Remote laser welding simulation for aluminium alloy manufacturing using computational fluid dynamics model

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ABSTRACT

The process of remote laser welding is simulated in this study to identify the keyhole-induced porosity generation mechanisms and keyhole. Three processes are simulated and discussed: laser power levels, laser-beam shaping configurations, and laser keyhole process. The simulation finding reveals that pore development is caused by strong melt flow behind the keyhole. As verification, the equivalent experimental test is also carried out. According to the findings, a welding speed with a high level helps to keep the keyholes released and prevents the flow of strong melt; a big advanced leaning-angle also provides inactive molten pool flow, making it difficult for bubbles to float to the backside of the molten pool. The conclusions of this study offer crucial insight into the method of porosity of aluminum (Al) alloys laser welding, as well as advice on how to avoid keyhole-induced porosity. It is also obtained that a smaller laser beam with constant power raises the velocity, welding pool depth, and liquid metal temperature.

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1. INTRODUCTION

Aluminum (Al) joints suffer from joint strength on remote laser-welded with keyhole-induced porosity. Because of its high relative strength and lightweight [1], aluminum (Al) alloys have been widely used in the construction of lightweight structures [2]. Laser welding is perfect to combine materials of high thermal conductivity, such as thin vehicle panels and aluminum alloys as such welding delivers rapid welding speed, high energy density, and slim heat-affected zones [3]. The method also offers large weight decrease opportunities through the ability for joining narrow flange alloys. Generally, laser welding can be divided into two process types: remote ones and conventional ones that are classified according to the beam traveling equipment. The traditional laser welding method, in which welding optics activate in the proximity of the joints without or with a filler wire, depends on the welding optics'mechanical motion to travel the laserbeam over the weldings lane. When the remote process of laser weld finishing occurs in a 700 mm space, the laser beam travels over the welding line by rotating two small galvo-mirrors. Accordingly, the remote laser welding procedure scans at a significantly higher rate than the traditional method [4]. The laser welding technique is contactless and autogenously, and it is often performed in keyhole mode to achieve deep penetration.

Therefore, weld porosity, which is frequently caused by the instability of the keyhole throughout deep penetration, is a significant difficulty in laser welding that works remotely [5]. Welded joints with a lot of porosity have a lot of problems with strength and fatigue [6]. Its asymmetrical design promotes stress concentration and fracture. One of the two forms of porosities involved in Al welding is the porosity caused by keyhole instability. Porosityowestolow-level boilingpoint components in the Al constituents, such as hydrogen and magnesium. If the alloys contain low-boiling elements or the hydrogen level is not controlled, this sort of pore has a perfect spherical shape and is frequently encountered in Al welds. Porosity prevention and mitigation due to lowboiling elements have been widely covered in the textbooks and literature, and will not be discussed here. The creation of irregularly shaped pores in the welding process of the keyholemode has been examined and linked to the dynamics of the keyhole [7]. Several experimental techniques for instance spectral analysis [8], high-speed charge-coupled device (CCD) filming [9], and sound monitoring [10] were presented to investigate the performances of molten pools and keyholes.The study [11] used an X-ray transmission imaging and high-speed optical system to study the mechanism of the keyhole, monitor the keyhole behavior directly, and porosity formations. Their findings examined that bubbles were shaped whilst the keyhole wall trapped and collapsed air inside or shielding gas.

The heat power of a laser beam is transmitted over the workpieces as the laser beam impacts the surface of the workpiece in this machining process. This heat energy melted the material on the workpiece surface and evaporated it. A power supply with a power range of 1.2 to 10 kW is used in laser beam equipment. A power source of high-voltage level is employed to light a flashlight tube, a flash tube or flash lamp is employed for chargingthe electrons of crystal's atoms, and a capacitor is utilized to run a laser beam equipment with pulses. Apumping medium, which is a Ruby crystal is with a number of an atom that absorbsenergy and produces photons at the electrons. The Laser beam machining is shown in Figure 1.

