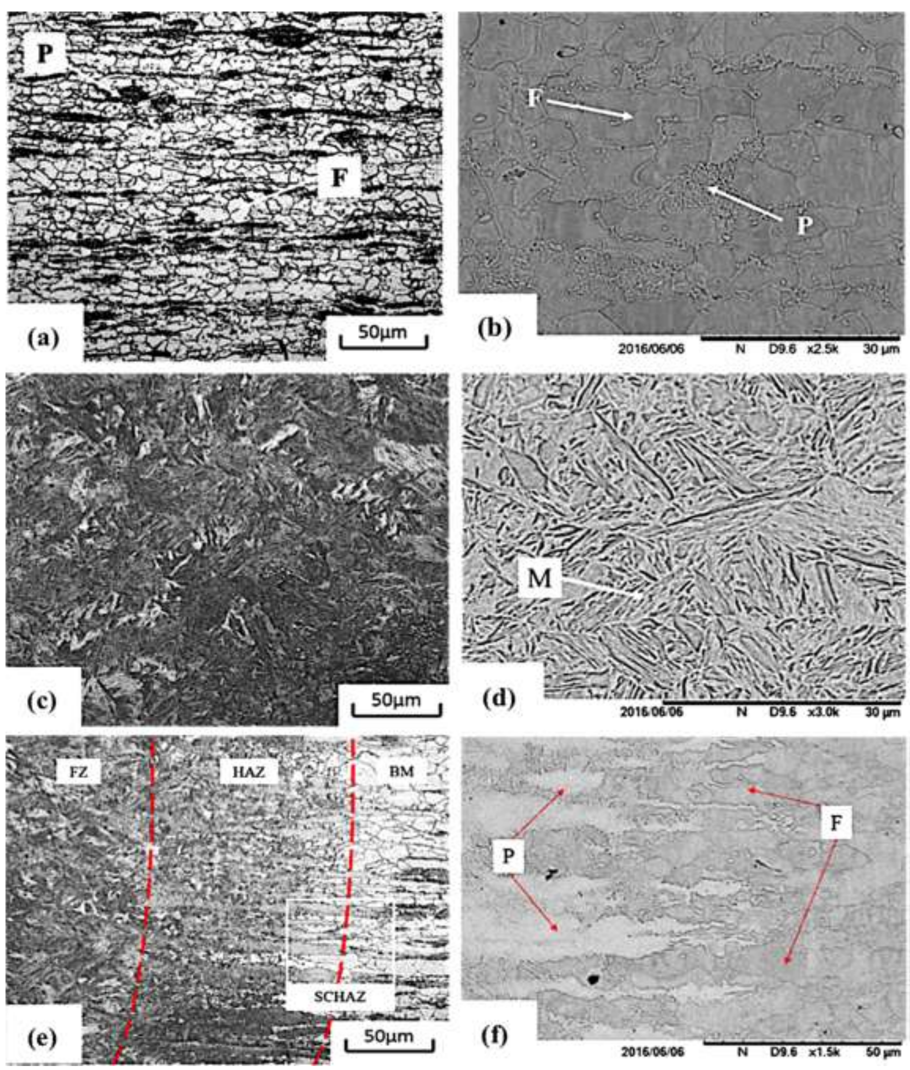

Fig. 15. Optical micrographs and SEM images of microstructure for (a) and (b) base metal comprising of ferrite (F) and pearlite (P) structure, (c) and (d) fusion zone consisting of martensite, (e) HAZ and (f) Subcritical-HAZ area consist of ferrite (F) and pearlite (P) [49]

Scanning electron microscope shows the formation of the delta ferrite in the fusion zone of laser welded ASS 304 and DSS 2205 as shown in Fig. 16. This is because of the rapid cooling rate during fibre laser welding. A decrease in the austenite phase was seen in base metal 304 side and the microstructure largely comprised of ferrite materials. As for the 2205 side, the austenite phase solidified which results in wide range of austenite and ferrite morphologies. The microstructure nearer to the 2205 was enhanced and finer than the initial dual phase due to the rapid cooling behaviour. Longitudinal columnar grains were scattered at the principal area of the FZ along the vertical course. The region beside the BM was ordered as equiaxed particles.

