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Overview and the transformative role of automation and robotics in welding amidst industry 4.0 and additive manufacturing.

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Abstract - *This paper explores the integration of automation and robotics in welding within the context of industry 4.0 and additive manufacturing. It begins with an overview of welding techniques and their evolution. Key topics include the technological advances in welding automation, the challenges and advantages of implementing industry 4.0, and the impact of base materials on weld quality. The paper also discusses best practices for welding dissimilar materials, welding in extreme conditions, and the role of welding in additive manufacturing. The study highlights future trends and concludes with the broader implications of these advancements for the industry.*

Key Words: Welding techniques, automated welding, welding in industry 4.0, smart welding, future trends in welding, robotics in welding.

1. INTRODUCTION

Welding is an essential process across various sectors, particularly in manufacturing and construction industries, where it is primarily used for assembly purposes. It involves creating a permanent bond between two material surfaces by altering specific physical and chemical properties. The techniques and technologies involved in welding are continuously evolving to meet rigorous international safety and precision standards. Additionally, new applications with extreme conditions or unique material limitations necessitate the development and adoption of diverse welding methods.

The advancements in welding are also being driven by the demands of industry 4.0 and additive manufacturing, both of which heavily rely on automation and robotics. Industry 4.0 aims to create smart factories with interconnected systems, where welding processes are integrated into automated production lines to enhance efficiency, consistency and quality. Additive manufacturing, which includes 3D printing, requires precise welding techniques to build complex structures layer by layer, often involving materials that present unique challenges. The continuous innovation in welding technologies includes the development of advanced welding robots, laser welding, friction stir welding, and hybrid welding methods. These innovations ensure that welding can be adapted to various applications, from constructing skyscrapers and bridges to assembling intricate components in the aerospace and automotive industries. Moreover, the focus on sustainability and environmental impact has led to the exploitation of eco-friendly welding techniques that minimize energy consumption and reduce emissions. Research and development efforts are directed towards improving the efficiency and effectiveness of welding processes, making them more suitable for a wide range of materials and conditions.

In this report, we will delve into these points in greater detail, exploring the evolution of welding technologies, the impact of industry 4.0 and additive manufacturing, and the future trends that will shape the welding industry. We will also examine practical examples to illustrate how welding continues to be a cornerstone of modern industrial practices.

2. OVERVIEW OF WELDING,

2.1 History of welding,

Welding has evolved significantly over the centuries, shaping and being shaped by technological advancements and industrial demands. The journey from primitive methods to modern techniques highlights a remarkable progression driven by the necessity to join materials with strength and durability. Only methods involved rudimentary forms of forge welding, when metals were heated in a fire and hammered together, a technique predominantly used for blacksmiths for centuries [4]. The advent of the industrial revolution marked a pivotal point in welding development. As industries grew and infrastructure demands soared, more sophisticated methods were required, the late 19th and the early 20th century witnessed significant breakthroughs with penetration of gas welding and electric arc welding [5]. These innovations provided more control and precision, enabling the joining of metals for a wide range of industrial applications.

World War I and World War II further accelerated welding advancements. The need for robust and reliable welding shipbuilding, aircraft manufacturing, and weaponry spurred rapid development in welding techniques and technologies [6]. During this period, arc welding became more refined, and new methods such as resistance welding emerged, offering improved efficiency and strength for critical applications [7]. Post war industrial expansion saw the introduction of more sophisticated welding processes, including tungsten inert gas (TIG) welding and metal inert gas (MIG) welding. These methods allowed for higher precision and control, catering to the growing complexity of industrial manufacturing. The latter half of the 20th century also saw the rise of automation in welding integration robotics and computer control systems to enhance productivity and consistency [8].

In recent decades, the integration of welding with advanced technologies such as laser welding and friction stir welding has opened new frontiers. These methods offer unparalleled precision and strength, essential for modern applications in aerospace, automotive, and electronics industries [9]. The ongoing evolution of welding techniques continuous to be driven by the demand for lighter, stronger, and more durable materials, reflecting the dynamic interplay between innovation and industrial needs. Welding's journey from ancient forge methods to contemporary high-tech processes underscores its critical role in industrial and technological progress. Each era of advancement builds upon the previous, continually refining and expanding the capabilities of this essential practice.

2.2 Types of welding,

Welding techniques can be broadly divided into fusion welding and pressure welding, based on the type of coalescence established between substrates [10]. The six major welding techniques widely employed in industries include Gas Tungsten Arc Welding, Gas Metal Arc Welding, Shielded Metal Arc Welding, Friction Stir Welding, Electron Beam Welding, and Laser Beam Welding [11].

