EXAMINING THE EFFECT OF ANGULAR POSITIONING ERRORS ON WELD QUALITY IN MANUAL LASER SPOT WELDING

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Abstract

This study focuses on the experimental evaluation of the effect of angular positioning errors on the quality of micro laser spot welding in stainless (inox) kitchen and hotel equipment applications. Obtaining the correct welding parameters to join thin stainless materials without causing visible defects is an extremely delicate process. The welding process must be precise enough to avoid any visual defects on the visible part of the stainless surface while also ensuring that the connection is strong enough to withstand the life of the device. Experiments conducted in this study reveal that the most common operator error in manual spot welding is angular misalignment between the laser beam and the plate surface. Certain welding parameters, such as laser signal intensity and duration, were kept constant to demonstrate the effect of welding angles. Then, welded samples were prepared with various laser beam angles, and tensile tests were used to measure the maximum loads each weld point could carry. Experiments show that when spot welding is done on thin stainless steel at angles larger than the critical welding angle, heat-induced scars or micro deformations occur on the visible surface of the thin stainless material. In addition, the flow of the lens protective gas is blocked as the outlet opening narrows and the life of the lens is shortened. On the contrary, it is understood that a sufficiently wide weld area cannot be created at angles larger than the critical weld angle. The study uses experimental findings to determine the optimal torch angle range for available laser welding parameters. The results highlight that the laser beam angle must be precisely adjusted within a narrow range in visual micro-laser welding applications, making it difficult for the operator to distinguish by sight.

Keywords: Inox, stainless, steel, sheet metal, micro-laser, welding

1. INTRODUCTION

A common application for joining thin-walled stainless surfaces is high-energy micro-laser welding. This method is preferred because it is not affected by the heat of a narrow area, is characterized by low residual stresses, has a uniform grain structure, provides high efficiency, and has lower operating costs than traditional welding processes. Laser welding offers advantages such as minimal thermal distortion, excellent mechanical properties, and superior repeatability thanks to precise heat control. Technically, micro laser welding applications create a funnel-shaped melting volume from the invisible surface to the visible surface. This method makes visible thin stainless steel less affected by heat. From an economic perspective, this application requires lower laser power, provides less heat input, and is associated with lower equipment investment and operating costs. There are limited studies on laser micro spot welding of stainless-steel alloys. Siva et al. compared simulation with experimental tests for laser micro spot welding of 2.5 mm thick austenitic AISI 304 stainless steel sheets [1]. Cedeno-Viveros et al. experimentally examined the effect of laser power and focal distances in laser micro spot welding on 0.254 mm thick austenitic AISI 302 stainless steel sheets in an overlapping joint configuration [2]. Kumar et al. investigated various aspects of replacing the existing micro-resistance spot welding (micro-RSW) with micro laser spot welding to join Inconel 718 thin foils to a thick 410 steel stack. They concluded the results based on weld quality, mechanical strength, microstructural properties, and high-temperature weld strength. evaluated [3]. Especially for micro-laser spot welding of ultra-thin foils, pulsed laser welding is preferred over continuous wave laser welding. This method offers the ability to reduce the heat-affected zone, residual stresses, and heat input through precise heat control [4]. In micro-welding applications, pulsed laser welding is used in many areas, such as medical device production, thin membrane sensors, welding of markers to stents, micro turbine manufacturing using ultra-thin foils, and so on [5-7]. In general, pulsed laser welding is a process in which high-intensity energy light intermittently focuses on melting and solidifying the material.

Process parameters of pulsed laser welding include factors such as pulse energy/laser power, pulse width, pulse frequency, laser spot size, and welding speed to achieve satisfactory welding quality [8 - 9]. In particular, studies involving the joining of high-temperature resistant materials such as Inconel 600 with stainless steel by micro laser welding method and the welding of tubular components used in nuclear power plants have become popular in recent years [10 - 12]. Ventrella et al. investigated the effect of laser energy in micro laser welding of 100 m thick AISI 316L stainless steel foil. They concluded that microstructural and mechanical reliability can be achieved by precisely controlling the laser pulse energy [4]. On the contrary, Lertora et al. studied CO2 laser lap joints between Inconel 718 sheets from 0.4 mm to 1.6 mm. They reported that despite microcracks, the lap welds comply with the requirements of aircraft engines [13]. High irradiance lasers striking metal surfaces create a complex and dynamic process in which the metal can rapidly change from highly reflective to strongly absorbing. This effect was discussed in an experimental study by Simonds et al. [14].

Manual micro spot laser welding is a welding method in which key variables such as the gap between the surfaces to which sheet materials are joined and the torch holding angle (the angle between the laser beam and the welding surface) are critical to achieve sufficient weld strength without creating heat marks on the visible surface [15]. Although the effects on weld bead geometry are already well understood, visual micro-laser welding details have not been clarified. One of the most common errors during manual spot welding occurs as an error in the alignment between the laser beam and the surface of the workpiece.

