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Research paper

Review on experimental study of Nd:YAG laser beam welding, with a focus on aluminium metal matrix composites

Amit Jyoti Banerjee [1]*, Manoja Kumar Biswal [1], A.K. Lohar [1], H.Chattopadhyay [2], Nagahanumaiah [1]

[1] CSIR-Central Mechanical Engineering Research Institute, Durgapur-713209, India
[2] Department of Mechanical Engineering, Jadavpur University, Kolkata-700032, India
**Corresponding author E-mail: ajbanerjee@yahoo.co.uk*

Abstract

The demand for high performance materials particularly in aviation and automobile industries gradually increases, CO_2 and Nd: YAG lasers are becoming most popular in processing these advanced materials. In this context, one of the most important process is joining by welding. It has been a constant endeavour by researchers to explore various methods and techniques to enhance the process efficiency of autogenous Nd: YAG laser welding of various materials i.e. without any filler materials. In this work, we present a comprehensive review of major research findings for the last decades or so, obtained by researchers about the effect of process parameters on autogenous laser beam welding (LBW) process performance. Main objective of such experimental research was to improve laser weld quality such as tensile strength, weld micro structure, heat affected zone (HAZ), weld penetration etc. In this paper, discussions are also made about different parameter optimisation techniques, design of experiments (DOE), modelling and simulation techniques, adopted by different researchers to achieve optimum weld quality. This review tries to bring out a foresight for direction of further research needed in this field.

Keywords: *Nd: YAG Laser Welding; Al-MMC; Weld Quality; DOE; Optimization.*

1. Introduction

Market demand for new systems performing in extreme conditions and demand for reduction of fuel/transport cost, encourages engineers to develop newer structural and functional materials. Metal matrix composites (MMC) especially with aluminium or its alloys as the matrix material exhibits great potential to be used for these purposes. Al-MMCs with different reinforcements like refractory fibres, graphite particles, ceramics, boron and intermetallics, has got tremendous application potentials in aviation, automobile and also in consumer industries [1]. For instance Al-alloy/ceramic particle composites due to its high wear resistance and compressive strength find enormous applications in functional machine elements [2], [3]. Another interesting aspect about Al-MMC is that the desired physical and engineering properties such as high strength and high specific modulus, low density, higher corrosion resistance, heat resistance, higher damping properties, higher electrical and thermal conductivity and lower co-efficient of thermal expansion can be achieved through appropriate selection of chemical composition and type of reinforcements. Despite these advantages, successful structural application in general engineering and transport industry is yet to be popular due to lack of appropriate secondary processes like joining. Laser beam welding (LBW) process shows a great promise here as a permanent joining method of MMC thereby opening greater application possibilities for it [4]. The advantages of Laser Welding in terms of different materials and laser sources can be found in Spalding [5].

LASER beam consists of photons of same frequency, wave length and phase, making it highly directional with higher power density and better focussing characteristics makes it very unique for secondary processing of MMC [6]. Due to these unique properties lasers are heavily used for joining, surface treatments, heat treatments, cutting, drilling, marking, micromachining etc. In LBW process, high energy density laser beam on incidence upon a work piece surface, transfer its thermal energy and melts a small amount of work piece material to create a fusion joint on solidification. CO_2 and Nd:YAG laser sources are most widely used in modern industries [6], [7], [8]. However, due to its unique characteristics, Nd:YAG laser processing of material is still a very attractive area of investigation for researchers. It has relatively low mean beam power but high beam intensity, easily focusable, narrower heat affected zone (HAZ), high absorbability on reflective surface such as aluminium due to shorter wavelength, better transmission capability through plasma and handling flexibility using fibre optic cable. Enumerated above are some unique properties of the Nd:YAG laser welding [9]. Due to its high heat intensity, LASER welding process gives deep weld penetration with minimum or no heat affected zone. However the process demands a careful edge preparation for very tight fitted well meshed edge surface. A Schematic layout of the Nd: YAG robotic laser welding set up is shown in fig.1 below.

In this setup the robot (ABB make 6-DOF) controller is interfaced with JK600 Nd: YAG laser system and the whole LBW process is controlled via LASER View software. Laser beam is supplied to the work piece through welding head fitted in the robot-arm via optical fibre. Gas supply is controlled manually and weld path is programmed using the robot controller with a teach-in system.

Effects of process parameters, on any manufacturing process performance, plays a vital role and should be fully understood in order to optimize tem to achieve optimum product quality and higher utilization of resources. LBW process parameters that effect weld quality can be categorized in three groups namely beam parameters, welding parameters and material parameters. It is important to optimize these parameters to achieve desired weld characteristics and maximum process efficiency. Important LBW parameters and its influences on the process performance are shown in table.1 below.

As newer high performance Al-MMC are being developed with improved mechanical properties, experimental investigations are needed to be conducted to develop comprehensive process models simulating Nd:YAG LBW process in order to fully comprehend the underlying science of interactions between the process parameters and output quality and optimize these parameters. Table.1 shows that pulse energy, pulse width, pulse rate and pulse shapes are most contributing factors influencing the weld quality. In the third column of this table SP stands for DOE significant process parameter that influences quality characteristics (QC) of the weld, where upward and downward arrows (↑↓) signifies increasing and decreasing trend. It can be seen that welding speed, defocusing distance, gas flow rate and direction has significant influence on the output quality. Effect of types of gas also may be of interest. Lim and Gweon [10], [11] developed an interesting technique to model weld quality in terms of weld geometry, HAZ dimensional variations and weld strength using infrared radiation features in pulsed Laser spot welding. They have studied the change in the initial temperature profile of the radiation features and established the explicit relationship between temperature profile and weld quality, i.e weld strength using artificial neural network and achieved a high correlation co-efficient of 0.98. In another publication Lim et al [12] suggested a new in-process monitoring of weld quality in pulsed laser spot welding by monitoring the absorbed weld energy measured online using infrared sensors (IR). It is demanded that this method is robust as it is free from the influences of measuring condition in case of radiated thermal profile.