Gas Tungsten Arc Welding (GTAW) is recognized for its consistent weld quality, arc stability, controllable operating power, minimal workpiece damage (weld can be done without overheating the workpiece), and economic viability [12]. However, it has drawbacks such as low weld penetration (molten weld pool does not extend deeply into the base material, consequentially the welded joint may have a thinner cross section at the fusion zone), long setup times, and unpredictable behavior under electromagnetic influence. Optimal weld parameters can significantly improve the output without compromising on weld properties. Factors like weld speed, current, gas flow rate, and penetration majorly influence tensile properties. Activating fluxes made of various oxides and halide compounds in GTAW greatly improve weld penetration [13].

GTAW welded alloys are affected by issues as cleavage and pit corrosion at the weld zone. When GTA welded, Nickel-copper (Ni-Cu) alloy exhibits high impact strength, high temperature corrosion resistance, strong ductility, and high fatigue strength, enhancing mechanical and metallurgical qualities in high-pressure corrosive applications. Dissimilar welds have shown superior mechanical properties compared to similar welds [14]. Below is an image depicting gas tungsten arc welding,

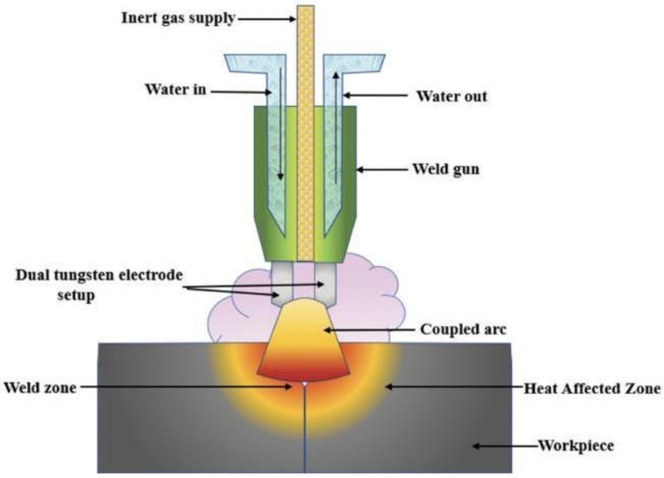

Fig -1: A image showing twin tungsten inert gas welding [15].

Gas Metal Arc Welding (GMAW) is renowned for its functional adaptability and ability to weld thick materials while maintaining high productivity, even when automated. This welding method achieves weld stability through meticulous control of various parameters, including Weld current, voltage, torch angle, wire feed speed, and electrode extension length [12,16]. The process typically produces a fine crystal, directionally solidified microstructure, which, while beneficial for mechanical properties, may exhibit porosity defects that can be mitigated by adjusting the weld Travel speed [17]. Alternating current GMAW is particularly useful for applications involving thin sheet metal welding or thick plate welding where strict control over burn through is required. AC-GMAW offers better control over arc stability, penetration depth, reinforcement height, and why are melting coefficient. This method allows for alteration in the welding current waveform to provide comprehensive control overheat input [18]. The continuous change in polarity ensures proper distribution of input energy, with the base current being appropriately modulated to optimize welding conditions. Below is an image representing gas metal arc welding,

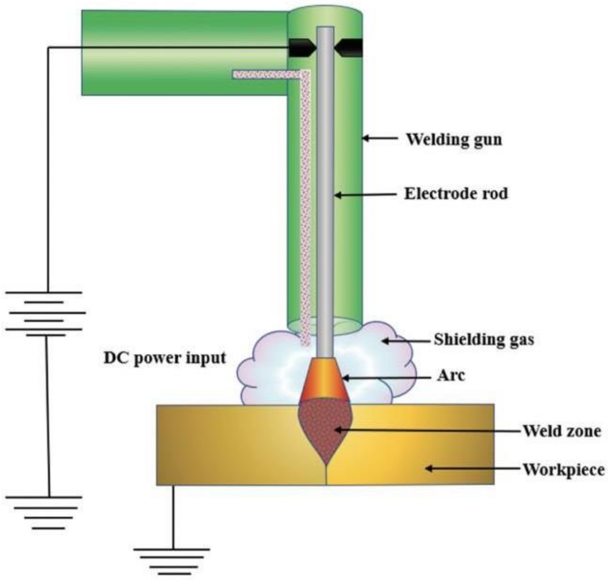

Fig -2: A image depicting gas metal arc welding [19].