In this study, samples with different laser beam angles were prepared to evaluate the effect of the welding angle. The tensile strength of each weld spot has been measured through rigorous testing. Experimental results show that angles exceeding the critical welding angle cause heat-induced scars or micro deformations on the visible surface of the thin material. It has also been observed that forming a sufficiently large weld area on thin stainless sheets becomes increasingly difficult as the weld angle further exceeds the critical threshold. These findings highlight how important precise control of the angle of the laser beam is, even within a narrow range, that operators may have difficulty adjusting visually. An auxiliary device has been developed to fix the manual welding torch and adjust its angular position to measure this effect.

This article highlights the importance of determining welding parameters when joining thin materials. It comprehensively investigates the effect of angular errors on micro-laser spot welding quality. It also discusses strategies that can be used to reduce operator errors and increase the overall efficiency and reliability of the welding process.

2. MATERIALS AND METHOD

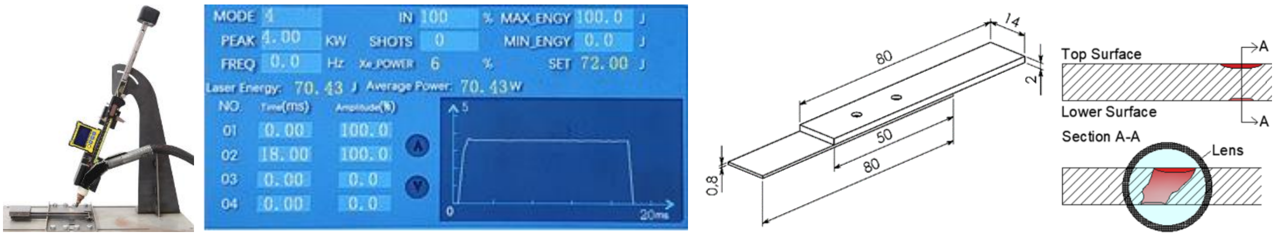
Manual laser welding is a welding technique in which an operator manually controls the laser welding process. Unlike automatic laser welding systems, manual laser welding requires the operator to constantly control the movement of the laser welder and the focusing of the laser beam. This approach has some key features and advantages. One of the notable features of manual laser welding is its flexibility for joining various materials. The ability to weld different materials such as metal, plastic, ceramics, and composites makes it suitable for many industries and applications. The equipment used for manual laser welding can be designed to be portable, making it possible to use it in a variety of locations and field applications. This flexibility is extremely valuable, especially in field welding or repair work situations. The results of manual laser welding depend on the experience and skill of the operator.

The operator's ability to accurately set welding parameters and effectively control the weld zone is critical to obtaining high-quality welds with the desired properties. Therefore, the operator's skill and experience play a big role in successfully implementing manual laser welding. In this application, while creating a sufficient welding area using a very short-term heat increase on the non-visible surface of the combined 304 series stainless thin steel sheets, welding is expected to be done with precision that will not create a heat mark on the visible front surface. 304 series stainless steel sheets are widely preferred materials in the production of industrial kitchen equipment due to their aesthetic appearance, corrosion resistance, and anti-fingerprint properties.

Welding test samples were prepared by joining together 304 series stainless steel sheets (Guangdong Yongjin Metal Technology Co., Ltd. Test Certificate, Certificate No: Yj2021122336, Review Date: 2021/12/17) with a 2 mm and 0.8 mm thickness. A hand-held welding torch (Turcweld LP300 series) and an auxiliary device have been developed to fix the manual welding torch and adjust its angular position to measure this effect (**Figure 1. a**). This joining process was carried out using the laser signal and parameters shown in **Figure 1. b** from two points to each other, as shown in **Figure 1. c.** The dimensions of each assembled sample are 80 mm long and 14 mm wide. After welding, the length of the assembled specimens to be subjected to tensile testing is 110 mm. To ensure gap-free contact between the weld surfaces of the two sheets, each weld sample was welded with the same pressure force. To measure the weld strength of overlap weld samples, the samples were subjected to tensile testing using a specially produced micro tensile device with 0.4 N precision at Bursa Uludağ University Laboratories. The weld's joints were broken under shear stress. The head speed was set at 10 mm/min during the test, and the tensile-shear force was slowly increased until the sample broke.