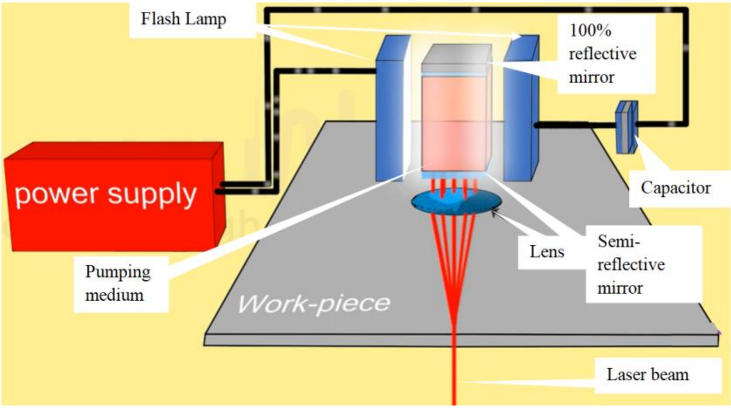

Figure 1. Laser beam machining

The laser beam machine'sadvantages are; i) no direct link between the workpiece and the tool; ii) it can process both non-conductive and conductive materials, iii) it is possible to be focused over an extremely tiny diameter, allowing for the cutting of extremely small diameter holes in the workpiece and improved machine precision; vi) Unlike traditional machining, there is no tool wear; v) complex shapes of various sizes can be machined since the laser can move in any direction, and vii) it produces a very good surface polish. The downsides, on the other hand, are that i) the machining process consumes a lot of energy, ii) the rate of material removal is very low, and iii) the lamp's life expectancy is limited. The metallic vapor jet dynamic pressure on the keyhole front side dented the keyhole back wall, causing this. They analyzed the flow of material in the molten pool encirclement the keyhole to discover the flow of vortex in the molten pool beyond the keyhole by inserting a tungsten particle in the base metal. Previous researchers have addressed the potential to reduce laser welding pressure by increasing the laser energy [12], [13]. Other attempts on welding a stainless steel material by controlling the power laser to about 26 kilowatts attained a reasonable quality welding of 75 millimeter of penetrationdepth with one meter per minute speed single-pass laser beam welding at one kilo Pascal pressure [14], [15]. So to obtain the required level of pressure, andthe evacuated chamber was set up to lower the pressure via three rotating pumps [16], but these methods have a certain limitation on their use of the method in the industry and the size of the workpiece, where the process of the welding time must be increased significantly.

Mohammed [17], Hong and Shin [18] summarize and offer important studies that are categorized according to the technology used for quality inspection (visual, acoustic emissions, camera, eddy current method (ECT), and ultrasonic testing (UT)). Another research looks at real-time laser welding monitoring, which may give a lot of useful information about the welding state and assist identify weld faults and achieving adaptive control [19]. However, these studies only offer results of other research in the laser weld area. Laser keyhole welding [20]–[22], where a mixture of experimental and modeling techniques is used to examine the metal mixing process in laser keyhole welding of incompatible metals. The parametric experimental investigation is being carried out in order to determine the effects of laser power, welding speed, and heat input on metal mixing in the fusion zone. Dissimilar metal mixing in the molten pool, on the other hand, frequently results in the production of harmful intermetallic compounds, which can compromise the performance of dissimilar metal joints. The rebound pressure is discovered to contribute to an upward flow that pulls copper from the bottom of the molten pool to the top. Meanwhile, the Marangoni force creates two side vortices and one backward flow to aid metal mixing. The recoil pressure and the Marangoni stress rise as laser power increases, causing more copper to move higher and combine with aluminum. Increased welding speed shortens the lifespan of the molten pool, reducing metal mixing by the fluid flow. Recently, with the growth of computer knowledge, investigators have been offering mathematical models for simulating laser welding methods in order to learn methods of porosity formation [23], keyhole configuration [24], and melt flow [25]. Courtois *et al*. [26] presented a model of three dimension (3D) keyhole laser welding by means of a level set technique to characterize vapor/liquid and liquid/solid interfaces so as to simulate keyhole free-surface development, with no keyhole fail was accounted for. Miltner *et al*. [27] has studied a sequence of research to expand numerical simulation models of laser keyhole welding, particularly on laser-keyhole interaction and heat source model. Various reflections were applied concurrently with their presented raytracing procedure. Methodologies being presented such as the multiple reflection model and heat source model have been performed into fluid mechanic commercial software (FLOW-3D) to simulate the laser welding process.