Shielded metal arc welding (SMAW) characteristics are influenced by weld speed, current, voltage, and external magnetic field. Alloys like super austenitic stainless steel, alloyed with molybdenum, showcase high corrosion resistance and strength, making them suitable for nuclear, chemical, and petrochemical industries. Preheating the alloy can improve the weldment hardness and penetration depth while reducing the heat input. Residual stresses are crucial in determining the load-bearing capabilities of the welded joint, and heat treatment can enhance the weld bead microstructure [20].

Friction Stir Welding (FSW) is a solid-state welding technique that employs a rotating tool tip traversing along the interface to achieve coalescence between similar or dissimilar metals. This process induces mixing of the base materials at the interface, effectively minimizing the chances of element segregation and enhancing resistance to stress corrosion cracking, distortions, and residual stresses [21]. The heat generated during FSW is just sufficient to cause mixing at the interface without melting the base materials, thus maintaining the integrity of the joint and reducing waste generation. The process allows for close control of parameters, high repeatability, and minimal heat input, leading to a more efficient and environmentally friendly welding process [22]. the welding process in FSW is governed by three independent parameters, feed rate, tool rotational speed, and axial force. An increase in weld pitch, which is the ratio of tool rotation speed to feed rate, leads to higher heat input, promoting grain recrystallization and resulting in finer equiaxed grains in the nugget region. Additionally, the axial force under a constant weld pitch directly influences the quality of the weld by affecting the hydrostatic pressure exerted by the weld shoulder, which is essential for inducing the required plastic deformation and frictional force for effective stirring [23]. Below is an image representing friction stir welding,

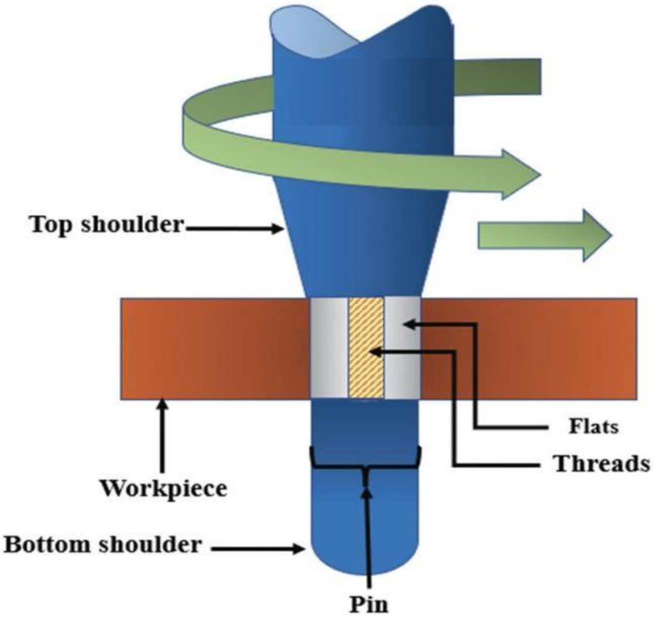

Fig -3: A image representing friction stir welding [24].

Electron Beam Welding employs a highly concentrated electron stream as the beam source, leading to rapid metallurgical reactions. Consequentially, weld characteristics such a mechanical properties and microstructure are significantly influenced by parameters like focus current and heat input [25]. An increase in energy density, managed by the focus current flow, enhances weld penetration. Additionally, the weld width varies with degree of beam focus on the top surface, generally widening as heat input rises. Heat input variations also affect grain size, with higher heat input promoting grain growth. The ratio of temperature gradient to crystallization speed plays a crucial role in microstructure development (a lower ratio transforms cellular dendritic grains into equiaxed dendrites) [26]. In dissimilar welds, particularly with Titanium alloys, the fusion zone exhibits maximum microhardness due to brittle phase formation. Fracture tests indicate these welds typically fail at the fusion zone, showing lower tensile strength compared to the base material [27]. For metals prone to oxidation, vacuum electron beam welding prevents exposure to oxidizing environments, minimizing heat input and accelerating cooling to reduce precipitation formation and enhance weld properties [28]. Below is an image representing the setup of electron beam welding,