The main motivation of this study is to determine the required welding angle and develop appropriate visual welding processes in order to weld stainless materials so precisely that they do not create visual defects and, at the same time to meet the loads that may arise over time under working conditions throughout their working life. In manual micro-point laser welding, the gap between the mating surfaces of the sheet materials and the torch holding angle (the angle between the laser beam and the welding surface) are among the most important variables to obtain sufficient welding strength without creating a heat mark on the visible surface. The absence of weld marks on the visible surface is a basic requirement of laser welding, but joint strength is often the critical quality criterion. For this reason, factors such as whether heat traces were formed on the visible surfaces of the test samples and the size of the weld section were examined in detail under the microscope. These examinations provide important data for determining the correct welding angle and other parameters and ultimately contribute to obtaining high-quality welds. After the tensile test, a special process was applied to analyze the weld sections on 2 mm thick stainless-steel plates. Here are the steps of this process: First, the entry and exit points of the welded plate were examined meticulously. This step is intended to detect potential defects or irregularities resulting from the welding process. Then, a smooth surface polishing process was applied to the cut surfaces. This process aimed to eliminate surface irregularities, defects, and contaminants. In this way, a refined and smooth appearance is achieved. The microstructural properties of the welds were observed and analyzed in detail using a microscope. This inspection allowed us to examine the intricate details of the welds, check structural integrity, and obtain valuable information about the quality of the welds. Aiming to unravel the complex relationship between welding process parameters and welding results, this rigorous analysis approach aimed to provide further improvements and optimizations in weld quality and performance.

The regions with the highest weld penetration were determined by cutting from the middle of the sections, as shown in **Figure 1. d**. These sections were then smoothed and polished using various abrasives, then examined under a microscope, and their images were recorded. As a result, with these steps, the examination and analysis of the quality and welding results of laser welding on stainless steel sheets have been completed.



(a) (b) (c) (d)

Figure 1 a.) Hand-held welding torch (Turcweld LP300 series) and auxiliary device developed for precise angular and linear positioning of the manual welding torch. b.) Laser welding parameters and signal form. c.) Dimensions of test specimens and welding of 2 mm and 0.8 mm 304 series stainless steel test specimens from two points, d.) Cross-section of the 2 mm thick upper sheet's weld melting zone.

3. RESULTS

While test samples are being prepared for different torch-holding angles, the torch-holding angle is measured from the normal to the welding surface. At holding angles very close to "0" degrees, there is a risk of damage to the lens as the outlet port of the welding torch will be completely blocked, and the gas flow protecting the lens will be blocked. For this reason, the tests were carried out in 5-degree increments, starting from 15 degrees, leaving a margin of safety. At angles greater than 60 degrees, penetration and welding could not be achieved in any sample, as the welding melt volume could not exceed the upper sheet metal. In the tests, the 15° angle, where no heat marks or blisters appear on the visible surface and where the welding strength is highest, which does not pose a risk to the lens, is the angular position with the maximum welding load. The division of the force carried by the weld from 15° to 60° by the maximum force at 15° will be called normalized weld load.

Figure 2 shows microstructure photographs obtained by metallurgical cutting and etching method at the welding point of the 2 mm thick top sheet (Nikon Eclipse MA100, Nikon Instruments Inc., Melville, NY, USA). Considering the positional changes of the welding surface with the torch, it is understood from the welding section's microscope images that the melting zone's angular position changes accordingly.

Figure 3 shows the variation of the normalized welding load carried by a single point welding with the torch holding angle for different torch angles. With the current laser signal parameters, a welding load of approximately 300 N is achieved at 15°. The chart shows suitable and unsuitable torch angles for welding with different colors and explanations. Angles greater than 60 degrees, where the torch is too horizontal to create a weld, are outside the graphic area. The 15°-25° ranges are the torch angular positions that do not create visible marks and have the highest welding resistance. It is considered that these ranges are the most appropriate angular position for the current laser signal parameters.

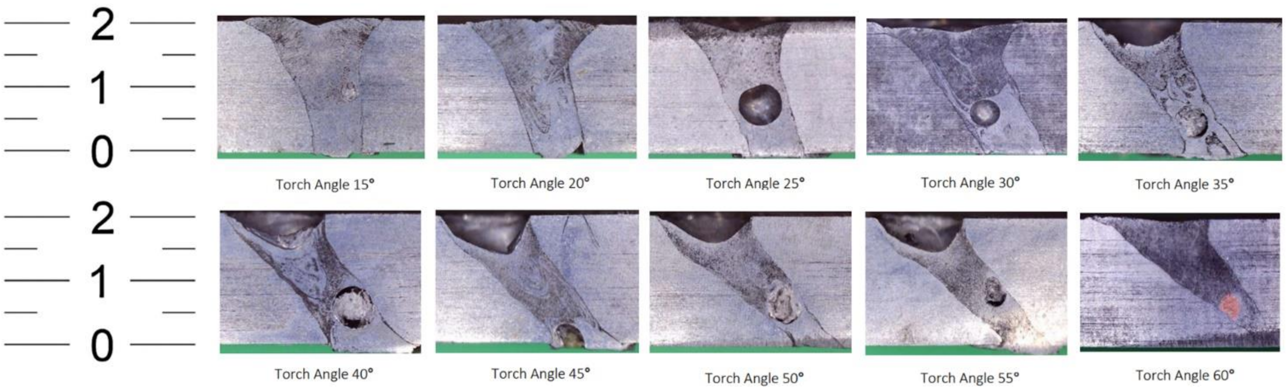


Figure 2 Cross-sectional images of the weld melt volume of the 2 mm thick upper sheet.

