OVERVIEW OF LASER SYSTEMS AND OPTICS APPLICABLE TO HYBRID LASER WELDING OF ALUMINIUM ALLOYS

Muyiwa Olabode, Paul Kah and Antti Salminen

Lappeenranta University of Technology, Lappeenranta, Finland

Received: January 27, 2015

Abstract. The need for green and sustainable energy is continually on the rise. The use of light weight yet load bearing materials like aluminium has become important as structural materials. Aluminium can be fabricated by welding which is challenging compared to steel due to the presence of aluminium oxide coating and high conductivity of aluminium. The objective of this paper is to present an overview of the optics and laser systems applicable to hybrid laser welding of aluminium. This article is a critical review on aluminium alloys and their weld defects including hot cracking, porosity and heat affected zone (HAZ) degradation. Furthermore, the effect of the properties of aluminium in fusion welding, hybrid laser welding optics and the challenges aluminium presents to hybrid laser welding are also studied. It is observed that aluminium limited the selection of hybrid laser welding system and optics. The configuration of the welding head is critical to the effectiveness and efficiency of the welding system. The required weld properties influence possible optimization of hybrid laser welding. This article can be used by welders and welding engineers for hybrid laser welding of aluminium in addition to understanding how viable is hybrid laser welding of aluminium.

1. INTRODUCTION

The need for lightweight metal for construction and fabrication is on the increase due to the advantages of sustainable energy and economy [1]. Aluminium is the second most used structural material after steel [2,3]. The increased rate is due to advantageous properties of aluminium such as its lightweight to strength ratio, relative corrosion resistance [2], ease of machinability. They are used in the transportation industry, due to its relative low density in comparison to steel, the lower dead-weight of construction and low energy consumption with minimal compromise to load carrying capacity [4]. About 50% of aluminium extrusions are used in the transportation industry [5]. Other sectors include construction and power transmission [6].

Aluminium and its alloys have their disadvantages like high reflectivity and high conductivity that makes welding challenging [7,8]. There are different welding systems applicable to aluminium welding like laser bean welding (LBW), friction stir welding (FSW), metal inert gas (MIG), tungsten inert gas (TIG), hybrid laser beam welding (HLBW), plasma arc welding (PAW), submerged arc welding (SAW), and others. TIG weld process had been the most industrially accepted welding process for aluminium [9]. Studies have shown that FSW, pulsed MIG and HLBW produce better welds than TIG [10]. This paper focuses on hybrid laser welding optics applicable to aluminium. It further presents the challenges of aluminium alloy welding in HLBW.

2. ALUMINIUM ALLOYS

Aluminium and its alloys are grouped into cast aluminium and wrought aluminium alloys [11,12]. The wrought alloys are usually used in fabrication be-

Corresponding author: Muyiwa Olabode, e-mail: muyiwa.olabode@lut.fi

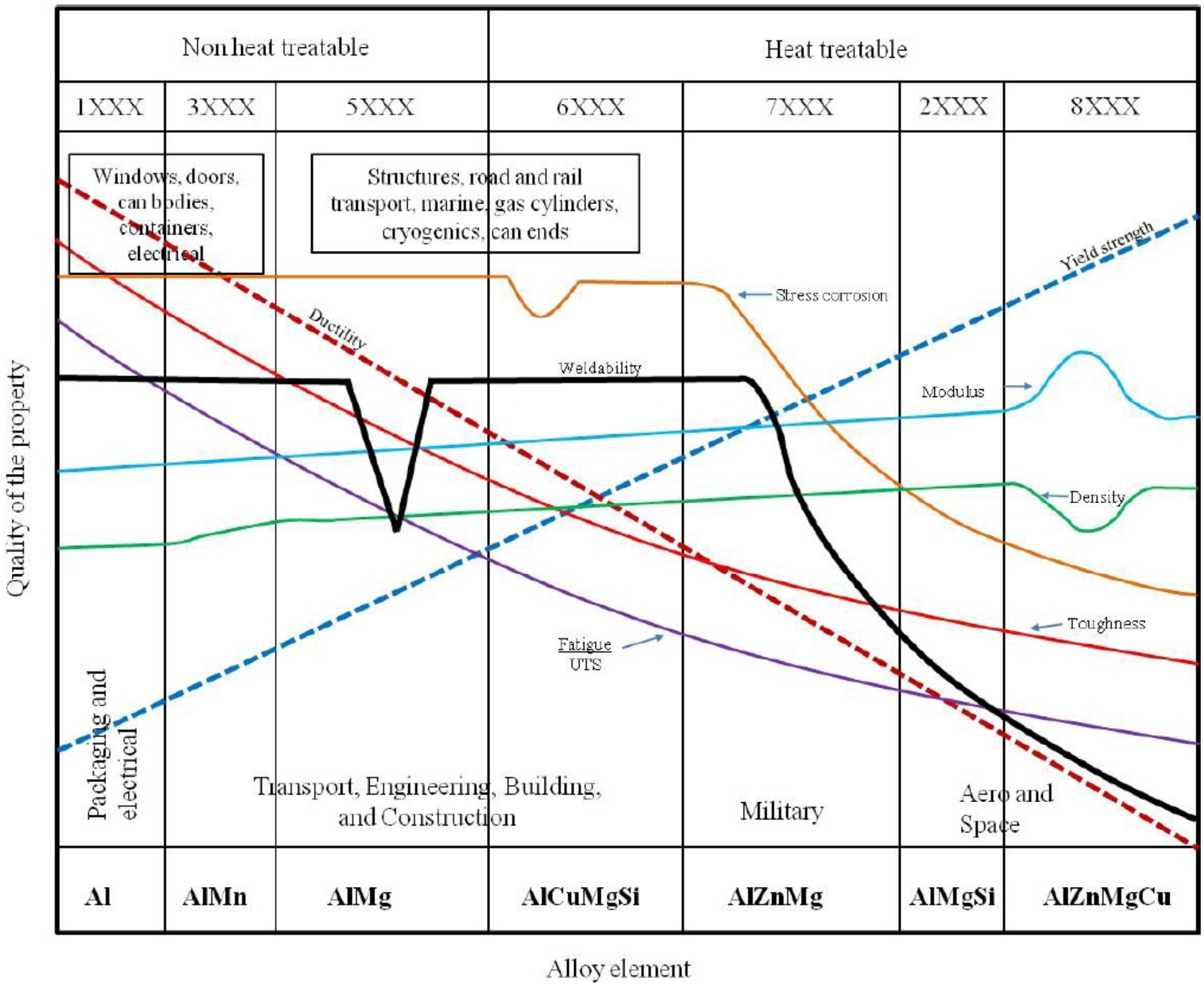

Fig. 1. Woodward diagram showing general relationships between some properties of aluminium alloys.

cause of its high strength compared to cast alloys [13]. This paper focuses on wrought alloys. The wrought aluminium alloys are grouped into series based on the chemical composition. They are denoted by 4 digits where the first denotes the characteristic alloying element. They range from 1xxx to 9xxx series. For example, 99% pure aluminium belongs to 1xxx series while high strength aluminium (HSA) alloy like 7025 belongs to the 7xxx series.

Aluminium alloys weigh about 1/3 of copper and iron at equal volume. It is slightly heavier than magnesium and slightly lighter than titanium and it is a relatively weak metal. Alloying of aluminium can be done to attain high strength. Aluminium is resistant to corrosion due to the formation of its thin oxide layer on exposure to moisture. Aluminium conducts electricity, heat and reflects light and it is easy to fabricate.

HSA alloys like the 2xxx, 7xxx, and 8xxx are becoming of high industrial interest because their yield strength is comparable to mild steel. However, the higher the yield strength the more difficult it is to weld (due to the chemical properties). Further relationship between the properties of aluminium alloys is presented in Fig. 1.

3. COMMON ALUMINIUM WELDING DEFECTS

Welding of aluminium is rather critical despite the fact that it has lower melting point compared to steel. Criticality of welding aluminium is due to the:

1. Presence of a stable surface oxide formed on exposure to oxygen
2. Presence of residual stresses that causes weld cracks due to aluminium’s high thermal expansion coefficient.
3. High heat conductivity of aluminium that implies that high heat input is required for achieving sound welds. High heat input on the other hand, increases the possibility of distortion and cracking.
4. High shrinkage rates on solidification, that enhance cracking.
5. High solubility of hydrogen in molten aluminium which causes porosity.

