Laser Welding Based on Digital Twins

Subjects: Engineering, Mechanical | Engineering, Manufacturing
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The benefits of laser welding include higher production values, deeper penetration, higher welding speeds, adaptability, and higher power density. These characteristics make laser welding a superior process. Many industries are aware of the benefits of switching to lasers. Laser welding of aluminum alloys presents a daunting challenge, mainly because aluminum is a less reliable material for welding than other commercial metals such as steel, primarily because of its physical properties: high thermal conductivity, high reflectivity, and low viscosity.

Keywords: laser welded blanks (LWBs) ; digital twin (DT) ; Industry 4.0

1. Introduction

The transportation industry has dedicated a lot of engineering effort and innovative research into reducing the weight of its products. Air pollution and emission of greenhouse gases from the transportation sector have had detrimental environmental and health effects for decades. For this reason, governments have enacted restrictive regulations on automotive industries to prevent and control the spread of vehicular emissions. Strict regulations have led car manufacturers to look for different solutions and new technologies to solve the problem. One of the strategies that has been adopted in this field is to reduce the weight of cars, leading to fuel consumption and carbon dioxide emission reduction. Given that the body and other exterior components are a large portion of the car's weight, using light metal structures such as aluminum alloys in automobiles is an effective way to lessen the overall car weight. Aluminum alloys are known for their superior properties, such as strength-to-weight ratio, heat resistance, and corrosion resistance. Laser welding is an effective method of joining materials with high accuracy, good flexibility, and low distortion [1]. However, laser welding of aluminum structures is associated with a range of difficulties due to excessive heat dissipation, the hydrogen solubility of molten aluminum, and an oxide layer inclusion. Manufacturers are motivated by Computer-Aided Inspection (CAI) to ensure high product quality and avoid production defects, which requires automated, rapid, and accurate inspection [2]. CAI commonly refers to automated inspection, among other computer-aided applications extensively used in different industries [3]. By using manufacturing standards and geometric dimensioning and tolerancing (GD&T) criteria, CAI is not only able to detect laser welding defects but also to compensate for these shortcomings. Advances in scanning technology, digital cameras, and controllers have led to a significant increase in real-time monitoring of laser welding processes. A digital twin (DT) aims to build a digital replica of a physical system in a virtual space, such that the digital replica represents the same elements and the same dynamics of a physical system. DT systems can be very helpful for understanding, analyzing, and improving a product, service system, or production [4]. DT systems can also be used to inspect the process, to enable visualization of the impact of variations [5]. Integration of real-time monitoring and real-time simulation in a laser welding process ultimately leads to adopting a DT in laser welding processes.

2. Digital Twins (DT)

Industry 4.0 is the latest revolution in the industrial era, and refers to the digitization of manufacturing by merging physical and virtual (digital) worlds. Digital twins (DTs) are a strategy within Industry 4.0, operating on the virtualization principle [6]. DTs are digitalized integrated systems to monitor, analyze, and simulate the behavior of a physical system. DTs are composed of three main components: the physical system, the virtual system, and the communication layer that connects these two systems. The communication layer is a linkage for data storage, data processing, and data mapping functionalities [7]. The data from the physical and virtual systems must be stored and processed in the communication layer. In this regard, the communication layer needs to be capable of transmitting a big amount of data (big data) in addition to easy fault detection characteristics. Internet of Things (IoT) technology can be used to make interactions between different layers of the integrated systems for real-time data transmission. IoT effectively maintains two-way synchronization of physical and virtual systems, to keep the virtual system updated and to provide real-time control commands for the physical system. The physical system changes are reflected in the virtual system; in other words, the virtual system is updated by employing feedback from the physical system. Real-time control commands are made based on the past and present conditions of the physical system to take care of the consistency of the manufacturing process and the quality of manufactured parts [8]. The constant synchronization between physical and virtual systems through the communication layer ends up in a real-time quality control platform which is also supported and updated by the physical system. As illustrated in **Figure 1**, all sorts of information originating from physical and virtual systems—GD&T standards, historical data, customer feedback, and fabrication protocols—are communicating with the cloud network to provide enough material to make decisions. Continuous and online communication between different physical and virtual data providers is only made possible by the ability of IoT [9] to transmit large volumes of data.

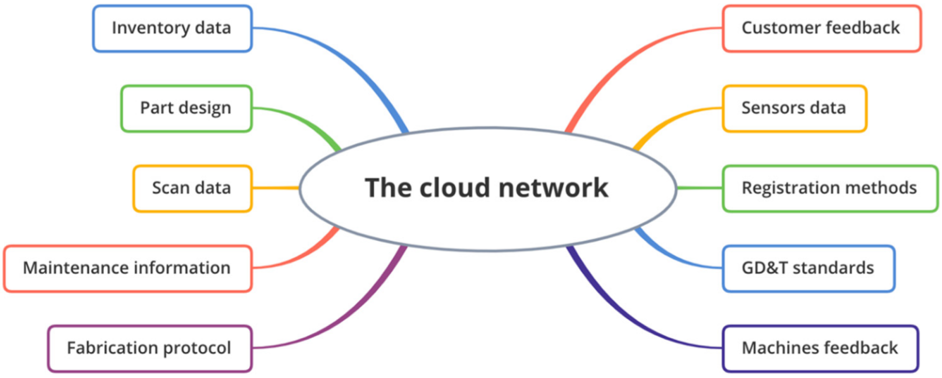

Figure 1. The cloud network in a 4.0 manufacturing factory.