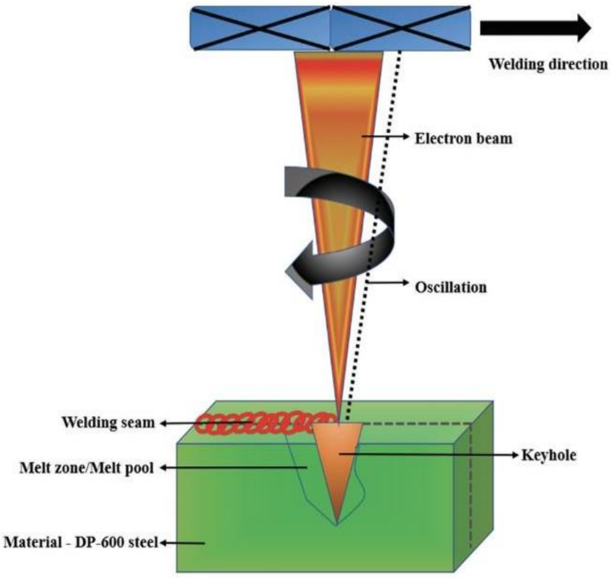

Fig -4: A image representing electron beam welding [29].

Laser Beam Welding (LBW) is a versatile welding technique known for its unique ability to manipulate heat input distribution, making it particularly well-suited for welding dissimilar metals and alloys. The methods characteristic low heat input results in a narrow HAZ, ensuring a smaller weld bead with minimal distortions. Additionally, LBW can be easily automated, enabling the welding of complex geometries while maintaining close tolerances [30]. The process is meticulously controlled through several parameters, including laser beam power, welding speed, the position of the focal point, and focal distance. By increasing the welding current and plasma gas flow rates, deep penetration into the workpiece can be achieved. The strength of the weld is directly correlated with an increase in laser beam power and focal length of the weld bead [31]. The resulting weld typically exhibits an asymmetric profile due to the differential heat response of each metal on either side of the weld. The microstructure of the weld is mainly influenced by the primary metal's microstructure and the thermal cycle during the heat input, which varies with the beam offset [32]. Below is an image representing the setup of laser beam welding,

3. AUTOMATION AND ROBOTICS IN WELDING,

Automation and robotics have become transformative agents in welding processes, elevating precision, speed, and safety to unprecedented levels. The integration of these technologies not only streamlines manufacturing but also addresses challenges associated with human limitations. One key aspect of this integration lies in the development of robotic welding systems, which bring a host of benefits to the welding industry. These robots usually feature a versatile three-dimensional arm designed to intricately weld metals. Integrated with a wire feeder, this robotic marvel utilizes a high-heat torch at its extremity, melting metals seamlessly during the welding process. A feeder attached to the arm facilitates a continuous supply of additional metal wire from the feeder, and arc shields efficiently prevent the high-heat arc from mingling with oxygen [34]. The images below depict welding robots used in today's industry. Images of the spot-welding robot, laser welding robot, plasma welding robot and arc welding robot is presented in the next page (page 5).

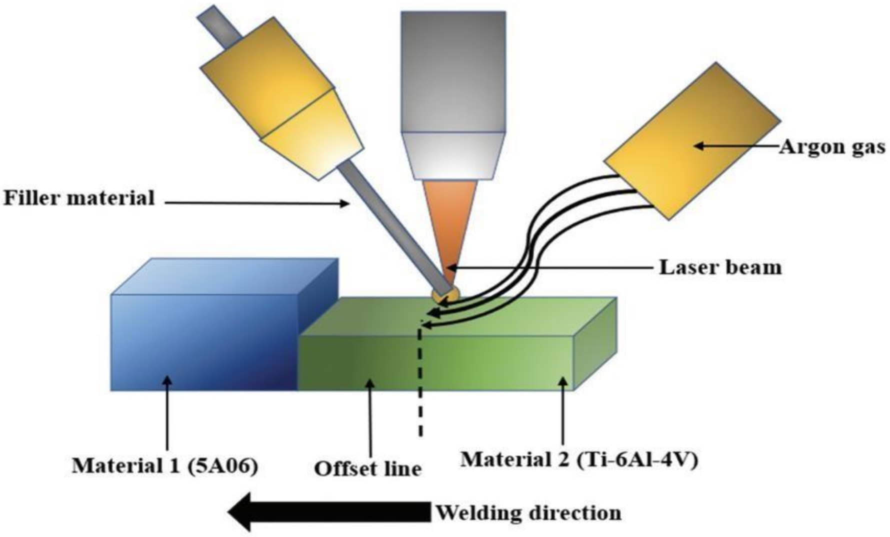

Fig -5: A image depicting laser beam welding [33].