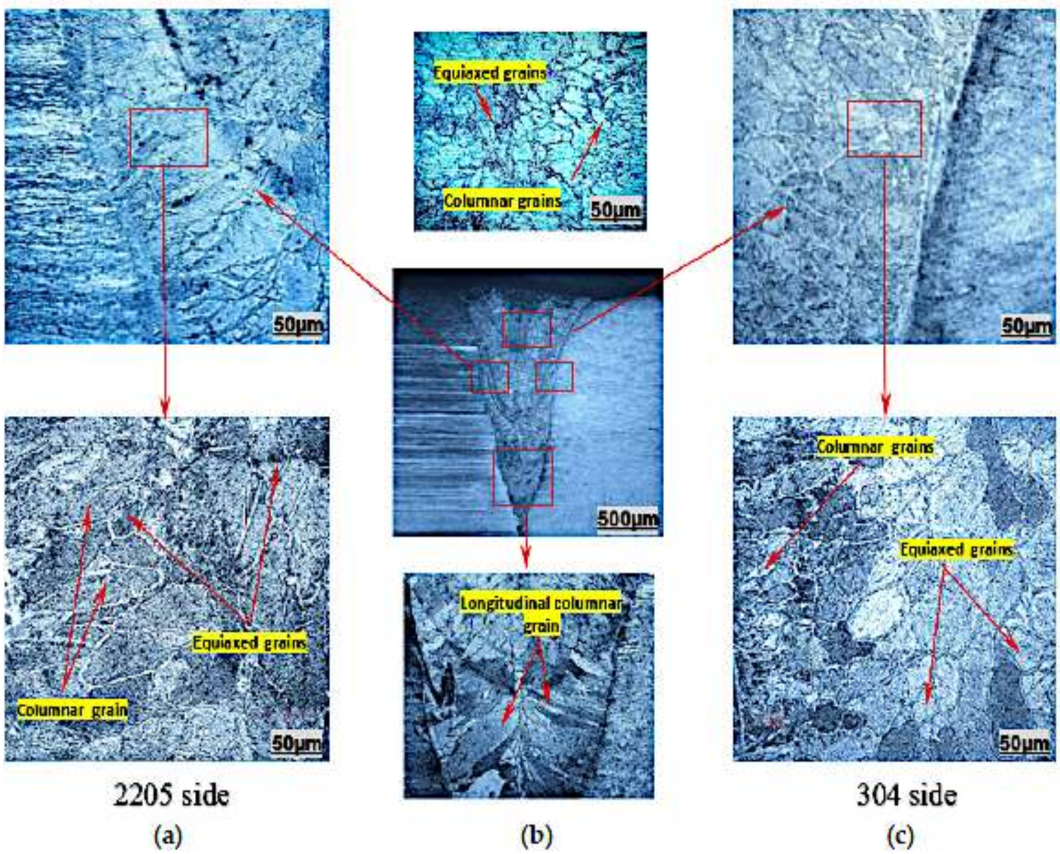

Fig. 16. Laser welded join of duplex stainless steel 2205 and austenitic stainless steel 304. Grain shape close to (a) 2205 side, (b) center line of fusion zone and (c) 304 side [33]

B. Effects of Laser Welding Parameters

Peak power is one of the main parameters in laser welding as it determines the heat input into the welding specimen. As laser control builds, sway quality relatively increments, as well. High temperature accomplished with high laser power would mean a more extensive weld pool, which would improve the joint durability [50]. Welding speed is another parameter that plays an important role in making a good quality weld. As welding speed builds, there is a littler weld pool given the high cooling rate, making a decrease in sturdiness. The impact of the weld pool size on the joint strength can be affirmed watching a comparability of the impacts of laser power and welding speed on weld bead parameters [51]. Laser beam diameter is an important parameter too that determines the weld quality. A decrease in beam diameter causes an increase in laser density at the same laser power, which eventually increases the weld depth [33].

Pulse width is also a parameter involved in laser welding. As the pulse width increases, the weld depth increases depending on the material used and thickness of the joint parts [33]. Pulse repetition rate is another important parameter to be taken note during laser welding. The unpretentious cover stage of the welding spot traps the plasma crest in the keyhole left inside and creates pores. It is asserted that porosity will lessen by increasing the frequency in GH3535 superalloys welding [52]. The formability of weld joints will be enhanced by increasing the pulse repetition rate [53]. Thus, welding parameters are very important, and a good combination of parameters is required to obtain a good weld quality.