Smart welding is heading inevitably toward the Industry 4.0 paradigm. A schematic of the DT model designed for intelligent laser welding leading to a product license for laser-welded blanks is presented in **Figure 2**. In this DT, all data from the physical system, including seam tracking, in-process depth meter, and weld inspect data, are communicating with the cloud to update and support the cloud. There is a two-way network of interactions between consequent stages of physical and virtual twins, to transfer and update information, guaranteeing high-quality laser seam according to standards, process command, and specifications defined in the cloud. The application of DTs might facilitate the provision of production licenses for parts manufactured in different production sites, with no need to re-inspect the parts.

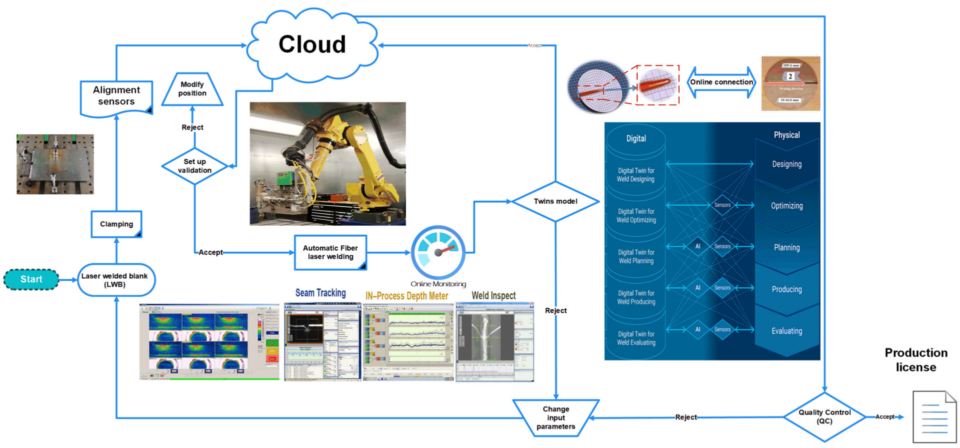

Figure 2. Digital twins model for Inspection 4.0 of laser-welded blanks.

In general, digital twins are efficient platforms for predicting every machine and device's performance, due to their intelligent data processing capability. In a virtual model or DT, physical models of machine operations will be combined with sensor data collected and processed from real assets during real-world operations. In this regard, operators of laser welding machines will benefit from being able to predict structural failure and to plan maintenance activities more effectively. This strategy will result in reduced maintenance costs and operational downtime during welding. As shown in the following model, aluminum sheets are prepared before welding to ensure there is no contamination on the surface. Then, the clamping procedure is adjusted to apply an equivalent force on the surface of the plates. To do so, alignment sensors are used to define the error, and the results are sent to the cloud for future action. By using the validation method, all the process parameters are set, and acceptance/rejection outcomes will be considered, to make a cloud-based smart decision based on the DG&T criteria. If the alignment has been accepted, automatic laser welding will start, and real-time monitoring will be done (seam tracking, in-process depth penetration, weld inspection, etc.). Using sensors and artificial intelligence, digital platforms and physical operations communicate data simultaneously. A cloud platform should be able to process big data and refine it based on pass/fail production criteria. Finally, a license will be issued for the quality assessment of each production. It is worth mentioning that this model can be used in mass production as well as remote manufacturing platforms in any location throughout the world. Thus, this model can be considered the first step toward cloud manufacturing and connected production which can be remotely accessible anytime.

3. Future Perspective

Investigation of the digital twins market reflects the challenges that have hindered cost-efficient application of digital twins (DTs) in manufacturing. Some of these challenges are due to the complex physics of manufacturing processes and production uncertainties, which in turn leads to difficulties in capturing physical phenomena by a virtual replica. The desire is to set up data-driven digital twins based on a hierarchical structure without any conflict between the physical and virtual systems, which entails appropriate communication and collaboration between them. However, the development of digital twins is still costly due to the restrictions of communication platforms. The ability to predict, prevent and resolve problems and faults also requires the proper implementation of data analysis, decision making, and problem-solving techniques.

In this regard, an overview of computer-aided process monitoring was reviewed, based on the digital twins concept for lightweight laser-welded metals. Different types of 3D geometric inspection, Computer-Aided Inspection (CAI) methods, and tools in the manufacturing industry, are presented and compared in this entry. CAI approaches address automated inspection challenges and requirements for different types of manufactured parts. The development of this process is essential in the production cycle of a part, and therefore should not be ignored. In addition, as moving further toward Industry 4.0, its concepts ought to be incorporated into geometric inspections allowing a comparison between nominal data (CAD model) with respect to a manufactured part, to determine whether it meets specifications without having to apply human judgment. An automated cloud-based Inspection 4.0 is therefore applied. Another objective is to propose an automated production cycle that does not require human intervention. This survey presents an agile approach allowing automation of the laser-welded blanks process. Applying CAI, the process is automated along with the implementation of its DTs. This original model allows remote monitoring of the process, increasing its precision by removing human intervention, increasing productivity, and providing a proper decision-making tool. The challenge now is to integrate artificial intelligence to delegate all redundant work to the machines, and have them provide feedback and auto-maintenance at some point. More research is also needed to develop cost-effective digital twins so that these solutions can meet Industry 4.0 requirements.

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