Fig -6: spot welding robot on the left [35] and arc welding robot on the right [36]

Fig -7: laser welding robot on the left [37] and plasma welding robot on the right [38].

Precision, a hallmark of successful welding, is significantly enhanced through robotic systems. These machines operate with meticulous accuracy, consistently reproducing welds with minimal variation. Unlike their human counterparts, robots do not yield to fatigue or distractions, ensuring continuous and high-level precision throughout the welding process. Advanced robotic welding arms, equipped with sensors and vision systems, can adapt to variations in materials and joint geometries, further refining the precision of welds [39]. This level of consistency not only improves the overall quality of welded products but also reduces material waste, a critical consideration in cost-effective manufacturing. The integration of automation and robotics brings a paradigm shift in the speed of welding processes. Robots operate at a pace that far exceeds human capabilities, resulting in accelerated production cycles. This increased speed is not only advantageous in meeting demanding production schedules but also in enhancing efficiency and output. Welding robots, guided by sophisticated algorithms and real-time data, can dynamically adjust their speed and movements, optimizing the welding process for maximum efficiency without compromising precision. This acceleration in welding speed contributes to a significant reduction in overall production time, enabling manufacturers to respond swiftly to market demands [40]. Safety is paramount in welding, and automation plays a pivotal role in minimizing risks associated with this inherently hazardous task. Robots are impervious to the environmental factors that can pose threats to human welders, such as extreme heat, fumes, and confined spaces. By replacing or augmenting human workers with robotic systems, particularly in hazardous environments, the potential for accidents and injuries is greatly reduced [41]. Additionally, robotic welding systems are equipped with advanced safety features, including sensors that can detect the presence of humans or obstacles in the workspace, prompting the robot to slow down or halt operations to prevent collisions [42].

Advancing the integration of automation in welding may introduce mind-controlled welding robots, where operators can guide the robot's actions through mental commands instead of relying on a computer interface [43]. Collaborative robots might undertake expensive operations, and artificial vision systems, powered by predictive control algorithms, could model parameters [44]. Intelligent robotic welding, utilizing vision sensors, would analyze characteristics and applications in the welding process. This facilitates remote monitoring and control, enabling operators to oversee operations from a secure distance [45]. This not only protects human workers from potential harm but also ensures continuous monitoring of welding quality, properly addressing any deviations from specifications.

4. CHALLENGES OF IMPLEMENTING INDUSTRY 4.0 IN WELDING,

Implementing industry 4.0 technologies in welding, while promising transformative benefits, poses several challenges. One significant hurdle is the integration of existing systems with advanced technologies. Many welding operations rely on traditional machinery that lacks the necessary connectivity for seamless interaction with smart devices and data analytics [46]. Retrofitting this system can be costly and complex. For example, a welding robot that once operated independently is now revamped to communicate its progress. Retrofitting in this case not only incurs costs for new hardware and software but also demands for expertise.

Another challenge lies in the cybersecurity realm. The increased connectivity inherent in Industry 4.0 introduces a higher susceptibility to cyber threats [47]. Safeguarding sensitive data and ensuring the resilience of networked systems become critical considerations. Comprehensive cybersecurity measures must be implemented to protect against potential breaches and ensure the integrity of the welding processes. Interoperability issues emerge as another significant challenge. Integrating diverse welding machines, sensors and data analytics tools from different manufacturers can be complex, as standardization across the industry remains a work in progress [48]. This lack of standardized communication protocols hampers seamless connectivity and data exchange, limiting the full potential of Industry 4.0 in welding environments.

Lastly, the transformational shift also demands a skilled workforce capable of operating and maintaining these advanced systems. Upskilling and retraining programs become imperative to bridge the gap between traditional welding practices and the demands of a digitally driven industry [49]. Overcoming these challenges requires a collaborative effort from industry stakeholders, policymakers, and educational institutions to foster a conducive environment for the successful integration of industry 4.0 technologies in welding.

