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Digital Twinning of a Magnetic Forging Holder to Enhance Productivity for Industry 4.0 and Metaverse

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Abstract: The concept of digital twinning is essential for smart manufacturing and cyber-physical systems to be connected to the Metaverse. These digital representations of physical objects can be used for real-time analysis, simulations, and predictive maintenance. A combination of smart manufacturing, Industry 4.0, and the Metaverse can lead to sustainable productivity in industries. This paper presents a practical approach to implementing digital twins of a magnetic forging holder that was designed and manufactured in this project. Thus, this paper makes two important contributions: the first contribution is the manufacturing of the holder, and the second significant contribution is the creation of its digital twin. The holder benefits from a special design and implementation, making it a user-friendly and powerful tool in materials research. More specifically, it can be employed for the thermomechanical influencing of the structure and, hence, the final properties of the materials under development. In addition, this mechanism allows us to produce a new type of creep-resistant composite material based on Fe, Al, and Y. The magnetic forging holder consolidates the powder material to form a solid state after mechanical alloying. We produce bars from the powder components using a suitable forging process in which extreme grain coarsening occurs after the final heat treatment. This is one of the conditions for achieving very high resistance to creep at high temperatures.

Keywords: digital twin; Metaverse; magnetic forging holder; smart manufacturing; cyber-physical systems; Industry 4.0; forging process

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1. Introduction

Forging is one of the oldest and most well-known metal manufacturing processes and forming technologies. Despite the widespread adoption and updating of many new and advanced forming technologies, metal forming remains in high demand in several engineering industries. Forged products have good mechanical properties with small material waste [1]. Radial forging is a bulk metal forming process for manufacturing axles and shafts and reducing the diameter of rods and tubes [2]. Compressive forces are applied to the initial material. These forces are applied through hammering, pressing, or rolling. Designing suitably shaped forging equipment and tools leads to the creation of plastic deformations in the formed material, which achieve the desired shape of the product without compromising the material's cohesion. Therefore, the design of dies for forged products has a great impact on the quality, cost, and delivery of forged products. However, the engineering design of the forging equipment requires extensive knowledge of and experience in forging technology to effectively meet a material's shape requirements.

Forging methods are distinguished mainly by the design and shape of the dies, the shape of the material, and the forging conditions. Generally, the forging process is classified according to the working temperature. If it is performed at room temperature, then it is called cold forging; if it is performed above room temperature but below the recrystallization temperature, then it is known as warm forging; and if it is performed at above the recrystallization temperature, then it is known as hot forging [3,4]. Based on the die shape, forging can be divided into open-die forging and closed-die forging. This means that the forging equipment is one of the main keys to accomplishing successful material forming.

Digital twinning has emerged as a breakthrough technology in the field of engineering and manufacturing, offering significant advantages, such as reduced development costs, optimized performance, and enhanced maintenance capabilities [5–8]. By creating a virtual replica of physical equipment, digital twin technology enables engineers and operators to monitor and simulate the equipment's behavior in real time, identify potential issues before they occur, and evaluate design changes in a risk-free environment. The magnetic forging holder is a critical component in a hydraulic press for the production of high-quality products and materials. A digital twin of this component provides us with the opportunity to connect the device to cyber-physical systems. This holder is considered as a virtual object, allowing for the continuous monitoring, simulation, prediction, and optimization of its performance. This technology can also help engineers and operators identify potential failures and problems in the equipment, optimize maintenance schedules to prevent downtime, and evaluate different design changes without risking the actual equipment. Furthermore, as the digital twin for the holder can be linked using cyber-physical integration and advanced sensors, it could provide an excellent opportunity to capture and analyze data in real time, which can be used to enhance situational awareness, operational flexibility, and energy consumption [9–13]. Additionally, the application of augmented reality and virtual reality with the digital twin can provide operators with a more immersive and interactive experience when interacting with the holder virtually. The creation of a digital twin for this equipment can improve the monitoring of the condition of the device and enhance maintenance processes, leading to improved performance, reduced costs, and increased operational efficiency [14–16].

In recent years, there has been increased interest in using digital twinning to enhance the monitoring of the condition of industrial equipment. Condition monitoring is a crucial task in monitoring the lifecycle of complex equipment, as it is used to monitor the equipment's condition and design accurate models for assessing its health and improving its performance. This research presents the design and development of digital and physical twins of a magnetic forging holder used in the compacting and hot forging of a newly developed composite material based on Fe—Al—Y with high creep resistance. The physical twin of the tool consists of a separate forging element called the die and a fastening part that holds the die in position. The tool is complex for digital twinning but more user-friendly for use in industry. The fastening part of the tool was produced using rapid tooling technology, which utilizes a folded sandwich construction of laser-cut parts from common sheet metal. This provides the ability to replace individual parts by bolting the entire structure and attaching it to the press. The die is fixed and quickly replaced using neodymium ring magnets. The forging tool is also equipped with leveling supports that allow for correcting any irregularities in the direction of the longitudinal axis. The entire tool was manufactured using a technology that does not require manual locksmith work except for assembly. Currently, the tool is being used in research, and requirements are being collected for the possible further simplification of and improvement in its design and operating characteristics.