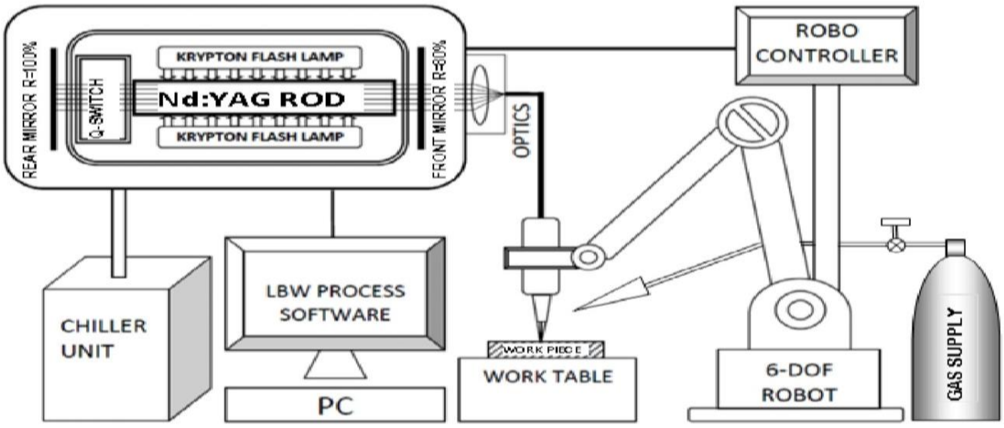

Fig. 1: Nd: YAG Robotic LASER Welding Set-Up.

Table 1: Important LBW Parameter and Its Influences on Weld Characteristics of Al-MMC

Sl. No.	Significant Parameters (SP)	Quality Characteristics (QC)	Influence at SP ↑	Remarks
1	Energy	a) HAZ b) Depth of Penetration c) Microstructures d) Tensile Strength e) Micro Hardness	SP ↑ QC↑ SP ↑ QC↑ SP ↑ QC↓ SP ↑ QC↓ SP ↑ QC↑	High Energy Larger Heat Affected Zone High energy desity less distortion(W. M.Steen 2005 [13] Pg.160) At higher temperature chemical dissolution is higher
2	Pulse Width	a) HAZ b) Depth of Penetration c) Microstructures d) Tensile Strength e) Micro Hardness	SP ↑ QC↑ SP ↑ QC↑ SP↑ QC↓ SP↑ QC↓ SP↑ QC↓	Higher pulse width deep welding (W. M.Steen [13] 2005)
3	Pulse Rate	a) HAZ b) Depth of Penetration c) Microstructures d) Tensile Strength e) Micro Hardness f) Bead Overlap	SP↑ QC↓ SP↑ QC↑ SP↑ QC↓ SP↑ QC↑ SP↑ QC ↓ SP↑ QC↑	J Niu et al. [14], 2006
4	Welding Speed	a) HAZ b) Depth of Penetration c) Tensile Strength d) Bead Overlap	SP↑ QC↓ SP↑ QC↓ SP↑ QC↓ SP↑ QC↓	Reduces with increase in feed (J. F.Ready [15] 2001 LIA.Pg.312 ; N. B. Dahotre & S.P. Harimkar [16] 182, 437, W. M.Steen [13] 2005) Speed Increase, No Proper Overlap
5	Gas Flow	a) HAZ b) Depth of Penetration c) Microstructures d) Tensile Strength e) Micro Hardness	Helps in cooling less HAZ. Good Shielding Good Penetration. Good Shielding Good Welding Quality.	Helps in cooling less HAZ Good Shielding Good Penetration Good Shielding Good Welding
6	Focus Position	a) HAZ b) Depth of Penetration c) Bead Overlap	SP ↑ QC↓ SP ↑ QC↑ Higher Spot Size better overlap	Focus is basically characterized by the minimum focal spot size (Ømin) and the focus depth (Z). Focal spot size is relevant to the determination of power density. Focussing below the surface improves depth of penetration
7	Gas Type	a) Depth of Penetration b) Microstructures c) Tensile Strength d) Micro Hardness	Shielding gas has definite influence on QC	
8	Pulse Shape	a) Microstructures b) Tensile Strength c) Micro Hardness	Pulse Shaping has positive influences on QC. Better control of flow in the weld pool and reduces formation of pores.	Good Micro Structure Uniform Structure

In the following sections, state-of-art of laser beam welding is reviewed. We have reported experimental work with or without DOE and numerical modelling for Al-MMC and other materials in separate sub-sections.

2. Experimental investigations

Literature review reveals that many researchers studied through experimental investigation, the influence of critical process parameters on weld quality without using any DOE methods and used the results to determine the effect of individual parameters and their influencing mechanism on the output quality of the weld. Many other researchers however, adopted DOE techniques for experimental investigation of LBW process. DOE method provides a systematic and rigorous approach to plan the experiment, to collect and analyse data such that it yields valid and objective conclusions with limited resources. There are several DOE and analytical methods available. In material processing experiments DOE methodologies such as Factorial Design (FD), Central Composite Design (CCD) together with response surface methodology (RSM) and Taguchi Robust Design are generally used [17].

2.1 Laser beam welding parameter study of Al-MMC without DOE

Experiments on Nd: YAG laser beam welding of metal matrix composites (MMC) of aluminium and its alloys have been reported by various authors. Basic objective of these studies was to find out the influence of individual parameters and its mechanisms without any consideration on the effect of parameter interactions on the process output.