5. ADVANTAGES OF IMPLEMENTING INDUSTRY 4.0 IN WELDING,

Implanting industry 4.0 technologies in welding heralds a new era of efficiency, precision, and adaptability in manufacturing. One of the primary advantages is enhanced automation, where smart welding systems equipped with sensors and connectivity seamlessly communicate and adapt to changing conditions. This not only boosts productivity but also ensures consistency, and high-quality welds, reducing the likelihood of defects. Industry 4.0 technologies bring about real-time monitoring and data analytics capabilities, allowing for proactive maintenance and optimization of welding processes. Predictive analytics can predict equipment failures, minimizing downtimes and reducing overall maintenance costs [50]. Additionally, the integration of data-driven insights enables manufacturers to make informed decisions, optimize welding parameters, and streamline production workflows. Connectivity facilitates remote monitoring and control, enabling off-site supervision of welding operations. This not only improves the safety of the work environment by reducing human exposure to hazardous conditions but also allows for quick response to deviations from specifications. Collaborative robots, another facet of Industry 4.0, can work alongside human operators, augmenting efficiency and handling labor-intensive tasks, while also ensuring a safer workplace [51]. Furthermore, the implementation of Industry 4.0 in welding fosters greater customization and flexibility. Smart systems can quickly adapt to changes in product specifications, making it easier to accommodate varying customer demands [52]. Overall, the advantages of Industry 4.0 technologies in welding contribute to a more agile, efficient, and responsive manufacturing ecosystem.

6. INTEGRATION OF AUTOMATION AND INDUSTRY 4.0,

The integration of automation and industry 4.0 has revolutionized modern manufacturing processes, including welding. Automation involves the use of machinery and technology to perform tasks without human intervention, enhancing efficiency, precision, and safety. Industry 4.0, also known as the fourth industrial revolution, builds on this by incorporating advanced technologies such as the internet of things (Iot), artificial intelligence (AI), and data analysis to create smart, interconnected systems [53]. Together, these advancements are transforming traditional welding techniques into highly sophisticated, automated processes that can meet the demands of contemporary industrial applications.

6.1 Complementary role of automation and industry 4.0 in welding,

Automation and industry 4.0 complement each other in welding by enhancing the precision, efficiency, and flexibility of welding processes. Automation streamlines welding operations through robotic welders that can perform repetitive tasks with high accuracy. Reducing human error and increasing production rates. These robotic systems are capable of handling complex geometries and maintaining consistent quality, making them ideal for mass production [54]. Industry 4.0 takes automation a step further by integrating smart technologies into welding operations. Iot devices can collect real time data from welding machines, sensors, and the work environment, providing valuable insights into process parameters such as temperature, weld speed, and material properties. This data is analyzed using AI algorithms to optimize welding parameters and identify potential defects before they occur [55]. The result is a more efficient and adaptive welding process that can respond to changing conditions and demands.

Additionally, the digital twin concept, a kay aspect of industry 4.0, allows for the creation of a virtual model of the welding process. this digital representation can be used for simulation, monitoring, and optimization, ensuring that the physical welding operation runs smoothly and efficiently [56]. By leveraging these advanced technologies, welding processes become more reliable and cost effective, meeting the high standards required in industries such as aerospace, automotive, and construction.

6.2 Role of IoT and real time monitoring in welding,

Real time monitoring, facilitated by IoT, plays a transformative role in modern welding processes, bringing unprecedented levels of precision, efficiency, and quality control. Iot devices, embedded with sensors and connected to the internet, enable continuous collection and transmission of data during welding operations. This data-driven approach allows for real-time monitoring of various parameters critical to the welding process, such as temperature, weld speed, arc stability, and material properties. One of the primary benefits of real time monitoring in welding is the ability to maintain consistent weld quality [57]. Sensors can detect deviations from optimal welding conditions immediately, triggering corrective actions to prevent defects. For instance, if the temperature falls outside the desired range, adjustments can be made instantly to bring it back to the optimal level. This immediate response reduces the occurrence of weld flaws, such as cracks or porosity, ensuring higher integrity and strength of the welds.

Additionally, real-time monitoring enhances predictive maintenance capabilities. They're continuously analyzing data from welding equipment, IoT systems can identify signs of wear or potential failures before they lead to breakdowns [58]. This proactive maintenance approach minimizes downtime and extends the lifespan of welding machinery, thereby reducing operational costs and increasing productivity. IoT-enabled real-time monitoring also facilitates better process optimization. By analyzing historical and real-time data, manufacturers can fine tune welding parameters to achieve optimal performance. This optimization can lead to faster weld times, reduced material waste, and improved energy efficiency. Furthermore, the ability to remotely monitor and control welding operations allows for greater flexibility and responsiveness, especially in large scale manufacturing environments.