In our research, we used FLOW-3D software to model the dynamics of the keyhole process and pore development. The effect of laser power levels, weld speed, laser keyhole process on porosity formation, and laser shaping configurations is investigated in the next sections by employing an analytical process simulation and corroborated by experimental tests. To eliminate the effect of the keyhole depth, the parameters of the welding process are designed in such a way that appropriate and consistent penetration in the overlap joints is ensured for all of the tests. Furthermore, the welding processes are simulated using Flow 3D's laser module, which takes into account multi-reflection and Fresnel absorption of laser beams to replicate remote laser welding. Aluminum 5182 Alloy (UNS A95182) has been taken to examine the mechanism of melt-flow, keyhole dynamics, pore formation, and porosity creation under varying welding processcircumstances are analyzed. In the conclusion section, the findings are summarized.

2. METHOD

Aluminum 5182 Alloy (UNS A95182) was selected for this work because of its well-known commercial susceptibility and its application to welding porosity. The 5182 Alloy composes of 95% Al, 4.5% Mg, and 0.3% Mn element concentrations. On turning the power source, a power with a high-voltage source is applied to the flash tube or flashlight that circulates the pumping area, which is Ruby crystal in this case. When turning the light on, it emits photons with highenergy. The ruby crystal absorbs these photons and converts them into heat. Most of the electrons in the ruby crystals' atoms are stimulated from their ground state at a high energy level as a result of the absorbed energy. When electrons from a high energy level return to the ground state after a brief time, they emit photons, which stimulate the excited electrons to return to their ground state. As they return to their ground state, extra photons are produced, yielding a pair of photons from a single photon. As the concentration of photons grows, the laser is generated, which we term amplification of light utilizing stimulated radiation. A 100% reflecting mirror is used to reflect all photons to the crystal, but a semi-reflective mirror reflects some photons while allowing others to escape, resulting in a high-energy laser beam. The laser beam is then focused onto the workpiece to be machined using a lens. The interaction of the laser and the workpiece generates a lot of heat, which vaporizes the workpiece's surface. Thus, laser beam machining is used in shipbuilding, automobile, aerospace, steel electrical, and medical industries to cut grooves of various shapes or cut the work piece; engraving, welding, surface treatment, cutting, drilling, and it is also used in shipbuilding, automobile, aerospace, steel electrical, and medical industries for precise machining of various parts. The study [28] presents a more straightforward use of vacuum-assisted welding for zinc-coated steel as shown in Figure 2.

A negative pressure zone is created directly on the top of the molten pool during the laser welding process by removal of the laser-induced plasma. The plume further enhances the copper tube installed on top of the welding. A significant increase in the penetration depth up to that is 200 percent as well as a quality improvement compared with the welding under atmospheric pressure. Although this technology requires additional equipment and increases the preparation time, further study in this field would be of great help in improving the laser beam building efficiency. The main giveaway is that the laser beam welding efficiency improvement can be achieved by increasing absorption. There are three basic ways to improve laser beam efficiency; the first is by modifying the workpiece through surface preparation, the second by modifying the process with preheating, and the third by lowering the pressure in the welding zone. Additionally, in thick section laser beam welding at high power levels that are greater than or equal to 10 kilowatts, absorption has a significant dependence on the edge surface roughness. The influence of this roughness level tends to increase with increasing laser power. The use of manufacturing methods that produce edge surfaces or predetermined roughness levels is recommended. Another point is that the plating techniques are preferable not only because of the resulting increase in process efficiency but also because of the reduction in occurrence risk of defects.