2.1.1. Investigation on Al-SiC MMC

Experimental investigations were carried out by Bassani et al. [18], on key-hole and conduction laser welding of A356–20% SiC composite with two different laser sources viz. CO_2 and diode laser respectively. They have carried out the microstructure analysis of the weldment from both the processes and compared the results. It was found that CO_2 Key hole Laser welding could not be accepted for its very high hardness and extremely low toughness at the weldment because of formation of Al_4C_3 by SiC dissolution. However they have observed that such dissolution of SiC could be controlled through welding parameters. Conduction mode welding using Diode laser resulted in a homogenous dispersion of SiC in the weldment and an overall good metallurgical quality. Authors have also carried out an autogenous bead-on-plate welding experiment of A356 alloy reinforced with SiCp 10 and 20 vol% using pulsed CO_2 laser at 3.2 kW peak power to study the microstructure and determine the mechanical properties of the weldment. Dahotre et al. [19], in their study carried out mechanical testing using Instron tensile testing machine. Both optical microscopy and analytical electron microscopy were used for microstructure characterization. They observed that with high duty cycle (91%) pulsed CO_2 laser, excessive formation plate like structures of carbides mainly Al_4C_3 and $Al_4Si_2C_5$ takes place through extensive dissolution of SiC particles in the molten metal, thus deteriorating the mechanical properties as well as the microstructures. However at intermediate duty cycles viz. 67% and 74 % good quality welds are achievable with optimum effects on microstructures and mechanical properties.

Calliari et al. [20], have reported the results of both CW and Pulsed Nd: YAG laser welding of Al-alloy/SiC and Al-alloy/Al_2O_3 composites with special attention given to the influence of the base alloys and the effect of process parameters on the microstructure of the welding bead. They have also studied the effect of both traditional (chromate) and innovative (cerate) conversion coatings on the SiC-reinforced joints. It was found that the cerate treatment appeared to be the most effective because it acted as a cathodic rate inhibitor with increased corrosion resistance. The use of argon as shielding gas was most effective, both in order to avoid the development of porosity and reduce Al_2O_3 clustering. However, the use of different shielding gases in the welding process of SiC reinforced composites appears to have no effect on the structure of the weld beads. Yue et al. [21], carried out Nd:YAG laser welding experiment of Al-Cu-Mg alloy/SiCp MMC and found the presence of brittle carbides in the central weld zone. They have observed that excessive formation of carbides in the fusion zone can be controlled by controlling appropriate laser parameters namely laser intensity and pulse duration. With lower intensity and longer pulse duration a good butt weld with minimum defects were produced. Earlier research work [21] on microstructural analysis of laser welded MMC reveals a typical image as shown in Fig.2. In this figure three distinct zones are highlighted. These zones are central weld zone ‘A’, fusion zone ‘B’ and undisturbed zone ‘C’. Zone ‘A’ is characterized by the presence of precipitates with needle like structures surrounded by somewhat finer platelets of lighter colour. Zone ‘B’ apparently shows the presence of more particles than the undisturbed zone ‘C’ where the microstructure of base material is preserved. The region ‘A’ is rich in Al_4C_3 carbides and Si, whereas the region ‘B’ is rich in SiC. Region ‘C’ is found to be depleted in SiC. Al_4C_3 is a brittle phase that forms in reaction of Al (matrix) with the SiC (reinforcement particle) and this phase is detrimental to the mechanical strength of the weldment. This changes in microstructure (occurring due to reaction between matrix and reinforcement particle) is again dependent on the laser welding parameters i.e., pulse intensity and pulsed duration. With the increase in laser beam intensity and/or pulse duration the amount and size of Al_4C_3 platelets increases. It was also seen that if pulse intensity and duration is kept low, the deleterious effect causing carbides can be restricted. These effects on weld microstructures are illustrated in the original literature [21].

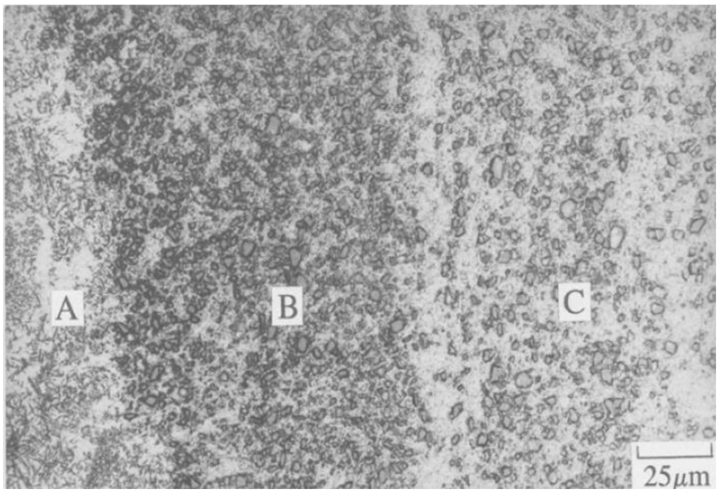

Fig. 2: Typical Microstructures of A Laser Weld Reprinted From Yue Et Al. [21] License from Springer.

Lloyd [22] in his experiment with Al/Sic MMC monitored the intensities of X-ray peaks of bothe Al_4C_3 and Si where the samples were remelted and soaked at different temperature above liquidus for various durations before quenching. He showed that it is possible to control Al_4C_3 formation by controlling Si content and also contact duration of SiC with molten metal. It has been suggested that alloys with high Si content are most suitable for SiC reinforcement and shown that a complete stability of Al_4C_3 can be attained with Si levels above 8 wt. % [7].

Fuerschbach and Cieslak [23] carried out a comparative study of laser welding of A40 alloy using pulsed Nd: YAG and (CW) CO_2 laser for both low and high restraint joints. A40 could be a good candidate for Al alloy-SiC MMC and can be used for electronics packaging for avionics industry. With this objective they have also studied Al 6061 and Al 1100. They observed that weld joint cracking depends on the degree of restraints of the welding. They also observed that A40 aluminium alloys can produce crack free joints using Nd: YAG and CO_2 laser in case of low and high restraint joints respectively. High restraint joints of A40 with either 1100 and 6061 alloy is possible using Nd: YAG laser. Grabowski et al. [24] carried out an interesting investigation to characterize optical, electrical and thermal properties of AlSi-alloy/SiCp composites using CO_2 laser and other experimental methods. They have observed that these properties are dependent on the volume fraction of the reinforcement i.e. SiC particles. Wang et al. [25] in their work investigated the effect of in-situ alloying with Ti during laser welding of SiCp/6061 Al metal matrix composites. It has been observed that the addition Ti as alloying element completely prevents the chemical dissolution of SiCp into pin like structure formation of Al_4C_3 carbides deteriorating the quality of the welding.