C. Mechanical Properties of Laser Welded Joints

1) Tensile strength: Fig. 17 shows the summary of the ultimate tensile strength of dissimilar weld. Generally, the weld strength is higher compared to the base metal tensile strength. This is because of the microstructural behaviour of the weld product. According to Ho Won Lee [54], the tensile strength of the weld using filler material of SM80 and ZH120, both showed an increase in tensile strength compared to the base metal which is boron steel. Boron steel generally have tensile strength of 600 MPa and ultimate tensile strength of 1200 MPa. The tensile strength using SM80 filler is 630 MPa whereas using ZH120 filler resulted in 682 MPa. In dissimilar welding of ASS 316L and UNS S32750, the tensile strength of the weld product was approximately 570MPa. The tensile strength of the weld is higher than the tensile strength of the ASS 316L steel (540 MPa) but lower than the tensile strength of DSS UNS S32750 steel (800 MPa) [55]. In similar welding of boron steel, the tensile strength of the welded steel increased slightly at 533 MPa compared to the parent metal of 530 MPa [49]. In dissimilar welds of ASS 304 and DSS 2205, the tensile strength of the weld product is higher compared to both parent metals [49]. Using 1.8 kW of PP, the tensile strength is 611 MPa while using 1.6 kW PP results in tensile strength of 646 MPa and using 1.4 kW of PP gives a tensile strength of 674 MPa. The base metal ASS 304 and DSS 2205 have tensile strength of 505 MPa and 621 MPa respectively. Therefore, this is significant that dissimilar welding improves the tensile strength of the weld joint and thus improving the strength of the steel.

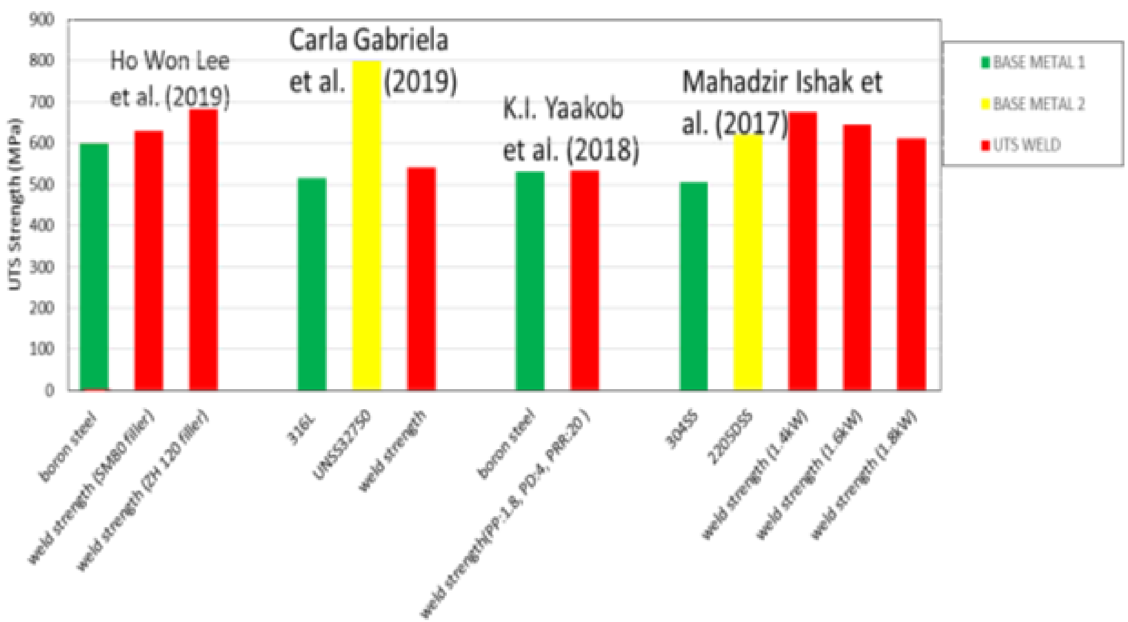

Fig. 17. A comparison of tensile test of various laser welded steels

2) Hardness test: The hardness across the cross-sectional weld bead from the base metal along the fusion zone through the heat-affected zone varies. The hardness is higher in the fusion zone. The weld joint possesses high hardness due to microstructural behavior. In dissimilar weld of ASS 316L and DSS UNS S32750, the hardness at the FZ is 329 HV compared to 238 $\pm$ 3.2 HV at the 316L BM and 292 HV at the UNS S32750 BM [55]. In similar welding of boron steel, the FZ had a hardness value of 535 HV compared to BM (200 HV) and HAZ (460 HV) [49]. In dissimilar welds of ASS 304 and DSS 2205, the hardness of the FZ is 432 HV while the hardness at BM ASS 304 is 292 HV and BM of DSS 2205 is 332 HV [33].