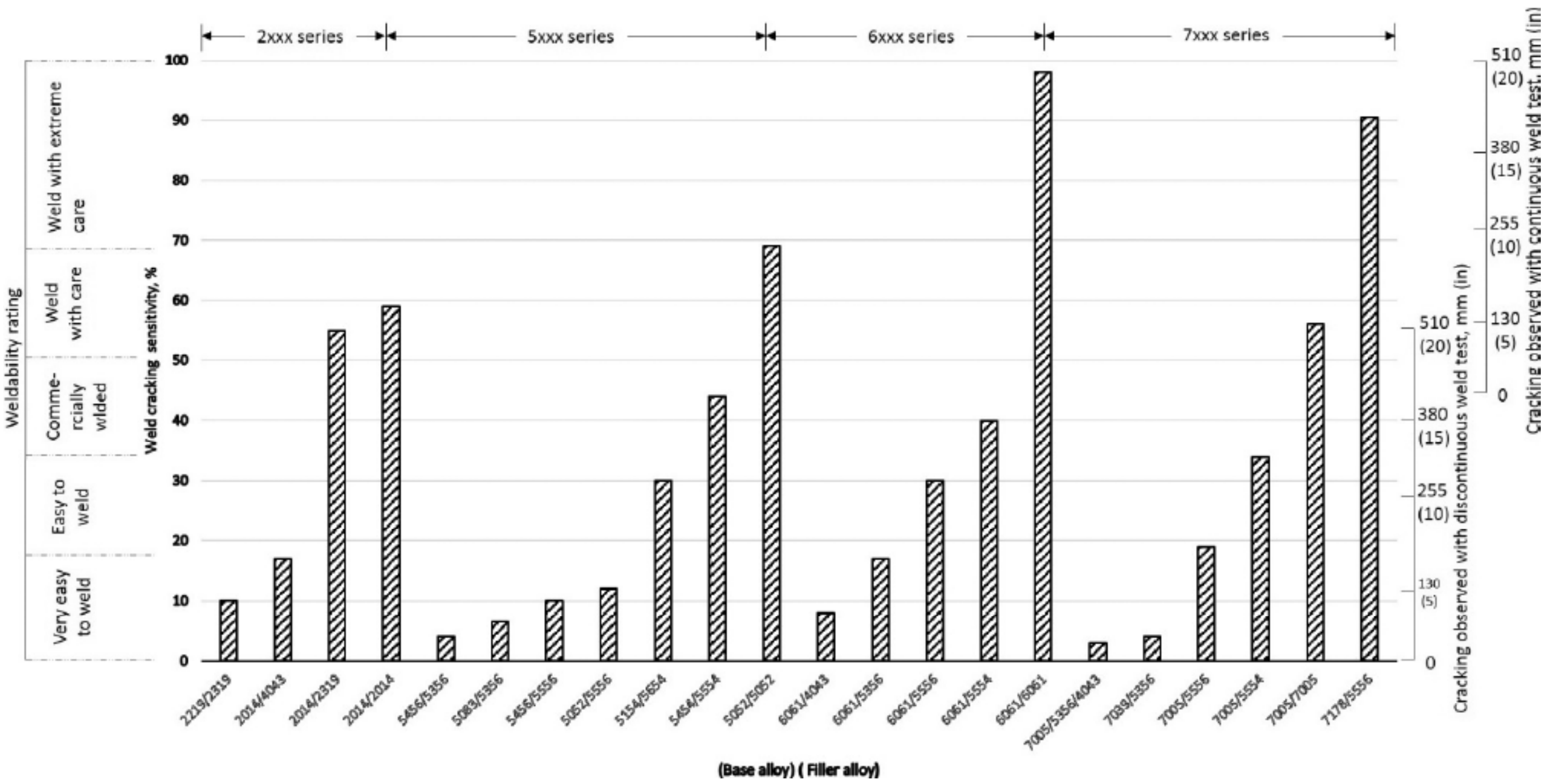

Fig. 2. Relative crack sensitivity ratings of selected aluminium (base alloy/filler alloy), redesigned from [15].

6. General susceptibility of aluminium to weld cracking [14,15] as presented in Fig. 2.

3.1. Hot cracking

The crack in aluminium welding occurs during weld metal solidification. It mechanically involves the splitting apart of liquid film because of the stresses and the strain that spring up due to solidification shrinkage and thermal contractions. The liquid film is related to the low melting eutectics. In situations where the difference between an alloy's liquid film and the lowest meeting eutectic is large, the large solidification range makes the liquid film shrink more. In addition, it is more demanding to feed shrinkage over large distances. When the base of the dendrites solidifies fully and the shrinkage is culminated, feeding inter dendrites liquid to the shrinkage is then critical [14].

The loss of properties due to hot cracking in an aluminium welded joint is due to the failure in the liquated region of the HAZ. The cracking susceptibility is based on the alloying elements. When the parent alloy adjacent to the fusion zone experiences high heating rates the phenomenon of non-equilibrium melting arises. Micro-cracks can also arise in the liquated regions in the presence of hydrogen and/or sufficient strain. In additions, a change in composition of the weld regions, toughness can be seriously impaired following ageing. Precautions can be taken to control liquation and liquation cracking by controlling the grain size, the residual impurities, the degree of homogenisation, and the alloy content.

3.2. Porosity

In high temperatures, during arc welding processes, aluminium approaches its boiling point on the weld pool surface. In this situation, aluminium undergoes two order magnitude changes of hydrogen solubility. The change occurs when it cools from initial high temperature to the onset of solidification; the activeness of hydrogen to aluminium is due to the temperature in the melted weld pool. Dissolution of hydrogen in aluminium is based on the high temperature equilibrium and the fast mixing of the pool (due to the electromagnetic forces). The weld pool therefore has high gas content relative to the surface temperature [14]. This effect is vivid in aluminium because the arc weld region is under super high heat and the pores can be supersaturated such that gas pore formation is possible without the aid of solidification. When the weld starts to cool, there is not enough time for the entrapped gas to move to the liquid's surface, and escape from the weld pool. The entrapped gases are the pores in aluminium welds [14-16]. The source of porosity is usually due to the entrapment of various gases in the weld, the type of filler wire used, and the weld pools cooling rate. There are numerous possibilities of gas entering the weld pool (shielding gas, air product of turbulent arc action and even dissolved hydrogen). Hydrogen or water is the source of porosity. Hydrogen is the typical source of porosity in aluminium

Table 1. Welding defects and remedies, modified from [17].

Problem	Causes	Solutions
Porosity	Turbulence of weld pool	Increase welding current to stabilise transfer of metal droplets.
	Hydrogen from hydrated oxide film or oil on wire, base metal, drive rolls and liner.	Keep wire covered. Store wire in a low humidity chamber at a constant temperature. Clean base metal of oil and oxide immediately prior to welding.
	Wet or contaminated shielding gas or inadequate flow. Fast cooling rate of weld pool	Reject bottles above -57 °C dew point. Increase flow rate. Shield from air currents.Use higher welding current and/or a slower speed. Preheat base metal.
Weld Cracking	Improper choice of aluminium welding wire or rod.	Select welding wires with lower melting and solidification temperatures.
	Critical weld pool chemistry range	Avoid weld pool chemistry of 0.5 to 2.0% silicon and 1.0 to 3.0% magnesium. Avoid Mg-Si eutectic problems (5xxx welded with 4xxx).
	Inadequate edge preparation or spacing	Reduce base metal dilution of weld through increased bevel angle and spacing.
	Incorrect weld technique	Clamp to minimise stress. Narrow heat zone by increased traverse speed. Produce convex rather than concave bead.Minimise super-heated molten metal, to control grain size. Proper weld size (not too small). Preheat base metal.
HAZ degradation	Excessive exposure of workpiece to heat input	Control the heat input and keep it minimal by controlling the current. Heat sinks can also be used to hasten the heat dissipation after welding. Optimizations that yield narrow weld seams should be used.

welding; other sources include oxygen, and other gases in the surrounding air [14].

Porosity affects the mechanical properties of aluminium welds. The degrading effect on the tensile strength and ductility depends on the size and distribution of the pores. Elongation drops immediately as porosity level increases, tensile ductility drops by as much as 50% from its highest level when the porosity is about 4% of the volume. At same porosity level, tensile strength is observed to be very tolerant and yield strength is slightly reduced [14]. In 7xxx series, zinc vapour is formed at the faying surface during welding which generates gas inclusion (porosity). aluminium has melting temperature of 560 °C and high boiling temperature of 2050 °C and (compared to 420 °C and 907 °C for zinc); thus cleaning zinc in the weld region mechanically or using arc heat to volatize zinc ahead of the pool helps to reduce the possibility of porosity.

3.3. Heat affected zone degradation

The HAZ is created beside the fusion zone and it results in the degradation of the parent materials caused by modification of the microstructure by devoted temperature. The nature of the HAZ is dependent on the diffusion in the region and the heat input. Due to the thermal dependency of the metallurgical transmogrification, the degradation depends on the type of welding process and parameters. Preheating parent metal before weld and using high heat input increases the HAZ region and the degradation level. The HAZ degradation may be limited by using multi pass welding, avoiding preheating, and by controlling the inter pass temperature [14].