Karaoglu [26], reported the effect on the laser beam welding characteristics of Al/SiC MMC produced through powder metallurgy rout due to the addition of B_4C particulate. He has observed that weldability improves with the addition of B_4C even in a small quantity.

Effects of centrifugal casting parameters for Al-alloy/SiC were investigated by Huang et al. [27], to characterize the fabrication result of automotive piston. They have also reported the macro morphologies and microstructure of the piston thus obtained showing improved mechanical and wear properties over permanent mould gravity casting. A comparative study of various fusion welding processes eg. Electron beam, Laser beam and gas tungsten arc welding versus friction stir welding of A6061/SiC MMC was reported by Storjohann et al. [28]. It was observed that friction stir welding process offer better microstructure and mechanical properties of the welding joints.

Effect of the in situ addition of TiB_2 filler in Nd: YAG laser welding of $SiC_p/AlSi_7Mg$ MMC was studied by Guo [29] and reported that situ addition of TiB_2 has a very conducive effect on the weld quality through formation and uniform distribution of TiC in the weld area and effectively causes a restrain effect on the formation Al_4C_3.

Mao-ai et al. [30] studied the electron beam welding of Al-alloy/ SiC_p composites to determine the mechanism of interfacial reaction. They observed that Al_4C_3 precipitates after dissolving of SiC and Al. The size and quantity of Al_4C_3 precipitates depend on the heat input and generally increases with the increase of heat input thus deteriorating the composite properties.

2.1.2. Investigation on Al-TiB_2 MMC

Meng et al. [31], studied evolutionary behaviour of TiB_2 during laser welding of Al-particulate TiB_2-MMC. They found that for higher TiB_2 particulate volume %, there are interactions between liquid Al and molten TiB_2 leading to fractures at the edge of the weld seam. Guo et al. [32] reported a study on laser welding of 4.3 mm thick rolled plates of AA1100-16 vol. % B_4C metal–matrix composites with addition of feeler of 150μ Ti-foil and Ø1 mm. Ti-wire; they have obtained joint efficiency of 63% (UTS) without Ti-feeler and 75% efficiency with Ti-feeler as foil. A new MMC Al0.3 Sc 0.15 Zr-TiB_2 is reported by Lohar et al. [33] in their work. Effect of addition of small quantities of Mg was also studied. Tang et al. [34] have studied the effect of laser welding parameters for Aluminium alloy AA5083 and reported grain refinement by introducing Ti/B as grain refiner in the weld pool to achieve improved mechanical properties. The objective of the study was to determine the minimal quantity of grain refiner under different laser welding parameters. Huang et al. [35], reported their findings of laser welding experiments of high performance materials where, full penetration of in-situ ZL101-TiB_2 MMC was successfully achieved with minimum defect using high power CO_2 laser at low welding speed (2 m/min) and with gas flow in the direction of the welding. Micro structural examination revealed more uniform distribution of TiB_2 particles in the weld zone than in the base material. Tensile strength test also revealed higher strength in the weld zone than base material.

Development of lightweight wear resistant Al MMC has interested researcher for its potential application in the aviation and automotive industries. Smith and Chung [36] developed a highly wear resistant Al-MMC with TiB_2 particle of 4μm size and 61 vol% as reinforcement through liquid infiltration method. They have also carried out rigorous mechanical and wear testing and found that it exhibits superior wear and mechanical properties than many Al MMC and comparable to many of the engineering metals.

El-Mahallawy et al. [37], reported the development of TiB_2/Al MMC through casting process and investigated the reactions resulted from both simultaneous and subsequent addition of two different salts viz. K_2TiF_6 and KBF_4 into the 99.999% pure Al melt at 800^0 and 1000^0 C.

Zhang et al. [38] reported their investigation on the effect of four types of reinforcing with four different particulates on the Al/TiB_2 MMC's dampening properties. They have observed that presence of Ti and Mg along with TiB_2 improves the dampening capacity of Al/ 5 wt% TiB_2 composite.

Luan et al. [39], reported in their study of the effect of warm peening of TiB_2/6353 Al-MMC on the residual stresses and the microstructural changes using X-ray diffraction. Solving the basic equation of Warren-Averbach method for determining the domain size and the dislocation density they have observed that the compressive residual stresses is improved. It was also observed that the increase in initial warm peening temperature increases the domain size and reduces the dislocation density and thus there is an improvement in fatigue properties.

Friction stir welding process of 10wt% TiB_2/Al MMC was studied by Vijay and Murugan [40] who reported the effect of tool pin profile on the mechanical and metallurgical properties of the weldment. He-guo et al. [41] reported their investigation on the formation of Al/TiB_2 MMC through exothermic dispersion reaction of Al-TiO_2-B_2O_3 system.

2.1.3. Investigation on other materials

Three Al metal matrix composites were developed using SiC, B_4C and Al_2O_3 with varying volume% (0-20) through stir-casting manufacturing route and followed by hot extrusion process by Shorowordi et al. [42]. They have detail material characterization using optical microscope, SEM and EDX spectrum analysis. They have carried out fracture surface analysis and observed that B_4C reinforced Al MMC exhibit better interfacial bonding and better particle distribution compared to others.

Investigation on the weldability of AA 7005-Al_2O_3/AA7020 MMC using MIG welding process was reported by Salazar and Barrena [43]. It was reported that loss of mechanical properties up to 60% was due to annealing effect because of dissolution of hardening phase. However, post heat treatment shows recovery up to 95%. Similar findings were obtained by Niu et al. [14], while investigating laser welding of SiC_w/ Al due to the formation of Al_4C_3 through reaction of matrix and reinforce material. Achieved tensile strength was 70% appx. That of the matrix. This reduction of tensile strength of the welded joint was attributed to the presence of brittle carbide products in the interface region arisen from interface reaction between matrix and reinforcing material by reducing laser energy intensity and increasing Si content in the weld pool. For that concept of a new parameter $\alpha[Si]min$ called critical Si activity is proposed.