7. EFFECT OF BASE MATERIALS AND THEIR QUALITIES ON THE QUALITY AND INTEGRITY OF WELD,

The quality of a weld is dependent on several factors, but most importantly, the weld's durability and strength will be mostly a result of three main factors: the composition, mechanical, thermal, and electrical properties, and microstructure of the metals involved in and around the joint. This holds true for both the base and filler metals [59]. As there are far too many hypothetical combinations and types of metals to discuss, the scope of this report will focus mostly on steel. In steel, lower carbon content is often associated with better weldability and integrity. As the number of alloying elements increases, so does the risk of liquation cracking along the weld or in and around the heat-affected zone (HAZ). Alloys with good resistance to high-temperature oxidation and creep are generally better at resisting hydrogen attack at high temperatures and pressures but must still be welded with care due to their high hardenability[59]. The composition of the metal may also influence how its microstructure changes as a result of welding and this needs to be taken into account given the desired application of the product and the stresses on the joint. For example, it was shown that as the nickel content in austenite steel increased, its solidification mode changed from ferrite-austenite to austenite-ferrite. This change in crystal lattice structure, its associated properties, and its implications for the desired application need to be kept in mind when choosing the composition of the materials in a given design [60].

7.1 Best practice for welding dissimilar materials,

When designing products, the specific application that the product will be used for may require that two pieces of dissimilar metal be joined together permanently through welding. This can prove to be a challenge for designers if they opt to go for traditional/conventional forms of welding such as solid-state welding, especially when the metals have significantly different mechanical properties. Differences in their melting points may cause one metal to remain solid while the other melts making it much harder to maintain both metals in the ideal conditions and phases for a strong stable weld. Another issue might arise if the two metals have different thermal expansion rates or coefficients as this would lead to distortion and make it much harder to position the two metals appropriately when joining them to ensure that the final result or the end product has the specified dimensions required or that the two pieces of metal didn't change shape near the joint and affect the product's desired specifications. A discrepancy in the metals' thermal conductivity could also result in miscalculated and crooked welds due to the weld bead being distributed unevenly across the surface of the metals [61].

There are a few possible methods for adjusting conventional welding methods to better accommodate dissimilar metals and mitigate or lessen any error that may result from their differing properties, mostly using specific filler metals that lessen the disparity within the metals' properties. But these are all suboptimal solutions in terms of quality, with their most redeeming qualities being their affordability and scalability for larger-scale applications [62]. Friction welding as well as diffusion bonding may also be viable alternatives although they are also not without fault [59]. Laser welding avoids many of the issues associated with conventional welding of dissimilar metals due to its accurate positioning and control of the weld bead along the joint, low distortion, and rapid heating and cooling processes [63].

Similarly, electron beam welding allows the welder to accurately control the beam size and location thus minimizing distortion of the two metal components, and the vacuum environment minimizes any contamination and subsequent reaction of the metal with oxygen, hydrogen, and nitrogen, meaning highly reactive and refractory metals can be welded together with fewer impurities in the joint [62].

7.2 welding in extreme conditions,

Welds are a primary method of assembly as well as repair, and often times they are required to be performed under extreme conditions, such as underwater, where maintaining the welding temperature might be an issue. Multiple methods could be used for underwater welding, such as wet welding, local cavity welding, and dry welding [64]. The most commonly used method is wet welding, where the base metal, weld arc, and welder are in the water without a mechanical barrier separating them from it, making it easier to weld complex geometries. Flux-cored arc welding (FCAW) and shielded metal arc welding (SMAW) are used for wet welding because using coated arcs for welding is the cheapest and most flexible method [64]. In addition to SMAW, temper bead welding (TBW) is used, a method where additional weld beads are deposited onto constructional weld beads, resulting in an annealing or tempering effect, thus reducing hardness and increasing ductility [65]. The arcs used in SMAW consist of a metal core with a coating that consists of a mixture of fine chemical powder and minerals bonded together. The coating differs depending on the application and base metal; an example is carbon steel, where hydrogen-controlled coatings or iron powder coatings would be used. As for underwater welding, a waterproof flux coating would be used. In general, ferrite electrodes with an iron-oxide-based coating are preferred due to their ability to resist hydrogen cracking [66]. In SMAW, a weld bead is deposited by the melting of the core metal along with the iron powder in the coating. Stabilizing substances are used to improve arc stability and reduce spatter [66]. Dry welding can be used as well, in which the welding is performed in a chamber that separates the weld from the water and usually contains air or hydrogen. Dry welding allows the use of most welding methods and often results in better welds, but it requires support equipment that results in a high cost that could be twice as much as that of wet welds [64].