A summary of welding defects and remedies applicable to aluminium are presented in Table 1.

4. EFFECTS OF THE BASIC PROPERTIES OF ALUMINIUM IN FUSION WELDING

An understanding of the peculiarities associated with aluminium fusion welding is important as the physical and chemical properties influence the weld [18,19]. Some of the properties considered include the high heat conductivity of aluminium, which is approximately three times the heat conductivity of

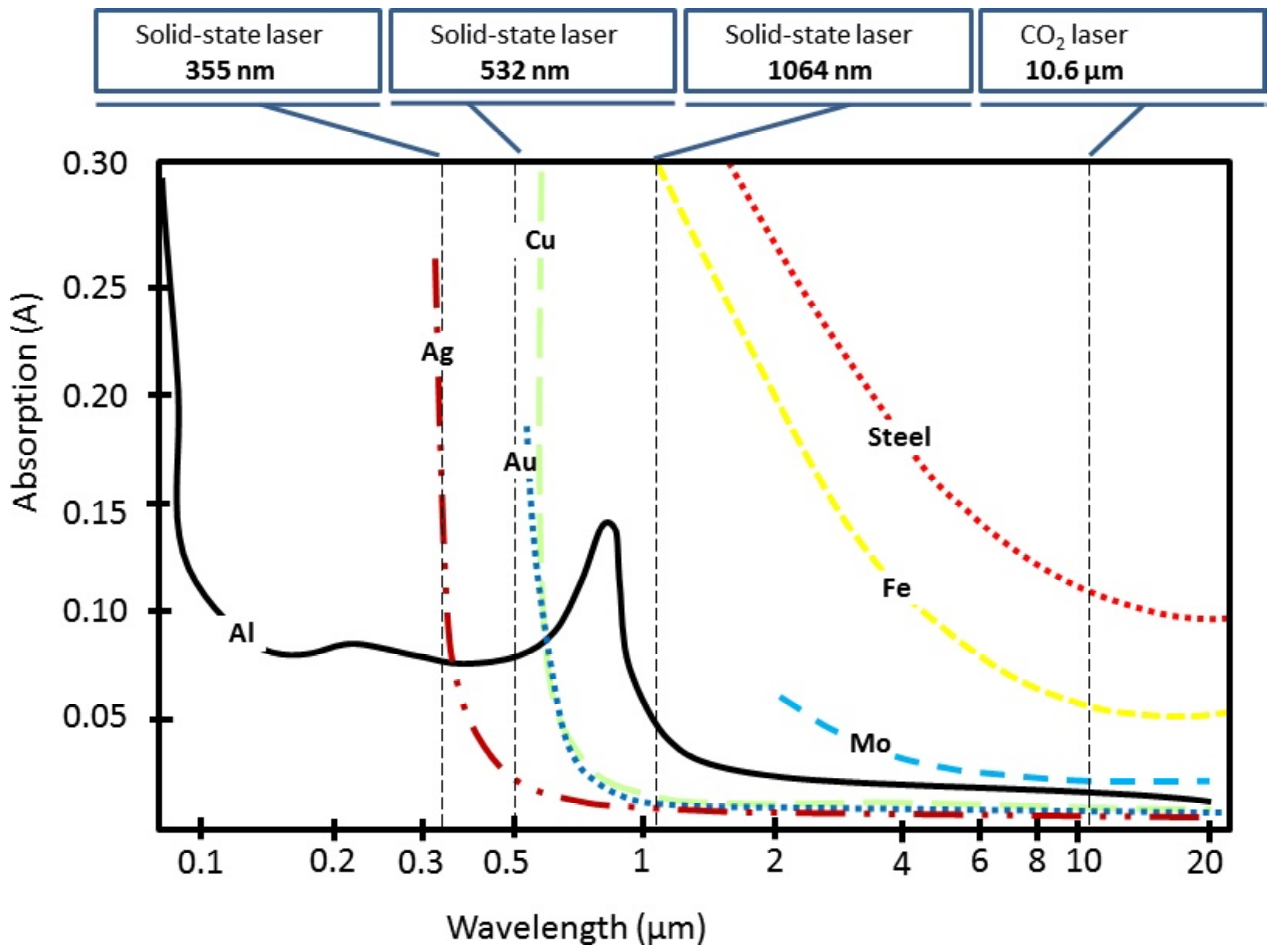

Fig. 3. Absorption of laser wavelength by metals, redesigned from [54].

steel [2]. This implies that high energy density welding systems like MIG, plasma and laser welding systems are applicable. With high energy density, there is a lower loss of strength in the HAZ and less distortion. Another property is the extent of expansion which is about twice for low alloyed steel [20]. On exposure to oxygen sources like air and water, the surface that becomes coated with a thin layer of naturally formed, chemically stable and thermally stable nonconductive aluminium oxide (Al_2O_3)[21], melts at about 2050 °C while aluminium alloys melts at about 560 °C [11]. This oxide layer has a melting temperature much higher than that of aluminium itself; moreover, it has a significant mechanical strength. Therefore, this oxide layer can remain as a solid film (or fractured in small particles due to the flow of the molten material [22]). This can result in severe incomplete fusion defects. It is recommended that the layer is removed by pickling or dry machining just before weld. It is important to state that the difference in melting point is not a problem during the processing by means of high energy density welding processes; for example, the presence of oxides during laser processing increases the absorptivity of aluminium alloys to the laser radiation [22,23]. It should be noted, that the main challenge in applying most joining technologies to aluminium is its tendency to form a thick, coherent oxide layer.

Another important property is solubility of hydrogen in aluminium. Hydrogen has high solubility in molten aluminium as opposed to the solid aluminium. The solubility is reduced to one twentieth of the solidification range in fusion welding processes. The hydrogen gas is usually segregated as regular spherical pores of typical diameter of 5 to 10 μm [2]. They can act as crack initiation in the weld and lowering the dynamics and static strength of the weld [24]. The sources of hydrogen in aluminium fusion welds include humidity and organic contamination on the filler material and base metal surfaces, hydrogen content of the base material and filler material, incomplete gas feeding of the weld. It is important to suppress the level of porosity in the weld so that the mechanical properties of the weld do not deteriorate drastically. Finally, the high reflectivity of aluminium to wavelengths limits the laser beam welding science that can be used [25].

5. HYBRID LASER WELDING OF ALUMINIUM ALLOYS

Aluminium alloys can be welded by most welding processes [2,26]. However, for fully automated systems, the common ones are MIG, TIG, LBW, and HLBW. Plasma MIG and other electron beam welding processes are however applicable with limitations and therefore restricted to welding of special products [26]. Newer technological developments on the MIG process like cold arc [27] or cold metal transfer welding (CMT) [28] are also applicable and are growing in the industry. The most commonly used hybrid welding system is laser hybrid MIG [9]

The usability of hybrid laser welding systems have been presented by Bagger and Olsen [29] then by Rasmussen and Dubourg [30]. Moreover, in the 1980s and early 1990s CO_2 lasers were the only ones with sufficient power for aluminium welding. Therefore, CO_2 lasers were the most investigated [25,31,32]. Today many more investigations with the solid-state lasers, about 80% of the laser hybrid welding processes investigated are carried out on solid state lasers like Nd:YAG lasers [33-35], high power-fibre laser [36-40]. As stated by Ueyoma [41] and researched by Wang et al. [42], defocused high-power diode laser beam can be used. There is limited research on the use of disk lasers as laser sources in hybrid welding of aluminium alloys [9].

More than 80% of recorded research has been carried out using MIG power source especially pulsed MIG [43-45]. TIG power sources have also been used but usually for basic investigations on interactions and parameter effects [25,46-50] In Ueyama research, AC MIG arc was applied in combination with high-power diode laser [41,51]. In some other experiment plasma arc has been used as a laser source [32,47,52].

The absorption of beam by aluminium depends on the wavelength of the laser beam. As presented in Fig. 3, due to the wave length of solid-state lasers Nd: YAG and fibre lasers are common laser power sources used in hybrid MIG welding. Compared to CO_2 lasers, Nd:YAG and fibre lasers have approximately double the wavelengths of CO_2 laser [25]. This advantageously minimises the keyhole welding intensity needed. The delivery of fibre and Nd:YAG lasers can be done using fibre optics which increases the process flexibility [53] and the possibility of having a robust welding system. In addition, in Nd: YAG and fibre laser, shielding of the laser beam by the arc plasma and laser induced metal vapour is not expected as compared to CO_2 systems.

Based on the amount of the research available, it can be stated that Nd: YAG laser with MIG is the most usable state of the art hybrid welding process for aluminium alloys. In addition, the Nd: YAG lasers can be replaced with solid-state lasers like the fibre laser.