Huang et al. [35] reported their findings of laser welding experiments of high performance materials like 1000MPa complex phase (CP) steel, Al-alloy ZL 101 with TiB_2 MMC and laser cladding of medium carbon steel using a 15 KW CO_2 laser. They achieved tensile strength comparable to the base metal in case of CP steel.

Ismail et al. [44], in their work carried out micro welding studies of dissimilar materials viz, pure aluminium and difficult to weld super thermal conductive (STC) Aluminium–graphite (Al-Gr) MMC using pulsed Nd: YAG laser. They have carried out experimental investigation as well as numerical analysis of the micro welding process. They have studied the effect of pulse shaping on the quality of the overlap weld and found that with appropriate pulse wave form it is possible to achieve quality weld free from defects.

A theoretical study of different methods of joining MMC in general and their relative advantages has been reported by Chernyshov et al. [4]· Study of autogenous laser beam welding of Ti-6Al-4V in dual mode i.e. conduction and keyhole was reported in their work by Squillace et al. [45]. They have investigated the effect of welding speed and laser power on the weldment quality, microstructure and mechanical properties using 2kW Nd: YAG laser. Prater [46] reported a survey on the challenges and potential solutions for joining metal matrix composites and concluded that solid state joining like friction stir welding has the potential to create defect free welding. Cao et al. [47], in their work presented the review of the research work done in the area of laser welding of magnesium alloys and discussed different issues related to the problems in laser welding of magnesium alloys. Fukumoto et al. [48], in their work, studied the effect of volume fraction of the reinforcement material and thickness of interlayer filler material Ti-Cu-Zr on the joint strength during diffusion bonding process of Ti-6Al-4V/ SiC continuous fibre MMC with Ti-6Al-4V alloy. They have observed that joint strength is inversely proportional with the reinforcement volume fraction (V_f) and 90% joint strength could be achieved with V_f less than 30%. Interlayer filler thickness less than 80μm has a negative effect on the joint strength due to the occurrence of shear fracture. In their review papers, Kaczmar et al. [49] discussed different production methods of MMC and comparative influence on the final products for various applications. Rosso [50], in his paper reported the current and future trends of processes and application for ceramic and MMCs. An analysis is also made on the influences characterizing its application and growth.

Skorokhod and Krstic [51] reported in their publication the effect of introducing TiB_2 particulates along with elemental carbon in improving mechanical strength and fracture toughness of B_4C-TiB_2 MMC. They have observed that 15 vol % produces optimal result through pressure less sintering process with in-situ thermal reaction.

A survey on current status and future trends of existing welding technologies have been reported by Kah and Martikinen [52] along with their appropriate application. Gracia et al. [53] in chapter 2 of the book “Arc welding”, dealt with the indirect (IEA) and modified indirect arc welding processes (MIEA) and showed that MIEA is promising process for welding aluminium MMC and for carbon steels.

Xia et al. [54] made a comparative study on formability of weldment using diode laser for two different type of steels viz DP980 and HSLA steels. Comparison was done through tensile and dome height test, measuring micro-hardness across the weld and microstructure examination. They observed that formability of HSLA is unaffected by the welding process, but DP steel shows reduction of formability.

3. LASER parameter study with DOE and process modelling

Design of experiments is a systematic, scientific approach to experimentation with an objective to generate a feasible and valid conclusion with minimum resources, towards solving engineering problems. It applies principles and techniques at the data collection stage and during its analysis. It scientifically determines the relationship between factors affecting a process and the output of that process. It is a more effective way to determine the impact of two or more parameters on the response.

In DOE, number of experiments depends on the number of controlled parameters and their levels. Generally l^k runs are required for k factors each at level l. The minimum number of level taken is 2. Total number of experimental runs can be reduced by using fractional FD technique in which some interactions are aliased with main factors [17]. Results thus obtained from DOE experimentation are generally analyzed using tools like, Analysis of Variance (ANOVA), Response Surface Methodology (RSM), Grey relational Analysis (GRA) etc. to determine individual parameter effects, parameter interaction effects and their significance on process performance. RSM is used in conjunction with experiments, performed using CCD matrix to generate a response model of second order [55].

In Taguchi Robust Design, parameter levels are selected very judiciously to nullify the effect of noise factors in order to make the process robust or insensitive to noise. Depending on the numbers of process parameters, their levels and responses, a standard orthogonal array (OA) is selected to perform the experiments and for each response, a quality loss function is calculated after conducting the experiment.

For each responses Signal-to-Noise (S/N) ratio (η) is mathematically calculated and the objective is to maximize it.

Those parameter levels for which S/N ratio is maximum, is taken to be the optimum and a confirmation test is performed to verify the improvement in process performance [56]. Significance of factors/interactions is determined using ANOVA. To optimizing multiple responses, normalized quality loss value for each response is calculated first and a single multiple S/N ratio is further computed [57].

Literature survey reveals that most of the researchers didn't use DOE in LBW experiments. However DOE methodology was used by few in Nd: YAG laser welding research.

3.1. Investigation on Al-SiC MMC

Liu, et al. [58], carried out a theoretical study of laser forming of Al6092/25% SiC_p metal matrix composite and developed a multi particle cell model using 3D finite element method to characterize the particle distribution effect on the deformation behaviour. The results from their analysis fairly tally with the experimental results as well as with that obtained from simple cubic cell model.

An analytical thermal model was developed by Bonollo, et al. [59] for CO_2 laser welding of Al, Al-alloy/SiC particulate. Effect of filler material on the quality of the welding is also reported. A theoretical study by simulation of solidification process for composite micro-region, considering incomplete wetting of reinforcing particles was reported by Cholewa [60].