8. WELDING IN ADDITIVE MANUFACTURING,

Welding processes in additive manufacturing (AM) rely on raw material as its base, usually in the form of powder, wire, or sheet, which is then melted and resolidified, forming a dense metal structure through the use of an energy or heat source such as a laser, electron beam, or electrical arc performed in a layer-by-layer manner [67]. The preferred AM process uses laser welding systems, which tend to yield products with good dimensional accuracy and surface finish in a short time [68, 69]. Yet electron beam welding systems are likely to produce parts with better mechanical properties since it is performed in a vacuum chamber under uniform high temperatures, thus reducing residual stresses in the final product [68]. Another procedure that could be taken to help reduce the residual stress caused by the cyclic heating and cooling involved with laser systems is joining separate components made by laser welding with the use of electron beam welding, creating the final part [69]. Laser welding systems are known by many names, such as selective laser melting (SLM) and laser powder bed fusion (LPBF) and are a process in which the printing platform is covered with metallic powder, which is then melted selectively by laser beams to the shape of the computer-aided design (CAD), then resolidified. The printed layer is then covered once again with metal powder through either a tool that deposits the layer or the baseplate lowering into the powder pool, and then the process is repeated [70].

SLM is commonly used in fabricating titanium Grade 5 parts used for biomedical and aerospace applications because it allows for the creation of a density gradient within the same component directly during the buildup. Titanium Grade 5 is commonly used for its low density and desired mechanical properties [71]. Another welding method that has been adapted for AM use is gas metal arc welding (GMAW). It is a process that makes use of consumable wire electrodes, allowing for the joining of metal parts and the deposition process by melting the electrode through heat that is the result of an electric arc stuck between the electrode and the base piece. The use of GMAW in AM involves the deposition of a series of beads over one another, forming the final design. A GMAW-AM system includes several components, among which are a power supply unit, shielding gas supply, wire feeder, and computer numerical controlled (CNC) baseplate. GMAW-AM is often preferred over other AM methods due to its low processing time, high deposition rate, energy efficiency, mechanical properties, and acceptable accuracy [72].

9. FUTURE TRENDS IN WELDING,

Emerging technologies in welding are paving the way for significant advancements in the industry, driven by the integration of digital and intelligent systems. The following are key emerging technologies shaping the future of welding:

Virtual and augmented reality (VR/AR): these technologies are enhancing training and precision in welding. VR provides immersive training environments, allowing welders to practice without the risk associated with live welding. AR aids in precision by overlapping digital information onto the physical world, helping welders align and place welds accurately [73].

5G technology: the advent of 5G enables faster and more reliable communication between devices. In welding, this translates to real-time data transfer and remote monitoring capabilities, allowing for better control and optimization of welding processes [74].

Cloud computing: This technology facilitates the creation of data-driven welding expert system. Cloud com offers a centralized repository for welding parameters and processing data, accessible from anywhere. IoT enables real-time monitoring and control, enhancing the efficiency and accuracy of welding operations [75].

Machine learning and AI: Ai techniques are being integrated into welding systems to enable adaptive control and decision making. Machine learning algorithms analyze welding data to predict outcomes and adjust parameters in rea-time, improving weld quality and consistency [76].

These emerging technologies are collectively advancing the welding industry towards more intelligent, efficient, and precise processes. Aligning with the principles of industry 4.0 and supporting the growth of additive manufacturing.

10. CONCLUSIONS

In conclusion, welding is a foundational process in manufacturing and construction, essential for ensuring structural integrity and durability. Integrating automation and robotics might usher in a new era within the industry, enhancing precision and speed. Industry 4.0 technologies may hold the key to several benefits, including real-time monitoring, proactive maintenance, and enhanced customization. Adopting these technologies could be a challenge due to cybersecurity, interoperability, and the need for a skilled workforce, but overcoming these hurdles could be achieved via collaboration among industry stakeholders and lawmakers. The implementation of Industry 4.0 brings efficiency, adaptability, and improved safety to welding processes. Additionally, there are countless factors that can impact weld quality, with a few examples given for steels. Dissimilar metal welding is also discussed with laser welding and electron beam welding appearing to be promising alternatives although more research and investigation may still be needed throughout the industry.

Underwater welding methods, particularly wet welding, showcase adaptability in complex environments. In additive manufacturing, welding processes evolve with laser welding systems like SLM and GMAW, offering rapid, precise fabrication. Welding is a relatively unexplored section of the engineering landscape, with near limitless potential for its applications and future technological advancements. Transitioning from the older conventional welding methods to Industry 4.0 showcases not just technological progress but an improvement in excellence and efficiency within welding practices and sets a higher standard for its future applications.

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