5.1. Hybrid laser welding optics

Optics found in hybrid laser welding systems applicable to aluminium welding includes mirrors, lenses and fibre optics. In hybrid laser welding, laser beam needs to be focused to achieve small spot diameter. The small spot diameter allows for higher beam density on the workpiece. The spot diameter is a function of the lens design and focal length. Beam transfer and focusing is achievable using diffractive optics, refractive optics or reflective optics.

5.1.1. Beam delivery optics before focusing

Most laser welding system consists of components like **mirrors** (for diffracting light). Mirrors can be planar or spherical in design. The mirror is fixed to a firmly adjustable screw with the ease of accessibility for cleaning, inspection, and replacement.

The usability of conventional mirror delivery is limited by the rigidity of the mechanical mounting and they cannot move relatively to each other to avoid misalignment. The mirror is limited in size therefore transferring beams over a long distance with high divergence can produce a beam diameter that is larger than the lens. However, the beam can be tailored with lenses in the beam path to prevent this phenomenon (this is called a relay system). Mirror as reflective optics are usually found in gas laser systems. The mirrors are generally made from bear metal or polished metal (usually molybdenum or copper) to improve the reflectivity. A material like gold can also be used for coating the surface of metal mirrors to produce high reflectivity. Metal made mirrors are less prone to damage compared to lenses because they can be easily cooled by passing water through the inner walls of the mirror thereby resulting in higher repeatability than transmissive lens. Usually, high-powered lasers use all reflective water-cooled optical components ruggedly built to survive in industrial environment and to require minimal maintenance. The mirrors can be as simple as having one to having ten mirrors.

Retaining rings and springs are used to keep the mirror in place thereby sustaining consistent pressure and limiting movement. The mirror mounting plate must be flat to avoid pressure that can force the mirror to warp causing beam distortion and difficulty in focusing the beam. Dielectric coatings are used on mirrors to eliminate phase shifting. This coating can be easily damaged during cleaning so mirrors should be cleaned using acetone and lens tissue. Cleaning is important to prevent build up and contamination that can result in heat absorption that will distort and destroy the mirror. In some special cases, the mirror's dielectric coatings are multi-layered to rotate the polarization of the laser beam by 90°. This is common for circular polarization needed for bidirectional welding and cutting so that beams can create consistent kerf width in all travel directions. These mirrors are referred to as quarter-wave phase retarders.

In some cases, the mirrors are coated so that it can absorb one component of linear polarization and reflect the orthogonal component. These are called anti back reflection mirror and are used for beam delivery along with phase retarders to absorb reflected energy that can otherwise travel back to the laser resonator and damage it [54].

Mirror can also be adaptive designed spherical or flat but can change surface curvature based on the input signal. Adaptive mirror is necessary in laser material processing for controlling raw beam propagation through the guide and beam delivery system. The principle of adaptive mirror operation is that it compensates the axial shift of the focal position that had been caused by the thermal load on the optical components. Therefore, the focal position is kept constant or changed to a desired position. In aluminium laser welds of components where ''flying optics" is used, the distance between the laser source and the welding head changes (depending on the shape of work weld piece), adaptive optics is therefore adequate [55].

Lens is another component for beam delivery usually for converging or diverging light. The lens can be a simple one-element optic generally with a focal length less than 254mm. They can be aspheric, Plano-concave/convex or meniscus [56,57]. Lenses can be compound, where the lens is made of two or more separate lenses that fit together to reduce spherical aberration common in a simple single lens. Aspheric simple one component lens is made to reduce spherical aberration. This is achieved by turning the lens with a diamond tool on the lathe to a certain calculated aspheric curve. It is important to note that glass is generally the material used for lenses in the visible spectrum. However, glass in the infrared (IR) region does not transmit. The lenses made to transmit in the IR region are called IR lenses. IR lenses can be made from germanium(Ge), silicon (Si), zinc selenite (ZnSe), zinc sulphide (ZnS), and gallium arsenide (GaAs). Other materials like diamond and calcium sulphide (CdS) and sapphire are less common [58].

Fibre optics is another component for beam delivery used in Nd: YAG to deliver beams due to the 1.06 μm wavelength transferable over glass fibres. Fibre optics utilizes the flexibility of glass fibre within the specified bend radii for fibre bundle (100-200 mm). They are attractive in comparison to conventional beam delivery especially due to the possibility of transporting beams over long distances of up to 50 m and around curves [59]. In addition, the optics is compact and easier to move around particularly useful in robotic welding. A highly consistent focal spot size is achievable with fibre optics compared to mirror. Time sharing and energy sharing with fibre optics is less complex and easily achievable than with mirrors. They degrade beam quality with larger focal spot sizes compared to mirror delivery. The usability of fibre beam delivery has therefore been limited to most welding systems where the focal size needed is larger than 100 μm [56]. It is important to state that fibre optics are not effective for transmitting ultraviolent (UV) wavelength and can be destroyed by CO_2 lasers. Fibre optics is common in diode lasers and Nd: YAG. Plastic material are also used in place of glass for fibre optics however, they are used for visible wavelength lasers. Plastics are not effective in Nd: YAG due to losses in transmission and lower damage thresholds.

Beam delivery optics before focusing include bending mirrors (e.g.CO_2), beam splitter (CO_2, Nd: YAG), optical fibre (Nd: YAG, Diode lasers, Disk and fibre laser), circular polariser and collimator. Laser beams are delivered to the workpiece by turning mirror system in CO_2 lasers and Nd: YAG lasers. For accurate repeatability of laser welds, it is important that the laser optics is firm and rigid, as misalignment and vibration are not desired. However if the laser optics is rigid then the workpiece will need to be moved around during welding. This becomes impracticable when welding large work pieces. For such fixed beam systems, the floor space for the machine must at a minimal be four times larger than the largest work piece for which it is designed for. On the other hand, moving optics will save floor space but high care must be put into controllig beam divergence, rigidity, and alignment. Nd: YAG laser heads are small thereby allowing it to be mounted on moving axis with limited deterioration to it focus, and therefore more flexible than CO_2 laser heads that are large and usually installed to operate stationary.

Laser applications that are categorised as 1 kW or less use transmitting optics for beam focusing in welding. The beam transfer can be achieved by conventional mirror, fibre optics, or a combination of both. Up-collimator or beam extenders are used to reduce beam divergence by increasing the beam diameter. Laser beam divergence along with the choice of focus lens determine the focal spot size, research study [9] has shown that, beam divergence can be improved by a factor of two with half times smaller focal size (using proper focus system) compared to a system without collimator by doubling the beam diameter. The usability of collimator is usually limited to low power CO_2 lasers and most Nd: YAG lasers to extend beam diameter from 6 - 10 mm to

Table 2. Lens shape choices for Nd:YAG and CO_2 lasers at various *f*-numbers, modified from [60].

f-number range	CO_2	Nd:YAG
4+	plano-convex	plano-convex
3 to 4	meniscus	plano-convex
2 to 3	diffractive-convex	doublet
< 2	triplet triplet	

12 - 25 mm. CO_2 lasers of above 500W usually do not need collimator because of the raw beam diameter and its low beam divergence.

5.1.2. Focusing optics

Focusing optics is common in low-power welding devices. Parabolic lenses are generally useful for focusing power above 1.5 kW of CO_2 lasers. Due to the low cost and minimal spherical aberration attributes of *f*-numbers above five, lenses are usually Plano-convex lenses. The *f*-number is derived by dividing the lens focal length with the beam diameter. When the f-number is less than four, complex optical lenses compared to Plano-convex lenses are used. The thumb rule is that the higher the *f*-number the higher the problem of spherical aberration [60]. A guide to selecting the best lens is presented in Table 2.

Laser protection is used in laser processes where the focal length is short or when the weld metal is volatile and contaminated; or when weld spatters can be generated. Debris can attach itself to the welding head lens. Aluminium highly reflects laser beam wavelength, and the reflected beam can damage laser optics. The solution adopted generally to solve this is to change to a laser with different wave length, paint or etch the surface of the workpiece to reduce reflectivity, or to use keyhole welding where the energy density of the spot diameter is great enough to overcome reflectivity; in addition to using a cheaper protective lens.

The presence of foreign particle on the lens can reduce transmission; create localized absorption on the surface of the lens thereby destroying the lens surface or any coating on it. Lenses can be very expensive and in such cases where an expensive lens life can be drastically reduced, a sacrificial cheap optic is placed in front of it as a window or a cover slide to protect the expensive lens. For example, Nd: YAG and Nd: glass lasers use the protective optics due to the low cost of the cover slide. It is less common in CO_2 lasers.