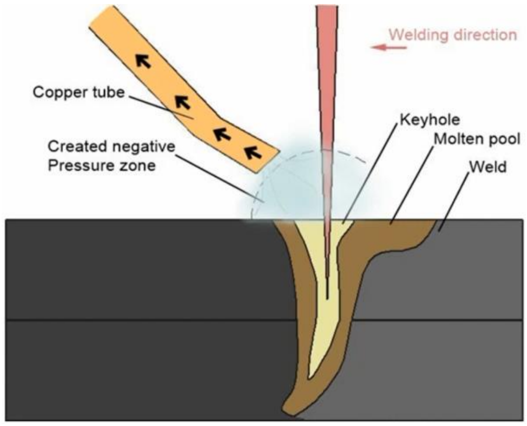

Figure 2. Vacuum-assisted welding for zinc-coated steels

Vacuum-assisted welding provides a significant increase in penetration depth and weld quality. The several described methods may be used together to promote an additional increase in absorption and efficiency. Therefore, the relationships and casualties of these factors require further investigation. Melt-pool modeling for laser welding means looking at defect prediction such as porosity, lack of fusion, surface roughness, and defect mitigation that includes controlling thermal gradients and heat affected zone(HAZ), developing process windows, and exploring process strategies. Therefore, we want to control some thermal gradients in heat-affected zones, we want to be able to develop process windows that increase production while reducing these defects, and then we can also explore strategies in them in this context. So looking at beam shaping, scan strategy, and material properties and how all of that comes together and plays a role in the propagation or lack of the defects. So Industries generally that were using this technology such as automotive in chassis design and build joining. The process control challenges include reducing spatter, heat-affected zones, and residual stress. Using simulation can provide a solution to identify these process parameters that reduce defects and control thermal gradients. The laser-weld simulation can provide time and cost-prohibitive to run many experiments. The simulation can deploy large-scale DOEs with simulation automation and can provide an ability to see process dynamics. Another challenge is the expensive imaging technology for in-situ monitoring that is solved by using high-resolution post-processing to visualize the process dynamics of laser Keyhole welding. An extra physics can be obtained when using simulations like Recoil pressure and upward vapor pressure that propagates from the bottom of the Keyhole. Each heat transfer coefficient (HTC) of the Keyhole can be different due to the presence of the Vapor of the material.

Remote laser-welded Al joints with keyhole-induced porosity have reduced joint strength. The distant processes of laser welding are simulated numerically in this work to disclose the keyhole-induced porosity and keyhole creation mechanism. According to the findings of [29], porosity is formed in three stages: bubble creation, and bubble drifting at the rear of the molten pool to bubble capture by the solidification front. Porosities are possibly be avoided by interfering with any of those three methods. The simulation of the process reveals that pore development is caused by strong melt flow behind the keyhole. It causes keyhole collapse, which results in significant fluctuations in keyhole depth and the production of bubbles. The bubbles are floatedbetween the molten pool towards the keyhole's bottom, whichis caused by the melt flow vortex-type beyond the keyhole. In addition, Al's strong melt flow and high thermal conductivity lead the bubbles impossible to escape. Several porosities prevention techniques are simulated to see how efficient they are in interrupting the three stages. As verification, the relevant experimental test is also carried out. The quantities of porosity predicted by the models match the results of the experimental test quite well. According to the previous findings, the welding process with a high speed can help to prevent strong melt flowand maintain the keyhole open. A wide inclination forward angle can also generate a quiescent molten pool flowing, making it difficult for bubbles to float through the backward molten pool. The study's findings shed light on the mechanism of porosity development throughout the aging process.

3. RESULTS AND DISCUSSION

3.1. Laser welding simulation of five different laser power levels

To explain the significance of accounting power level effects, A total of five different laser power situations were tested. The simulation was set up so that the initial experiment was by applyinga laser power source of an *x* rate on the Al sheet. Next, a power of *2x* is applied, then, power of *2x* value is applied with shield gas, then, a source of *2x* power value is used with recoil pressure and shield gas. Finally, a laser power of *2x* value has been combined with laser reflections, shield gas, and recoil pressure to the simulation. The simulation result at the time 0.1-sec interval is shown in Figure 3.