3) Surface roughness: Surface roughness is influenced mainly by welding speed and eventually heat input. Generally, with a slower welding speed, the surface roughness increases. This is because the lower welding speed gives more time for laser-matter interaction. The width of the weld bead increases and thus the surface roughness increases as shown in Fig. 18. High heat inputs affect the molten weld pool causing porosity and spattering due to recoil pressure induced. This also eventually affects the surface roughness of the weld joint. Based on Fig. 18, the width of the bead is narrower when the welding speed is 10 mm/s compared to the wider bead at 4 mm/s.

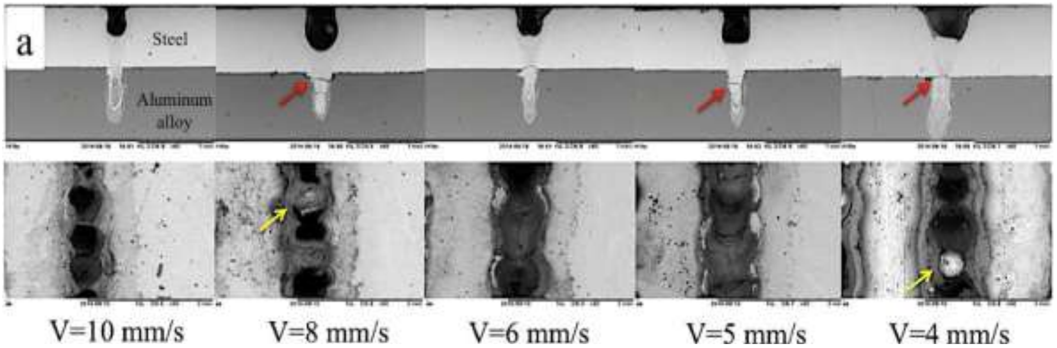

Fig. 18. The cross section, top view and the beads' surface roughness views for different welding speed [56]

VI. DEFECTS IN WELDS

A. Underfill

Defects prone to occur during welding. Impartial penetration and keyhole, not form is a defect in welding. This is normally due to less heat input which led to welding in conduction mode. Under-fill is a defect that occurs during welding which is due to excessive energy input. The under-filling defect causes insufficient material available by virtue of enhanced vaporization. This induces recoil pressure. Thus, spatter is formed which is credited to the discharge of the liquid pool during recoil pressure induced. Fig. 19 shows the spatter effect. The discharge of material is also influenced by the processing parameters such as peak power and peak power density. The mix of these parameters controls the measure of material removal and infiltration profundity. Pulse seam welding using low power can control spatters once the value of peak power density was limited up to 0.89 MWcm^2 [57]. Undercuts are undesirable as they act as stress concentrations and initiate fatigue cracks in laser welding. Undercuts should be 0.07 of the thickness of the base material or lesser in order to produce a class A weld [58]. A depth of undercut could increase up to 0.15mm with increasing laser power [59]. The main reason why undercuts occur is because of increased laser power, which results in evaporation and expulsion of the molten material.

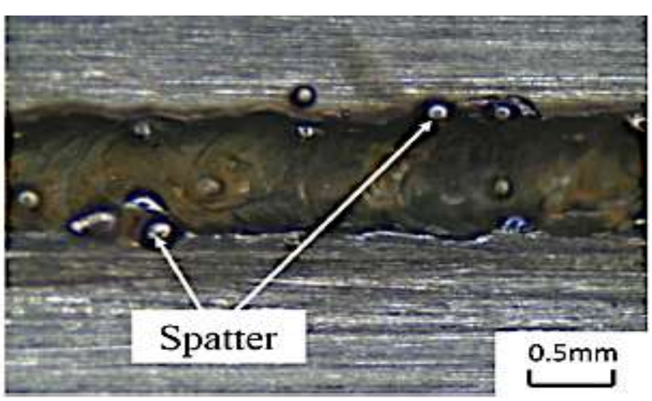

Fig. 19. Spatter effect on the surface of welded specimen [49]