5.1.3. Hybrid laser focusing head

The performance of beam delivery system determines the quality of the laser beam processing. It is desired to be simple and as small as possible having neither actuators nor sensors to allow for easy manipulation and integration on to a robotic welding system. However, the available technology for laser welding head is attractive that consumers still tend to buy the technology thus the laser heads are becoming more and more complex. Common technologies in laser focusing heads include the presence of integrated actuators and sensors, closed loop systems, self-learning and self-adapting systems.

The combination of laser beam and arc can be of varying configurations which remarkably influence the weld performance. It is important to mention that in hybrid laser welding, the primary heat source is laser while the secondary can be any arc process. Laser assisted arc welding is the vice versa [9].

The welding head is based on the heat source type and relative position of the heat source to one another [61]. The principal classification criteria are presented in Fig. 4 (based on the heat source type) and Fig. 5 (based on the configuration). The choice of the secondary heat source can be either arcs with consumable electrodes or arc with non-consumable electrodes. The earlier is selected due to the necessity of filler metal to solve specific weld problems otherwise, the latter is preferred.

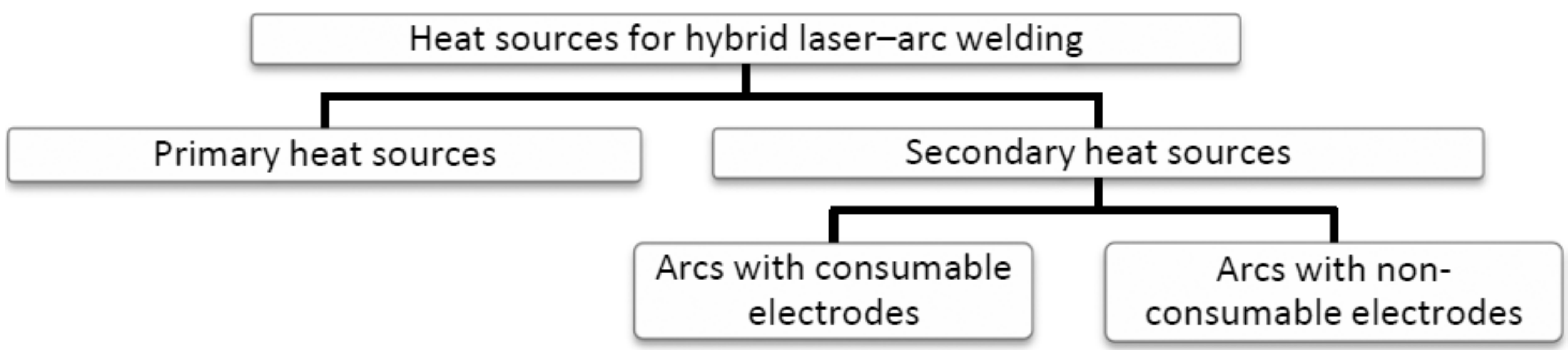

Fig. 4. Schematic presentation of heat sources available for hybrid laser–arc combinations.

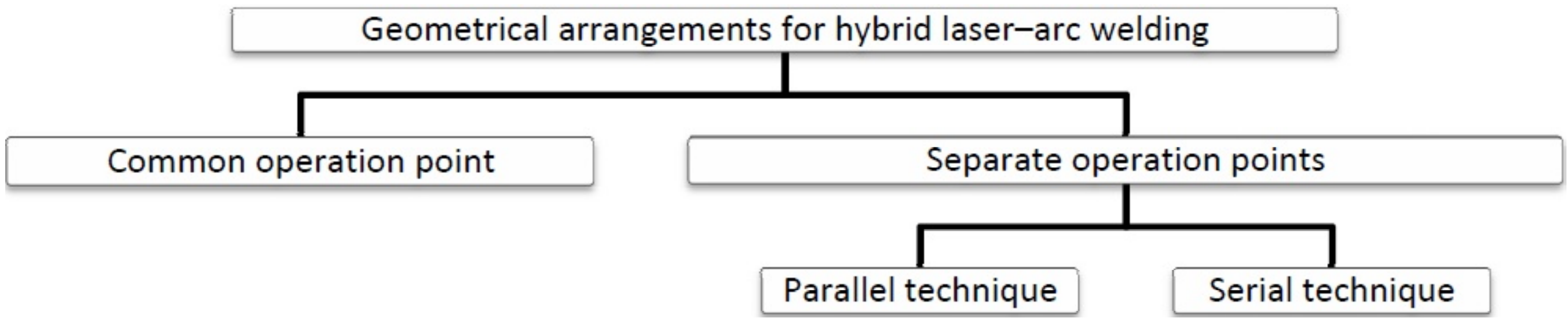

Fig. 5. Geometrical arrangements for hybrid laser–arc welding.

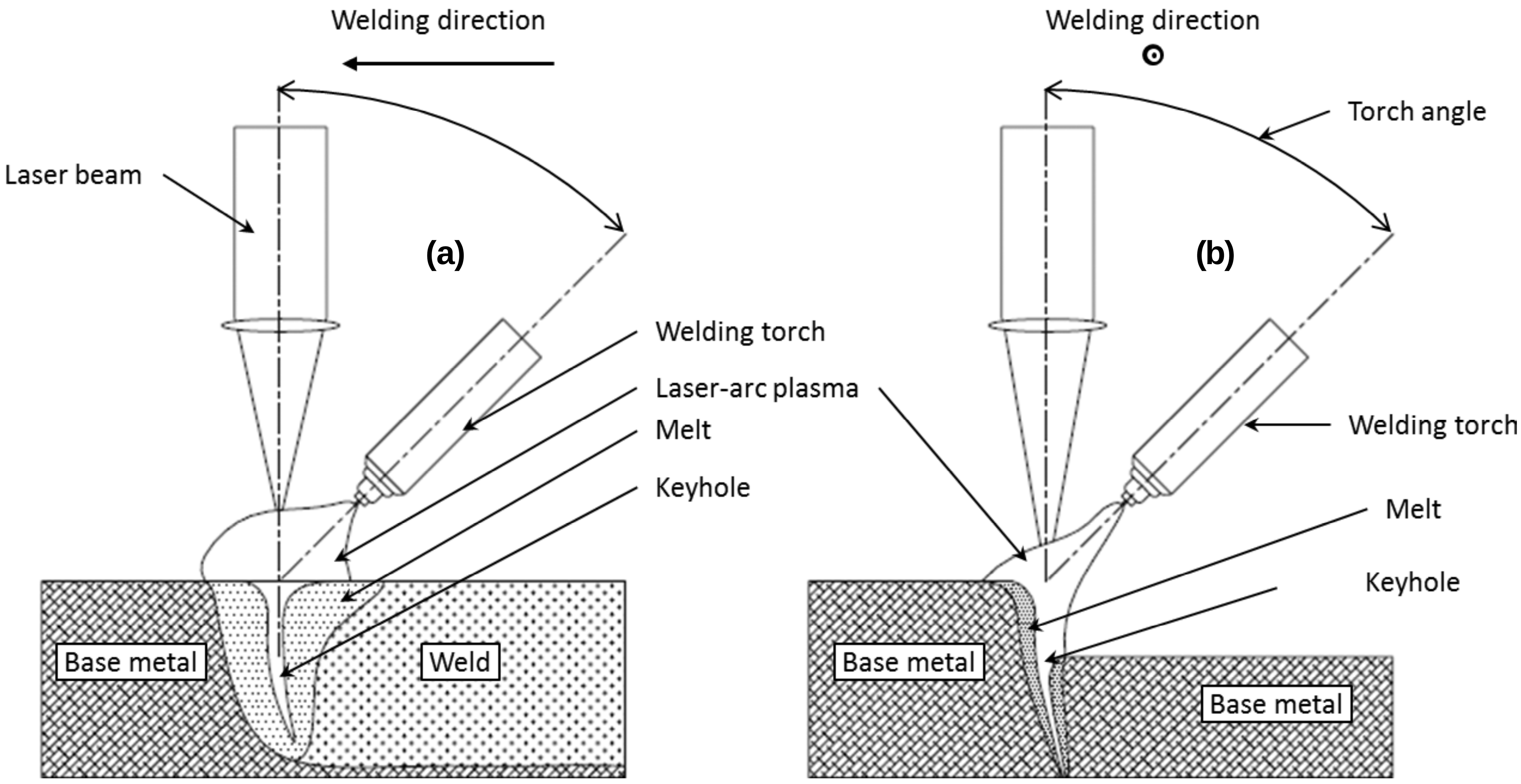

Fig. 6. Schematic diagrams of hybrid laser–arc welding with a common operation point, redesigned from [9].