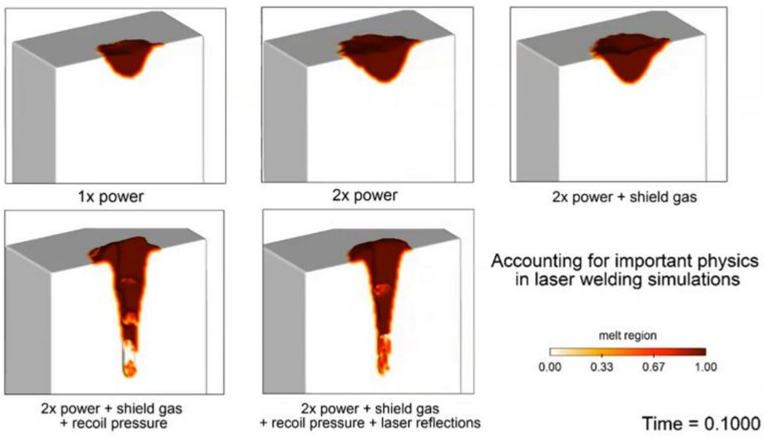

Figure 3. Simulation of five different laser power over 0.1-second intervals

Starting at the top left 1X power, the impact of adding physics models to the simulations reveals a conduction mode riches. The melt pool widens and deepens as the power is increased to 2X. The influence of melt pool dynamics due to shield gas pressure may also be detected. Figure 3 depicts the impact of adding vaporization and recoil pressure. As we can see from the keyhole formation, this results in a completely distinct molten profile. As demonstrated in Figure 3, accounting for laser reflections causes the keyhole formation to spread wider. This illustration demonstrates why accounting for these principles is critical for obtaining a complete picture and knowledge of a welding process.

3.2. Laser shaping

On the multiple dynamics, three alternative multi-core configurations are used to see the effects of beam shaping on laser melting. Figure 4 depicts the results. The configuration on the left with the smallest radius leads the drain bold to be more fading, whilst the right configuration has more stable multiple profiles and flows through the wealth. This allows you to define any arbitrary form with varying degrees of power densities, allowing you to try out different configurations.

3.3. Keyhole laser welding

When the welding process is required with deep penetration, welding in keyhole mode in a remote location is common. Aside from multi-modeling recoil pressure and phase change, there are typically other physics to consider in order to effectively describe the keyhole dynamics itself, which includes vapor pressures that are higher than normal. The keyhole is quick as it senses upwards as the material vaporizes within it, which is possible hasspectacular implications on the flow of 3D welddynamics. It takes into account various coefficients of heat transition that can exist inside the keyhole process, as As illustrated in Figure 5, variations in temperature across the keyhole wall can have a considerable impact on heat transfer from the molten metal to the surrounding body.