B. Solidification Cracking

A solidification crack is also a form of defect in welding. This occurs due to high heat input during welding. This normally occurs in austenitic stainless steel which has less hardness and heat conductivity in elevated temperatures [33]. The microstructure of crack-susceptible stainless steel has the basis of impurity development and easily meltable liquid film along the grain boundaries at the last stage of solidification [38, 60]. For alloys with chromium and nickel ratio of lower than 1.5, austenite is the main phase of solidification. Primary solidification will be ferrite if the chromium and nickel ratio is in the range of 1.5 to 2.0. If the nickel and chromium ratio is more than 2.0, the solidification phase will be completely ferrite which is exhibited by duplex stainless steel [61]. Duplex stainless steel exhibits high chances of cracking to indeterminate alloys which have austenite or austenite/ferrite solidification [4]. Based on Fig. 20, the crack was formed in the center of the weld and propagated towards the base metal.

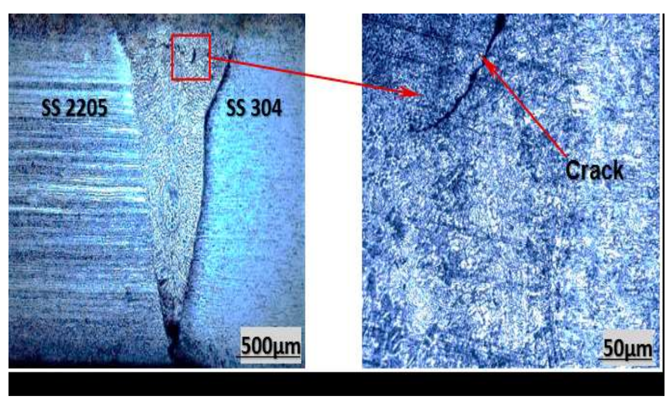

Fig. 20. Solidification crack in the fusion zone in the 304 austenitic steel side [33]

C. Porosity

Porosity is contamination in weld metal due to trapped gases in the molten weld pool. To avoid porosity, keyhole stability is very important. Shielding gas can help in the stability of the welding process and reduce the plasma plume size [62]. Impingement of assisting gas flow enables the front of the liquid pool surface to become concave on the laser/material interaction. The concave shape helps lessens the liquid pool around the keyhole gap and hence grows and balances out the keyhole opening. Porosity can be caused by trapped gas bubbles inside the molten pool. For example, due to the decrease in hydrogen solubility of Ti6AL4V during solidification, hydrogen pores can be formed in the fusion zone [63]. According to Gao et al. increasing overlapping in pulsed-wave mode laser welding can help trapped gas bubbles in escaping from the weld pool [64]. Therefore, more studies and research are being carried out to reduce defects during laser welding. This is to ensure a good weld quality is produced.

VII. CONCLUSION AND RECOMMENDATIONS

In this brief literature survey, the following conclusions can be drawn;

- Nd: YAG and fiber laser welding is commonly employed for laser welding of steel with the former proving more economical and energy-efficient.
- The high energy density of laser causes a microstructural transformation in the weld zone, primarily in the fusion zone contribution to change of phase.
- The change in the phase significantly affects the tensile strength and microhardness.
- The microhardness experiences an increase in value in the fusion zone followed by a rapid decline in the heat-affected zone.
- The tensile strength of various engineering steels alloys obtained by the laser welding process lies in the range of 500 MPa to 800 MPa.
- Laser welding is an extremely sensitive process and is prone to the formation of defects such as spatters, porosity and cracks gave any inconsistency in the process parameters selection in addition to poor shielding.

It is implied that laser welding of high strength is a promising field and automotive industries are rapidly adopting the process owing to its advantages of flexibility, robustness, and faster production times. Further research in welding quality control, noise processing, smart monitoring systems in addition to welding emerging steels such as maraging steel will prove more fruitful.

Declaration of Conflicting Interests

The authors declare no conflict of interest.

Acknowledgments

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