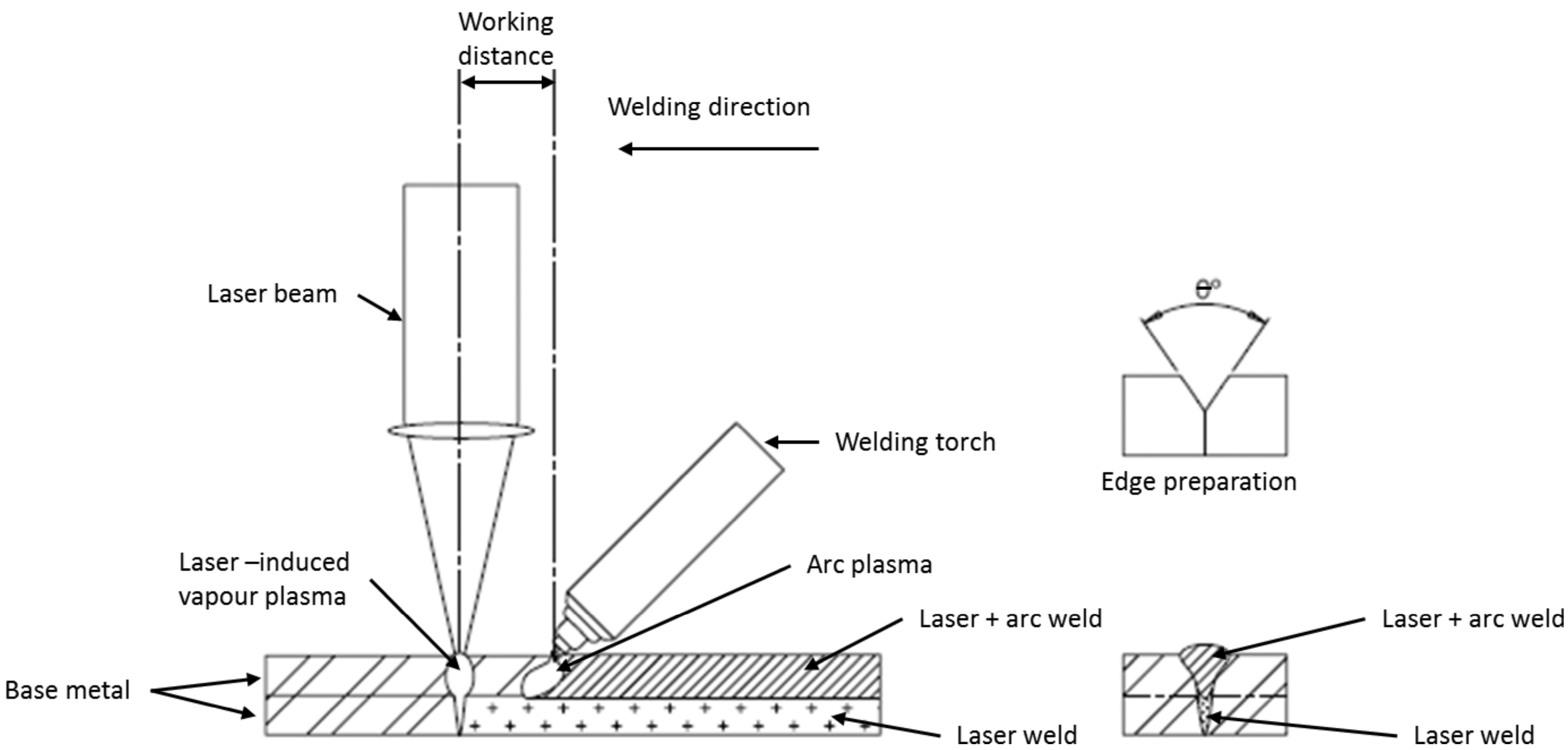

Fig. 7. Schematic diagram of hybrid laser–arc welding with separate operation points, redesigned from [9].

The arrangement plays important role for the effectiveness and efficiency of the weld system as well as the welds. The heat source can be arranged to have a common (Fig. 6) or separated (Fig. 7) operation point as illustrated. In common operation point, the arc root and laser beam spot centre are in the same surface location of the workpiece. Many hybrid laser-arc configurations use arc welding torch inclined to the laser beam along the weld direction (Fig. 6a) or across (Fig. 6b). The position of the arc torch affects the focal point position.

Table 3. Configuration advantages of conventional hybrid laser welding.

Laser leading configuration	Arc leading configuration
Useful in aluminium welds because it helps remove oxide layer before arc welding [63]	Generates deeper weld penetration[9]
Creates superior beam appearance because the laser as it gas does not affect the molten pool created by arc heat source[64]	Allows for weld preheating
Improves the homogeneity of the weld metal[64]	Requires less heat input per volume of weld metal (J/mm^3)[64].
Better stability in terms of current and voltage measurement [65]	

Beyer et al. (1994) reported according the configuration in Fig. 6a that laser power was responsible for attainable weld penetration depth and the arc parameters were responsible for the adjustment of the weld seam width [62]. The same research group used the setup in Fig. 6b for tailored blank of two different plate thicknesses. The result showed that the configuration (1) reduced the need for edge preparation (2) increased molten material volume and (3) generated a smooth zone transition between the plates because the arc burns the thicker plate's edge therefore improving weld appearance.

A separated operation point arrangement can be of serial technique or parallel technique or a combination of both. The serial technique is a configuration in which the primary and secondary heat source has an acting point distance known as "working distance" between them in vertical or horizontal direction along path. The arc source can lead or trail the laser beam. Leading arc source allows for preheating thereby increasing laser heat source efficiency due to a reduction in heat loses by conduction. It also increases the weld seam quality because of more stabilized keyhole. Leading arc generates deeper welds because at close working distances, the laser beam strikes the deepest part of the weld pool surface suppressed by the arc forces. To attain deepest weld penetration, the focal point must be set to hit at the lowest weld pool surface.

Trailing arc source with short working distance provides stability and efficiency due to the common phase plasma interaction between the heat sources and also due to the thermal impact on the weld. With greater working distances, trailing arc source can act as heat treatment for the weld which is favourable in HSA welds for the improvement of joint properties. A summary of the principal advantages of a leading and training arc is presented in Table 3.

A parallel technique is a configuration where there is a displacement between the laser focal point and the arc acting point. The thermal load spreads in different region as opposed to serial configuration where the thermal load spread to the same region. It is important to state that in many cases it is difficult to distinguish between a parallel and a serial technique as they are usually applied simultaneously. In Seyffahrt et al. (1994) a separate operation point configuration was carried out with the purpose of increasing weldable metal sheet thickness. Laser heat source welded the root and the top layer was welded by the arc source Fig. 7 [66].

Other hybrid laser welding configuration with more than two heat sources have been experimented and presented in Fig. 8. Winderlich (2003) used the configuration where a CO_2 laser beam and TIG arc touch acted on the same side while the second TIG torch acted on the opposite side of the weld. The configuration provided attainable notch-free weld seam useful in dynamic loading while improving fatigue resistance [67].

Another configuration referred to as Hydra (hybrid welding with double rapid arc) is presented in Fig. 8b. It was initially experimented by Dilthey and Keller (2001) using CO_2 laser and MIG heat sources. The configuration increased the possible deposition rate and thus increasing attainable welding speed and reducing thermal load, in comparison to conventional hybrid laser welding configuration [68]. As illustrated, the working distance of the leading arc can allow for preheating while the trailing arc can provide heat treatment. Wieschemann (2001) shows that two leading arc configuration provides optimum gap bridgability [69].

Another configuration discovered by Stauter (2007) is presented in Fig. 8c where the second arc torch is a tandem having two consumable electrodes. The electrodes depositions are controlled by two separate power sources. This configuration increases deposition rate and productivity and the cooling rate is easily optimized by varying the work distance between the conventional hybrid configuration and the tandem torch (working distance between torch 1 and torch 2).