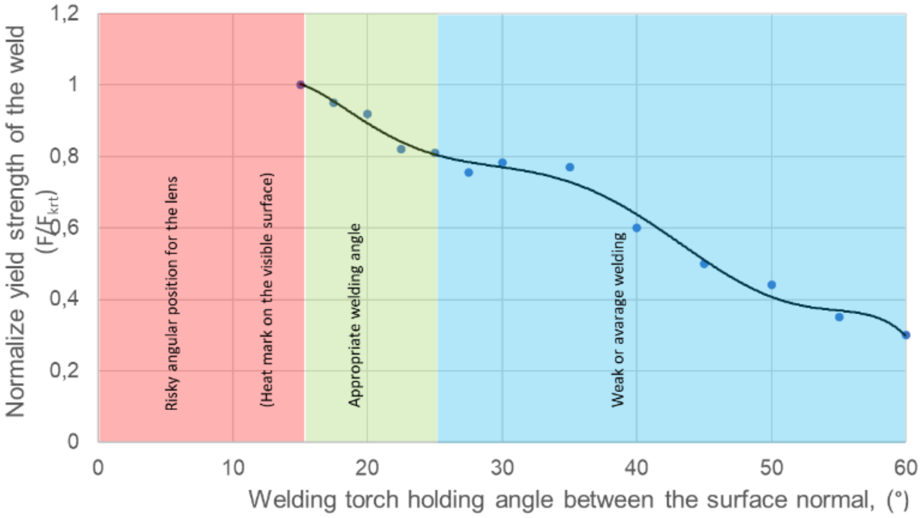


Figure 3 Normalized yield strength of the weld versus laser torch holding angle.

4. CONCLUSION

In industrial areas with a small number and different types of products and customer-oriented design and production, the manual welding method can be seen as more efficient than the robotic welding method in terms of cost and speed. This is especially true when products change frequently, where constant revision and reprogramming of the robotic welding line can slow down production processes and increase costs. Although standard parameters have been established for the laser welding process, factors such as plate spacing, the angle at which the laser light hits the surface, surface blemishes, and reflection rate can affect the weld quality. One of the most important factors for the operator in visual micro laser welding applications is the holding angle of the welding torch. It may be difficult to adjust the angle of the laser beam and the welding surface in the operator's eye, especially in narrow areas with complex geometry and different surface angles. This can lead to the production process becoming uncontrolled. Manufacturers are, therefore, forced to strike an economic balance between the overhaul cost of robotic welding lines and the scrap product costs caused by manual micro-welding. When production quantity is low, the manual welding method is generally preferred.

This study focused on the operator's welding torch holding angle to reduce visual errors in manual welding. It examined the effect of the operator's angular error on welding quality and visual errors. The steeper the angle between the welding torch and the weld surface, the shorter the weld path, reducing energy losses and increasing weld penetration. Additionally, the final product must be aesthetically pleasing, considering the quality and thickness of the material used. Excessive penetration can lead to heat marks on the surface of the thin sheet. For this reason, maximum welding power may not provide optimum quality, especially for inox materials. The study shows that the effect of angular position on weld quality is as important as power, frequency, and other parameters. The appropriate torch angle range is determined not to cause visual artifacts and ensure the highest weld quality for specific laser power and signal parameters. In the future, hand torch angle sensors and support systems may be used to help the operator keep the laser angle within the appropriate range. This minimizes human errors in manual micro laser welding applications, allowing faster and higher quality products to be produced in various applications, such as the industrial kitchen, food, and healthcare industries. The findings obtained, together with microscopic examinations, clearly show the effect of torch holding angle on weld penetration and weld geometry. A steeper torch hold angle results in a wider and deeper weld penetration, while a larger torch hold angle results in a narrower and shallower penetration. In manual laser welding devices, parameters such as laser power, frequency, pulse duration, and laser beam diameter may change in the long term but can be fixed in the short term. The results of this study provide critical information to optimize weld quality and achieve the desired results in manual laser spot welding applications. This study can be an important resource for improving welding procedures, increasing welding quality, and obtaining the desired results in micro-laser spot welding applications. As a result, this study aims to improve current welding practices and can be a reference source for future laser spot welding projects and applications. Manual laser spot welding applications are often used in special and critical applications such as joining precision workpieces or welding thin metal sheets. Therefore, knowledge in this field is important to industry professionals and engineers. This work may help manage welding processes more effectively and improve results in such applications.

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