Zhou et al. [61], carried out both theoretical and experimental investigation into the failure mechanisms of Al 6061/ SiC_p MMC under thermal shock loading induced by Nd:Glass laser irradiation and also mechanical loading simultaneously. A theoretical model was developed to explain damage failure mechanism backed up by finite element simulation. The damage as well as complete failure threshold was calculated using the model and the results were experimentally validated.

3.2. Investigation on Al-TiB_2 MMC

In their work, Cui et al. [62] developed a mathematical model for key hole laser welding of 12 vol. % TiB_2 particle reinforced ZL101 (Al-7Si-0.3Mg) MMC in order to investigate particle migration, shape of weld cross section and particle distribution. Volume-of-Fluid (VOF) function was used to track free fluid surface. The simulation was carried out assuming the fluid flow to be Newtonian, laminar and incompressible and without any consideration for diffusion of particles in the fluid or any particle loss in the welding process. They have also carried out confirmatory experiments using 7 kW laser power source. Experimental result shows good agreement with the simulation result.

Yi et al. [63] reported development of a numerical model to predict the effect of vol. fraction TiB_2 on the effective elastic moduli (EEM) of A356/TiB_2 and A132/TiB_2 MMC. Predicted EEM values were consistent with the actual values were consistent with the actual values for eutectic A132/TiB_2 MMC, while the predicted values of EEM of A356/TiB_2 MMC deviated from actual results due to other influencing factors viz. shape, size and distribution of the reinforcing TiB_2 particulates.

3.3. Investigation on other materials

As the LBW process because of its efficient processes performance, being sought for wider application, studies on various other materials like SS, titanium alloys etc were carried out by many researchers employing difficult techniques. In order to understand fully the underlying principles of these processes, review of some studies are carried out below.

Zhou et al. [64], carried out a theoretical study of Laser Keyhole welding of 304 stainless steel and developed a comprehensive thermal mechanical model to analyze heating, melting, cooling, solidification processes to investigate stress evolution process during keyhole welding using 175kW Nd: YAG pulsed Laser and incorporating a thermal model and the temperature dependent material properties into the ANSYS® finite element model.

Singh et al. [65], in their work reported the development of a process based model to predict the laser weld geometry using an Ytterbium fibre laser on plain carbon steel (DC05). They have employed neural network along with genetic algorithm (GA). Both counter propagation neural network (CPNN) and back propagation neural network (BPNN) were used. Modelling was conducted in C++ environment, where codes were written for GA optimized BPNN and CPNN using MATLAB. It was observed that traingm and trainbr training algorithms are most suitable for modelling weld geometry profile and weld hardness profile respectively.

A 3D numerical simulation model of Nd:YAG laser welding process of DH-36 steel and Al 6061-T6 aluminium was developed using macro-routine within the ANSYS finite element code and reported by Moraitis and Labeas [66] to predict the residual stress and distortion fields in the weldment.

Zhou et al. [67] have carried out a numerical and experimental study to investigate the transient keyhole formation and collapse process as well as weld pool dynamics during laser welding process of AISI 304 stainless steel. They reported development of a numerical model employing continuum phase dynamics during melting and solidification process, volume-of-fluid method for free surface handling and enthalpy method was used for latent heat. They have also considered the laser absorption and thermal radiation by the plasma in the keyhole for developing the model. Using the model researchers calculated temperature distribution, penetration depth, weld bead size and geometry which are in good agreement with experimental result.

Chang and Na [68], reported the development of a combined model of finite element analysis and neural network for prediction of weld bead geometry during laser spot welding of AISI 304 stainless steel. Authors used heat conduction theory for finite element Methods and showed that thermal & mechanical aspects can be decoupled assuming that the dimensional changes during laser spot welding are insignificant. A back propagation algorithm was used for predicting weld bead geometry. The combination of FEM analysis and simulation based on neural network effectively predicts bead geometry with marginal errors.

Acherjee et al. [69], reported application of artificial neural network to establish correlation between laser transmission welding parameters viz. laser power, welding speed, stand-off distance and clamping force with weld bead qualities such as lap-shear strength and weld-seam width using a non-linear model. As per the researchers experimental results of transmission laser welding of thermoplastics agreed well with the model predicted result.

Modelling of laser welding of AISI 304 stainless steel was reported by Balasubramanian. et al. [70], using artificial neuron network (ANN) with back propagation network algorithm and least mean square algorithm. Box-Behnken design of experiment was adopted to generate input parameters viz. laser power, welding speed and beam incident angle to generate output variables such as depth of penetration and bead width for use in the training of the ANN. Predicted results from the ANN model with different configuration was compared with experimental results. It showed that a comprehensive ANN model is viable for usable predictions.

Development of an integrated methodology for laser butt weld quality evaluation for Al alloy with the help of an index was proposed by Galantucci et al. [71]. Using quality index as per ISO: 13919 international standard and artificial neural network, the authors developed a process model to predict laser parameters for a given weld quality index.

A numerical model for solid body heat conduction to calculate temperature distribution was developed by Mahmood et al. [72], for transmission laser welding of two dissimilar materials viz. titanium and polyimide using finite element method. Results predicted by the model were verified with experimental results which showed good agreement.

Padmanabhan and Balasubramanian [73], has experimentally studied the laser welding process of $AZ_{31}B$ magnesium alloy using face centered central composite design of experiment to optimize laser welding parameters. An empirical model was developed to predict laser parameters for maximum tensile strength using RSM and tested model adequacy using ANOVA technique.

Laser Transmission Welding of polycarbonate was studied by Acherjee et al. [74], using Central Composite Rotational Design of experiments followed by regression analysis for producing hermetically sealed strong weld free from thermal or mechanical stresses with little or no flash. Thermal analysis using 3D FEM was carried out and a mathematical model was developed. They have also used sensitivity analysis technique to determine how different values of an independent variable will affect the efficiency of welding performance under a given boundary conditions.