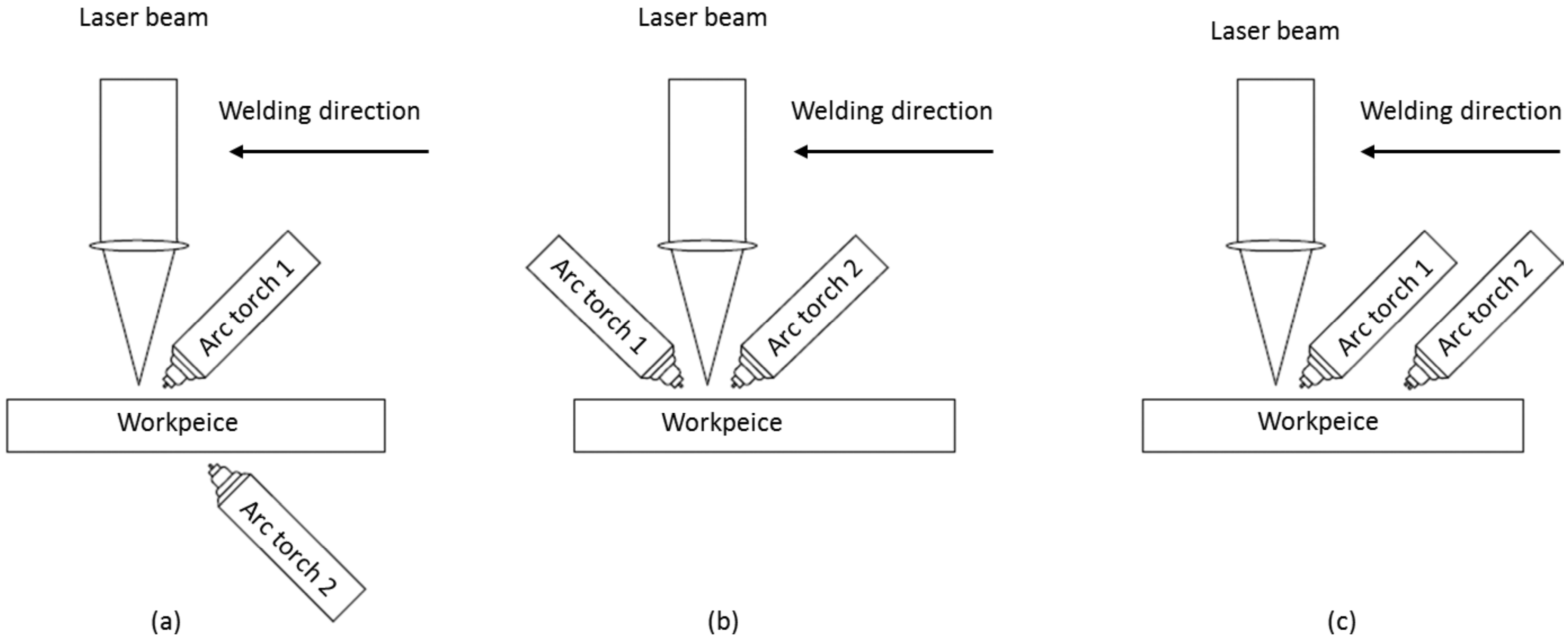

Fig. 8. Schematic diagrams of hybrid laser–arc processes with two secondary heat sources, redesigned from [9].

5.2. Challenges for aluminium welding

Aluminium alloys presents challenges for hybrid laser welding optics. One of the challenges limiting the welding system and the optics is; the high reflectivity of aluminium alloy that limits the choice of laser beam source for example to Nd: YAG and fibre laser.

Firstly, the melts zone (MZ), and HAZ are larger in hybrid welding, than in laser welding. The molten zone at the weld top is wider due to the welding arc process [70]. This compromises the metallurgical properties of the weld. Secondly, due to the wider weld pool and high melt temperature in HLBW difficulty arises in covering the weld pool, which can lead to contamination of the weld, and porosity [30]. Thirdly, alloys with volatile elements like 5xxx series can evaporate from the normally generated keyhole thus resulting in lower metallurgical properties of the weld and even porosity if the gas bubbles are trapped in the weld. This can be improved by proper selection of filler material [53]. In addition, volatile elements present in aluminium alloys can generate spatters during welding that can adhere to the lens and damage the lens. A precaution is to use a protective lens. Fourthly, aluminium alloys have low surface tension; they have poor ability for root-side melt pool support. This tends to cause difficulty in full penetration welding specifically in thick butt welds [45]. Finally, the presence of high number of welding parameters that is non-independent of each other in interaction compared to MIG or laser welding process, in addition to the metallurgical challenges in aluminium fusion welds. Therefore hybrid laser beam welding of aluminium alloys are complicated to design and operate [71]. Rasmussen et al. (2005) shows that successful welding of aluminium using a hybrid laser beam welding demands that, a clear understanding of the governing parameters, the effects and their interactions are understood [30] to be able to maximise the advantage of hybrid laser beam welding as a robust industrial welding process [71].

6. CONCLUSIONS

Aluminium alloys have become an important structural material and have found applications from general kitchen utensils to aerospace vehicles. They are grouped into cast and wrought aluminium alloys. The wrought aluminium alloys are sub grouped mainly into seven. Pure aluminium is weak, light and corrosion resistant. It conducts electricity, heat, reflects light and easy to fabricate. When alloyed, it can attain strength comparable to mild steel. However, some of its properties are detrimental to its fabrication. For example, the high strength alloys have poor weldability. They are relatively prone to weld defects due to for example, it's self-forming Al_2O_3 oxide layer, hydrogen solubility in molten aluminium, high shrinkage rate on solidification.

The properties of aluminium have affects on fusion welding. For example, the high heat conductivity implies that high heat energy densities are needed to weld the alloy that in turn increases HAZ degradation. The presence of Al_2O_3 although can be broken with high heat energy density welding process during welding, it has a significant mechanical strength that it can remain solid even when the surrounding metal is molten which can result into incomplete fusion. In addition, the high solubility of hydrogen in molten aluminium makes HLBW of aluminium prone to porosity although with proper know how, it can be minimized.

HLBW systems are used for welding aluminium and the most commonly used is hybrid MIG welding. The optics are used as resonator optics, beam delivery optics and processing optics. The optics include output windows, fold mirror, rear mirror, beam splitters, optical fibre, circular polarizers, collimator, scanning optics, and other special optics.

The usability of HLBW system is mainly limited in aluminium alloys due to the limited absorption of laser wavelength by aluminium. Therefore, the commonly used laser power sources are fibre laser and Nd: YAG. The focusing optics used is selected with reference to the *f* - number with the aim of avoiding spherical aberration. A rule for selecting optics is based on the fact that the higher the *f* - number, the higher the problem of spherical aberration. Beam delivery can be done using mirror optic or fibre optics; but mirrors are limited due to the need of a rigid mechanical mounting and the difficulty of transferring beams over long distances. On the other hand, fibre optics is limited by the bend radius and beam quality degradation. HLBW focusing heads are desired to be simple so that it is easy to integrate. However due to the numerous advantages the available technologies, they have only become more complex. Some of them have mechanical moving parts to allow for more manipulation in attaining closed loop, self-learning and self-adapting systems. The choice heat source and their configuration plays important role for the effectiveness and efficiency of HLBW. The challenges faced in HLBW of aluminium alloys are HAZ degradation, possibility of contaminated weld pool due to the presence of a wider weld pool compared to LBW, the presence of a volatile element in the alloy like zinc causing porosity and degradation of metallurgical properties. In addition, the presence of low surface tension that makes full penetration welding difficult in thick butt welds. Finally, there is the presence of a high number of interdependent welding parameter, in addition to the metallurgical challenges that are present in aluminium fusion welds.

REFERENCES

[1] G. Kopp and E. Beeh // *Materials Science Forum* **638** (2010) 437.

[2] F. Ostermann, *Anwendungstechnologie aluminium* (Springer Verlag, 2007).

[3] H. Schoe, *Schweißen und Hartlöten von Aluminiumwerkstoffen* (Verlag für Schweissen und verwandte, Verfahren DVS-Verlag GmbH, 2002).

[4] J.R. Davis, *Corrosion of aluminum and aluminum alloys* (ASM International, OH, 1999).

[5] T. Cock, *Aluminium - a light metal* (European Aluminium Association, 1999).

[6] C. Vargel, *Corrosion of aluminium* (Elsevier, Amsterdam- Boston, 2004).

[7] J.M. Sánchez-Amaya, Z. Boukha, M.R. Amaya-Vázquez and F.J. Botana // *Welding Journal* **91** (2012) 155.

[8] J.M. Sánchez-Amaya, Z. Boukha, M.R. Amaya-Vázquez, L. González-Rovira and F.J. Botana // *Aluminium Alloys Materials Science Forum* **713** (2012) 7.

[9] F.O. Olsen, *Hybrid laser-arc welding* (Woodhead Publishing, Cambridge, 2009).

[10] L. Quintino, R. Miranda, U. Dilthey, D. Iordachescu, M. Banasik and S. Stano, In: *Structural Connections for Lightweight Metallic Structures* (Springer, Berlin, 2012), p. 33.

[11] G. Mathers, *The welding of aluminium and its alloys* (Woodhead Publishing Cambridge, England, 2002).

[12] R.D. Joseph, *Aluminum and aluminum alloys* (J. R. Davis & Associates, ASM International, 1993).

[13] S.R. Yeomans // *Aust. Weld. J.* **35** (1990) 20.

[14] F.C. Campbell, *Manufacturing technology for aerospace structural materials* (Elsevier, Amsterdam -San Diego, 2006).

[15] *ASM International Handbook Committee, ASM handbook. Volume 6: Welding, brazing, and soldering* (ASM International, Ohio, USA, 1993).