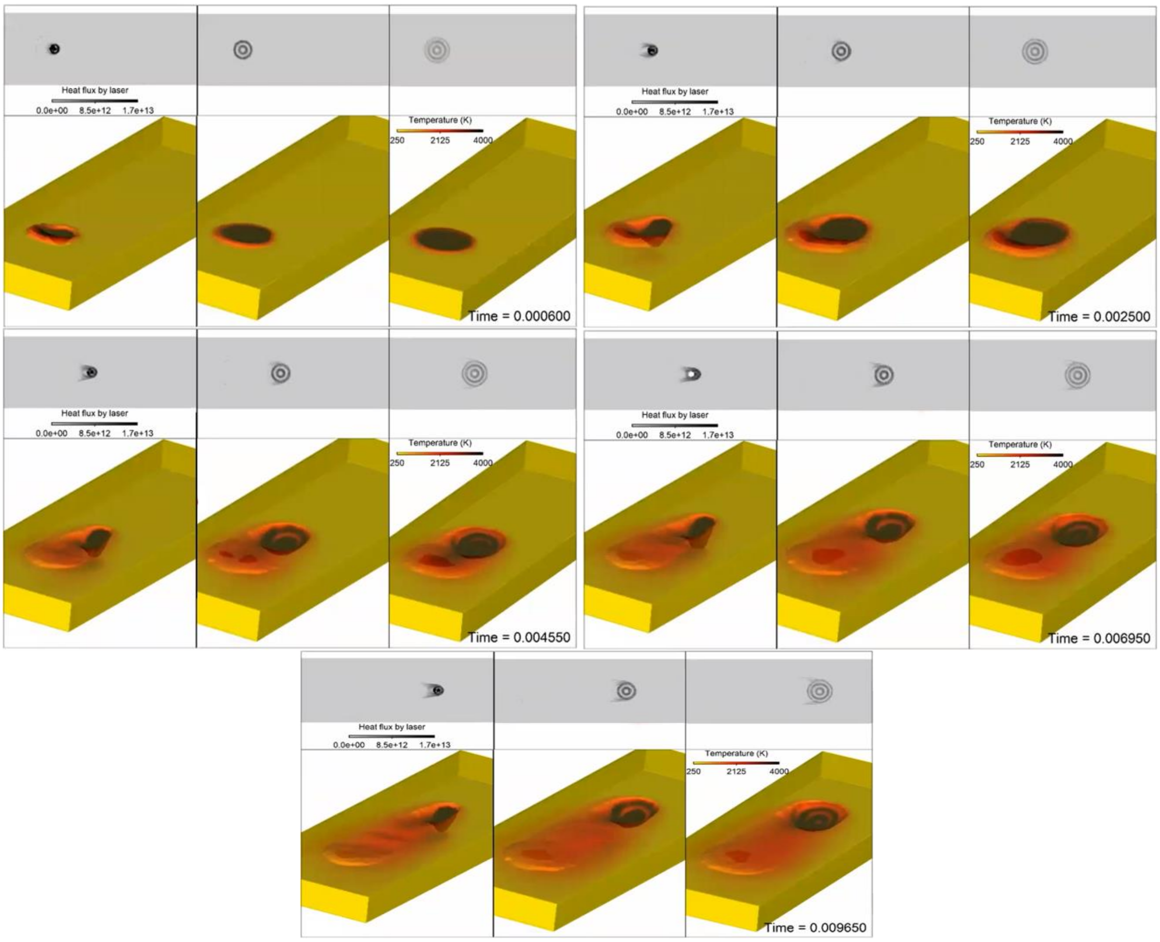

Figure 1. On multiple dynamics, the process of three alternative multi-core setups

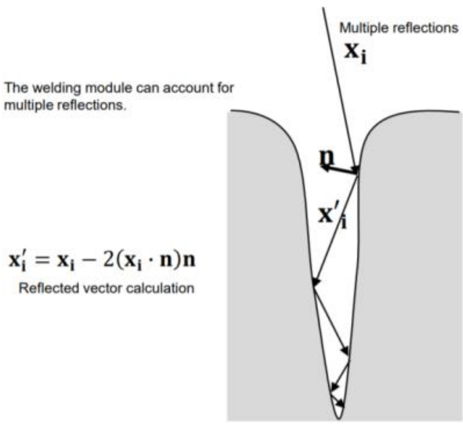

Figure 2. Keyhole laser welding with multiple reflections

The inner wall is irradiated by the laser, which varies depending on the angle. Instead of being totally absorbed, it may reflect further into the keyhole. As a result, heat is retained within the keyboard to a greater extent, which can have a significant impact on its evolution. Therefore, flow through the weld can take into account these laser reflections in three different ways: cosine function, temperature dependency, and so on. As illustrated in Figure 6, this also influences the relation between various material absorption ratesand the parameters of the laser process.