Balasubranian et al. [75] developed a mathematical model using response surface methodology to predict the grain size and hardness of the weldment obtained through a pulsed TAG welding method for welding Ti-6Al-4V alloy. A rotatable CCD matrix was used for optimization of welding parameters and adequacy was tested using ANOVA.

Benyounis and Olabi [76] carried out a survey and showed that combining two optimization techniques would reveal better results for finding out the optimum welding parameters.

Taguchi DOE with L18 orthogonal array has been implemented successfully and optimisation of process parameters has been carried out using S/N ration and ANNOVA by researchers KIM and Lee [77] in case of LASER-MAG hybrid welding of 6061-T6 Al alloy. They have also carried out GRA methodology to compare both the results and showed that GRA method could simplify the process optimisation of complicated process performance.

4. Discussions and concluding remarks

A comprehensive and in-depth literature survey is presented here reviewing different approaches adopted by various researchers for experimental investigation on laser beam welding (LBW) of aluminium matrix composites (AMC). These investigations bring out the capabilities and application of LBW process highlighting the effect of various controlled parameters on process performance. It can be seen that all the parameters affecting the LBW process performance can be grouped under three categories and they are:

1) Laser parameters such as wavelength, power and mode of operation.
2) Material parameters such as material type and sample thickness.
3) Process parameters such as welding speed, defocusing distance, repetition rate, energy, pulse duration, pulse shape and type of assist gas, its pressure and flow rate.

Most important process outcome in LBW process that are studied by researchers, are HAZ, tensile strength, micro hardness, bead overlap and microstructures. Though Nd:YAG laser beam welding of Al-MMC has many advantages but its low energy efficiency, HAZ, micro structural damages, chemical dissolution of reinforcement at high temperature and high reflectivity of the material suggests a very careful selection of these parameters. Therefore, appropriate selection of parameters is of great importance to achieve good weld quality and optimization of process parameters plays a crucial role in process performance.

Different LBW process parameters and their effects on final weld quality are already enumerated in Table 1. Literature shows that process parameters like energy, pulse rate, pulse width, focal plane distance significantly influences weld qualities like tensile strength, depth of penetration, microstructure etc. as shown in Figs. 2 to 5 (Niu et al. [14], YUE et al. [21]). It has been reported in literature that parameters like power and repetition rate has significant influence on weld strength. It decreases with the rise in laser beam power. However the strength increases with the increase in repetition rate.

Both these parameters are in turn, affect the metallurgical features in the weld pool which influences the weld strength. Fig.4 shows the relation between peak power (i.e. E/t) and weld penetration depth. It can be clearly seen that increase in peak power increases the depth of penetration for all three different pulse duration values.

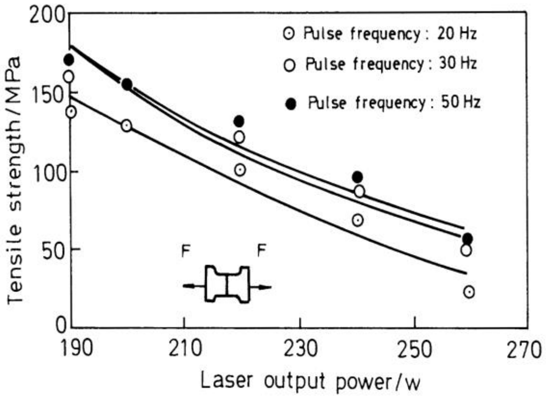

Fig. 3: Effect of Laser Welding Parameters on Welding Joint Tensile Strength @ Welding Speed = 5mm/S, Gas N_2 License from Springer Reprinted From Niu Et Al. [14].

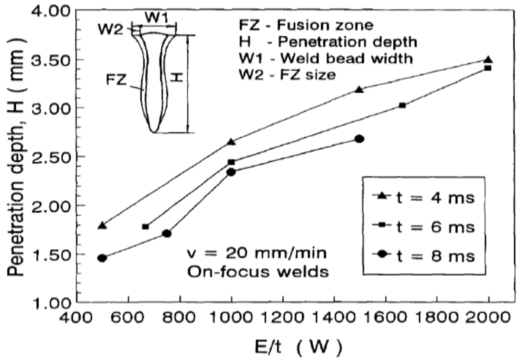

Fig. 4: Effect of Peak Power on Penetration Depth, Reprinted From Yue Et Al. [21] With License from Elsevier.

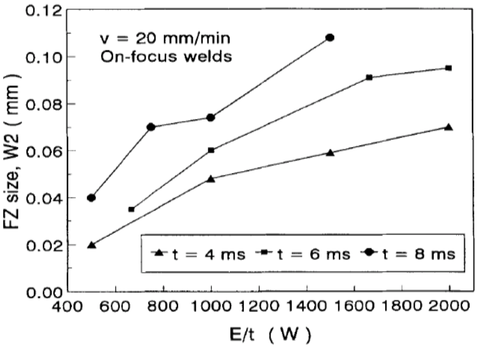

Fig. 5: Effect of Peak Power on Fusion Zone Width, Reprinted From Yue Et Al. [21] With License from Springer.

Fig.5 depicts that with the increase in pulse intensity and duration, the size of fusion zone increases. This is a simple reflection of the fact that higher energy input would give rise to a larger processed zone. It was also seen that defocusing in either direction increases size of the fusion zone. The above phenomenon can probably be attributed to the fact that laser energy density reduces with increase in the defocusing due to the enlargement of the irradiated area [13]. This results in the consumption of higher amount of energy in melting and correspondingly a smaller keyhole.

Effects of welding velocity on microhardness and tensile strength for various % of SiC are shown in figure 6 & 7 by Durmuş and Meriç [78]. It can be seen that optimum mechanical properties are obtained at a specific welding speed, beyond which it declines because of poor penetration and other welding defects like froths and pores.