[16] G.S. Ba Ruizhang, *Welding of Aluminum-Lithium Alloy with a High Power Continuous Wave Nd3+:YAG Laser 2004;* IIW Doc. IV-866-04 (accessed 2012).

[17] *Welding consumables pocket guide*, ed by P. Cigweld (SPW GROUP PTY LTD, Preston, Victoria, Austalia, 2008).

[18] W. Chang, In: *International Welding/Joining Conference* (Korea 2012), p. 79.

[19] J. Enz, S. Riekehr, V. Ventzke and N. Kashaev // *Physics Procedia* **39** (2012) 51.

[20] G. Schulze, H. Krafka and P. Neumann, *Schweißtechnik* (VDI Verlag, Düsseldorf, 1996).

[21] M. Schütze, D. Wieser and R. Bender, *Corrosion resistance of aluminium and*

aluminium alloys : corrosive agents and their interaction with aluminium and its alloys (Wiley-VCH, Frankfurt -Main, Germany, 2010).

[22] A. Riveiro, F. Quintero, F. Lusquińos, R. Comesańa and J. Pou // *Surf Coat Tech* **205** (2010) 1878.

[23] J. Xie and A. Kar // *Weld J* **78** (1999) 343.

[24] H. Herold, *Eignung metallischer Werkstoffe zum Schweißen* (Dt. Verlag für Schweißtechnik, DVS-Verlag, 2002).

[25] T. Diebold and C. Albright // *Welding Journal* **63** (1984) 18.

[26] J.I. Johannessen, *Structural Materials Fabrication* (EAA - European Aluminium Association, 1994).

[27] S. Goecke and E. Mündersbach // *DVS Berichte* **237** (2005) 44.

[28] J. Bruckner, K. Himmelbauer and H. Hackl, In: *The CMT process and its prospects, in particular the joining of steel to aluminium* (DVS Verlag: Düsseldorf, 2004), p. 201.

[29] C. Bagger and F.O. Olsen // *Journal of Laser Applications* **17** (2005) 2.

[30] D. Rasmussen and I. Dubourg, In: *Proc. 7th International Conference on Trends in Welding Research* (2005), p. 133.

[31] C. Maier, P. Reinhold, H. Maly, K. Behler, E. Beyer and von N. Heesen, In: *Schweißen und Schneiden* (DVS Verlag, Düsseldorf, 1996), p. 198.

[32] P. Fuerschbach, In: *Proc. 18th International Congress on Applications of Lasers & Electro-Optics* (1999), p. 102.

[33] J. Ji, U. Jasnau and P. Seyffarth // *Schweissen und Schneiden* **59** (2007) 200.

[34] J. Ji, U. Jasnau and P. Seyffarth // *Schweissen und Schneiden* **59** (2007) 334.

[35] J. Ji, U. Jasnau and P. Seyffarth // *Schweissen und Schneiden* **59** (2007) 555.

[36] C. Thomy, T. Seefeld and F. Vollertsen, In: *Proc. 3rd International WLT-Conference on Lasers in Manufacturing* (2005), p. 27.

[37] C. Thomy, T. Seefeld and F. Vollertsen // *Laser Technik* **3** (2005) 28.

[38] C. Thomy, M. Schilf, T. Seefeld, H. Kohn and F. Vollertsen, *Laser and laser GMA welding of steel and aluminium alloys for heavy industry applications* (IIW Doc XII-1856-05, 2005).

[39] C. Thomy, H. Kohn and F. Vollertsen, In: *Proc. 2nd International Conference on Laser Technologies in Welding and Materials Processing* (2005), p. 46.

[40] C. Thomy, T. Seefeld and F. Vollertsen // *The Industrial Laser User* **42** (2006) 22.

[41] M. Lohr, T. Ueyama and H. Tong // *DVS Berichte* **237** (2005) 194.

[42] J. Wang, H. Nishimura, K. Fujii, S. Katayama, M. Mizutani and S. Uchiumi, In: *Proc.10th International Conference on Joints in Aluminium* (2007), p. 151.

[43] C. Allen, G. Verhaeghe, P. Hilton, C.P. Heason and P.B. Prangnell // *Materials science forum.* **519** (2006) 1139.

[44] B.J. Aalderink, B. Pathiraj and R.G.K.M. Aarts // *The International Journal of Advanced Manufacturing Technology* **48** (2010) 143.

[45] M. Andersen and A. Jensen, In: *Proc. 8th Nordic Conference on Laser Materials Processing* (2001), p. 371.

[46] I. Decker, J. Wendelstorf and H. Wohlfahrt, In: *Laserstrahl-WIG-Schweißen von Aluminiumlegierungen Schweißen und Schneiden* (1995), p. 96.

[47] J. Hackius, B. Brenner, B. Winderlich, J. Standfuß, E. Beyer and S. Naegeler // *LaserOpto* **33** (2001) 49.

[48] S. Katayama, Y. Naito, S. Uchiumi and M. Mizutani, In: *Proc. of the Third International WLT-Conference on Lasers in Manufacturing* (2005), p. 193.

[49] S. Katayama, Y. Naito, S. Uchiumi and M. Mizutani // *Transactions-JWRI* **35** (2006) 13.

[50] R. Kling, F. Otte, C. Stahlhut and J. Hermsdorf // *DVS Berichte* **244** (2007) 40.

[51] N. Tomita, T. Ueyama, S. Hasegawa, T. Yasufuk and Y. Ueda, *Development of laser-arc hybrid welding robot system* (IIW Doc XII-1791-2004, 2004).

[52] C. Thomy, F. Möller, G. Sepold and F. Vollertsen, *Interaction between laser beam and arc in hybrid welding for dissimilar materials* (IIW, 2008).

[53] W.W. Duley, *Laser welding* (Wiley, New York, 1999).

[54] D. Kaminski. *Laser Marking: How to choose the best laser for your marking application* (Laser focus world, 2011).

[55] M. Jurca, In: *LIA handbook of laser materials processing*, ed. by J.F. Ready and D.F. Farson (Laser Institute of America, Orlando, 2001), p. 125.

[56] *LIA handbook of laser materials processing*, ed. by J.F. Ready and D.F. Farson (Laser Institute of America, Orlando, 2001).

[57] L.P. Connor, R.L. O'Brien and W.R. Oates, In: *Laser beam welding, cutting, and associated processes* (American Welding Soc.2006), p. 503.

[58] D.L. Sherman, In: *LIA handbook of laser materials processing*, ed. by J.F. Ready and D.F. Farson (Laser Institute of America, Orlando, 2001), p. 116.

[59] D.A. Bakken, In: *LIA handbook of laser materials processing*, ed. by J.F. Ready and D.F. Farson (Laser Institute of America, Orlando, 2001), p. 101.

[60] T.R. Kugler, In: *LIA handbook of laser materials processing*, ed. by J.F. Ready and D.F. Farson (Laser Institute of America, Orlando, 2001), p. 316.

[61] A. Mahrle and E. Beyer // *Journal of laser applications* **18** (2006) 169.

[62] E. Beyer, R. Imhoff, C. Maier, J. Neuenhahn, K. Behler and U. Dilthey // *Laser Materials Processing* **2500** (1994) 183.

[63] S. Uchiumi, J.-B. Wang, S. Katayama, M. Mizutani, T. Hongu and T. Fujii, In: *Proc. of the 23rd International Congress on Applications of Lasers & Electro-Optics* (LIA, San Francisco, USA, 2004), p. 76.

[64] P. Kah, A. Salminen and J. Martikainen // *Mechanika* **3** (2010) 68.

[65] T. Sugino, S. Tsukamoto, T. Nakamura and G. Arakane, In: *Proceedings of the 24th International Conf. on Applications of Lasers and Electro-Optics* (2005), p. 108.

[66] P. Seyffarth, B. Anders and J. Hoffmann // *DVS Berichte* **163** (1994) 377.

[67] B. Winderlich, *Erhöhte Dauerschwingfestigkeit von Schweißverbindungen durch Laserstrahl-Hybridschweißen mit integrierter Wurzellagenschweißung. IWS Jahresbericht 2003* (Fraunhofer Institut für Werkstoff- und Strahltechnik IWS, Dresden, 2003).

[68] U. Dilthey and H. Keller,In: *Proceedings of the first international WLT-conference on lasers in manufacturing* (2001), p. 453.

[69] A. Wieschemann, *Entwicklung des Hybrid- und Hydraschweißverfahrens am Beispiel des Schiffbaus* (Shaker, 2001).

[70] C. Page, T. Devermann, J. Biffin and N. Blundell // *Science and Technology of Welding & Joining* **7** (2002) 1.

[71] G. Sepold, C. Thomy, T. Seefeld, M. Schilf, R. Vollertsen and R. Hoffmann, In: *Proceedings of the Second International WLT Conference on Lasers in manufacturing* (Munich, Germany, 2003), p. 149.