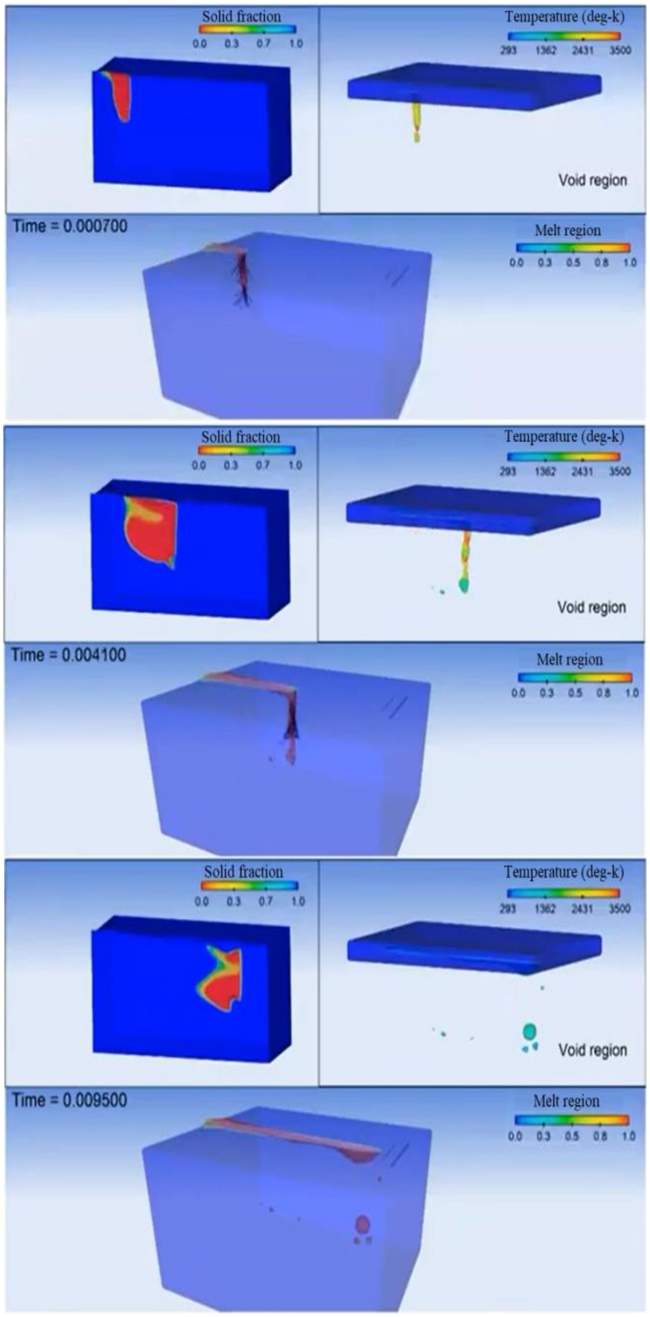

Figure 3. Keyhole laser welding progress over time

On the third panel, we can see how these laser reflections record the present simulation, while theyaverttheregions as expected on the solid fraction and the second panel that is initially captured. These achievements demonstrate that weld bead geometries and solidification patterns may be predicted with reasonable accuracy by utilizing image process techniques. According to these findings, an estimating welding features model of various laser parameters and welding situations has been developed.

4. CONCLUSION

According to the findings, a welding speed with a high level helps to keep the keyholes released and prevents the flow of strong melt; a big advanced leaning-angle also provides inactive molten pool flow, making it difficult for bubbles to float onthe scorching pool's backside. The floating bubbles that transfer from the bottom of the keyhole to the molten pool are caused by the vortex melt-type flows at the back of the keyhole, and the strong melt flow and the high thermal conductivity of the Al produce bubbles impossible to get away. In the study, a variety of porosity avoidance measures are simulated to see how efficient they are at interrupting the three phases. The study's conclusions offer crucial insight into the method of porosity generation throughout Al alloys laser welding, as well as advice on how to avoid keyhole-induced porosity.With a higher level of laser power, both the maximum temperature and the melted metal velocity increase, resulting in larger penetrations. Heat has an effect on laser welding, according to the simulation results. As a result, no melt penetrations occur when the laser spot diameter is larger and the laser power density is lower. A smaller laser beam with constant power raises the velocity,welding pool depth, and liquid metal temperature. As a result of the reduced broader beam diameter and liquid metal velocity, the top temperature is lower. Finally, using the greatest scanning velocity, such as 2 m/s, can boost weld efficiency and procedure productivity.

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