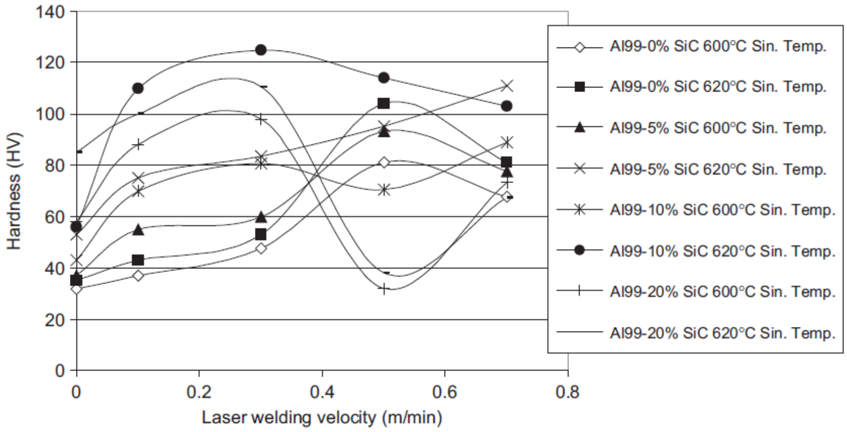

Fig. 6: Melting Metal Hardness Values According to Laser Welding Velocity of Al99-Sic Composites © Hülya Durmuş and Cevdet Meriç [78], Journal of Composite Materials, Vol43, No.13/2009, 1435-1450, Reprinted with Permission.

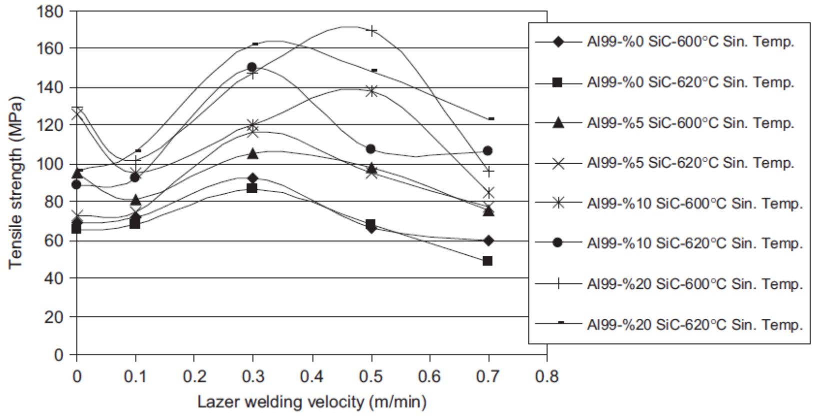

Fig. 7: Tensile Strength Values at Different Laser Welding Velocity of Al99-Sic Composites © Hülya Durmuş and Cevdet Meriç [78], Journal of Composite Materials, Vol43, No.13/2009, 1435-1450, Reprinted with Permission.

Methodology of experimentation is an important tool to achieve optimum process performance. Use of different DOE techniques increases experiment efficiency by reducing the loss of quality and cost of experiment. Though the factorial design (FD) method requires huge experimental run in case of more number of parameters but it is simple and contains all possible combination of experimental runs. FD also allows determining the effect of parameter interactions and optimizing for higher process performance. In RSM, though qualitative variables can’t be optimized, but it is the best method of parameter optimization with reduced number of experimentation without affecting the accuracy of results. Taguchi robust design can optimize qualitative variables when sufficient process data are available for better accuracy. It reduces loss of quality and experiment cost by reducing process variations. Taguchi quality loss function can be used for simultaneous optimization of more than one quality characteristic.

Modelling and simulation is well accepted as a vital engineering tool having potential to revolutionize the engineering science. It is generally cheaper and safer than conducting experiments in the laboratory depicting the real process. They are often more realistic than traditional experiments as they allow the free configuration of environment parameters found in the operational application field. They can be conducted faster than real time. Literature survey shows that few researchers has developed mathematical and simulation model only partially for the laser beam welding process. A robust comprehensive model is yet to be developed.

Through the study of literature it can be seen that Nd: YAG laser beam can be applied to diffusion joining of Al-MMC successfully. Though aluminium and its alloys pose some difficulty due to its highly reflective surface, still Nd: YAG laser can be applied for welding them as it posses shorter wave length and higher frequency which is readily absorbed by high reflectivity materials. Laser, with pulse duration in the range of micro to nanoseconds, are used to weld high thermal conductivity materials to avoid any thermal damage in the microstructure.

We could find from above that TiB_2 has a tremendous potential as reinforcement material. Though some work has been carried out, more study is required in a comprehensive manner to develop suitable post processing technology using DOE technique, statistical analysis and mathematical modelling.

Among new generation of Al alloy MMC such as Al-0.3Sc-0.15Zr-TiB_2 composites reported by Lohar et al. [25], exhibits higher strength, better wear resistance and compatibility between the reinforced phase and the matrix compared with Al matrix composites reinforced with other particulates. Nd: YAG Laser welding of Al-TiB_2 plays a very important role in creating opportunities and applications, but the weld ability of TiB_2-reinforced Al MMCs was rarely reported. Much work is needed to be carried out in this direction.

From the above review following conclusions can be comprehensively made:

1) Identification of three types of parameters has been made;
   i) Important Laser Parameters: Wave Length, Power and Mode of operation
   ii) Important Material parameters : Material type and Sample Thickness
   iii) Important Process Parameters : Welding Speed, Defocusing distance, Repeatation rate,
   iv) Energy, Pulse duration, Pulse shape and type of assist Gas, its pressure and flow rate etc.
2) Most Important Process responses: HAZ, Tensile Strength, Micro hardness, Bead Overlap and
3) Micro Structure
4) DOE and Statistical analysis are vital tools for study of LBW process to optimise process parameters for a good

quality weld. Modelling is found to offer improved insight into the process.

5) Pulsed Nd: YAG can be successfully employed for diffusion joining of Al-MMC.
6) Aluminium alloy with TiB2 reinforcement has tremendous potential for engineering application. But need further research in comprehensive manner.

New Generation Al-0.3Sc-0.15Zr with TiB_2 reinforcements exhibits its superior properties and further studies are required for its secondary post processing, i.e.-Laser Welding.

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