The main contribution of this paper is the development of a digital twin of special open-die hot-forging equipment that is held by magnetic forces, with the aim of enabling its integration into a smart manufacturing environment. The design process for the digital twin was carried out using SOLIDWORKS software, which enabled us to optimize the design of the equipment holder to ensure compatibility with the Bussmann Hydraulic Press HPK100. This compatibility is crucial for the successful operation of the equipment within the smart manufacturing environment.

2. Implementation of the Physical Twin

To fully understand and utilize the concept of digital twinning, it is important to first describe the physical twin of the device that was produced in the research. This section presents an important contribution of this research: the process of designing and manufacturing the magnetic forging holder, along with some other essential support tools, such as the press. Generally, the physical twin serves as the real-world counterpart from which the digital twin is created. Essentially, the physical twin is a real-time copy of the device, which can be synchronized and tracked using sensors and other IoT devices. Once the physical twin has been identified, the digital twin can be created through a software analogue that simulates the internal processes, technical characteristics, and behavior of the physical twin. This digital twin can then be used to gather real-time data and analytics, monitor performance, test and run simulations, troubleshoot issues, and optimize the device, without the need for physical interventions or disruptions. By having a digital twin, engineers and developers can identify potential problems in the physical device before they arise by running simulations based on real-time data gathered through IoT sensors. In the following section, we describe these physical parts of the system.

2.1. Hydraulic Press

The proposed magnetic forging holder's physical and digital twins were designed and developed to use the Bussmann HPK100 press (Figure 1) for forging processes. The press is powered by a hydraulic pumping system, which uses hydraulic fluid to generate the required operating force. The press features two primary hydraulic cylinders. The upper cylinder compresses the material being processed and applies force to it, while the lower cylinder controls the movement of the die, the tool used to shape the material. In addition to the primary cylinders, the Bussmann HPK100 press also has an auxiliary cylinder integrated into the upper plate. This cylinder acts as an ejector, facilitating the removal of finished products or compacts from the upper punches, making it especially useful for compacts with overhangs or parts extending beyond the punch edge. The Bussmann Hydraulic Press HPK100 is a complicated piece of machinery designed for precision manufacturing. Its hydraulic pumping system and various cylinders work together to apply the necessary force and control the material's movement during processing, resulting in high-quality finished products. Nevertheless, this press requires a specific holder for certain special forging operations.

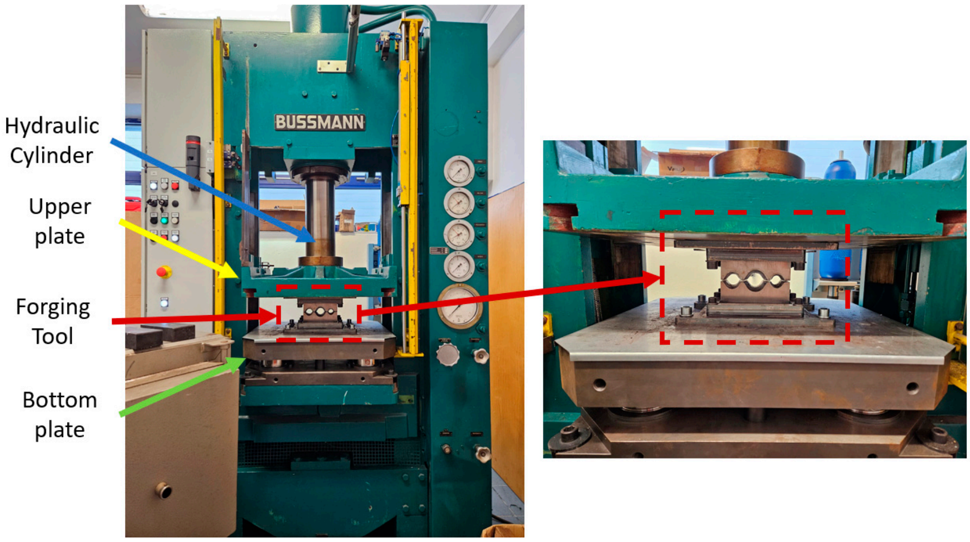

Figure 1. The physical twin of the Bussmann Hydraulic Press HPK100 with the forging tool.

The electric and hydraulic control panel houses all the essential controls necessary for the flexible operation of the press. The sequence control, which is operated by limit switches, is adjustable to the part being compacted. It prevents any potential harm to the press or die by interlocking each cylinder movement with the next, thus rendering the press fail-safe.

2.2. Custom Holding Table

Figure 2 illustrates the holding assembly. The custom holding table assembly was meticulously designed to seamlessly integrate with the hydraulic press, with a T-slot connection that provides a sturdy and secure attachment and prevents any unwanted movement during operation. The load cells integrated into the assembly are highly accurate, allowing for precise load measurement that is especially useful in situations where precise control over the amount of force applied to the material is important. The screw holes on the upper plate of the assembly make it easy to connect external equipment and dies to the hydraulic press, giving it a high degree of flexibility to accommodate a variety of materials and processes. The mechanical plate holder on the upper plate of the press can accommodate plates of varying sizes and eliminates the need for additional screws or holding devices, streamlining the setup process and improving the overall efficiency. All of these features combine to make the holding table assembly in Figure 2, an extremely sophisticated and precise piece of equipment that is essential for any manufacturing or processing operation that relies on a hydraulic press.

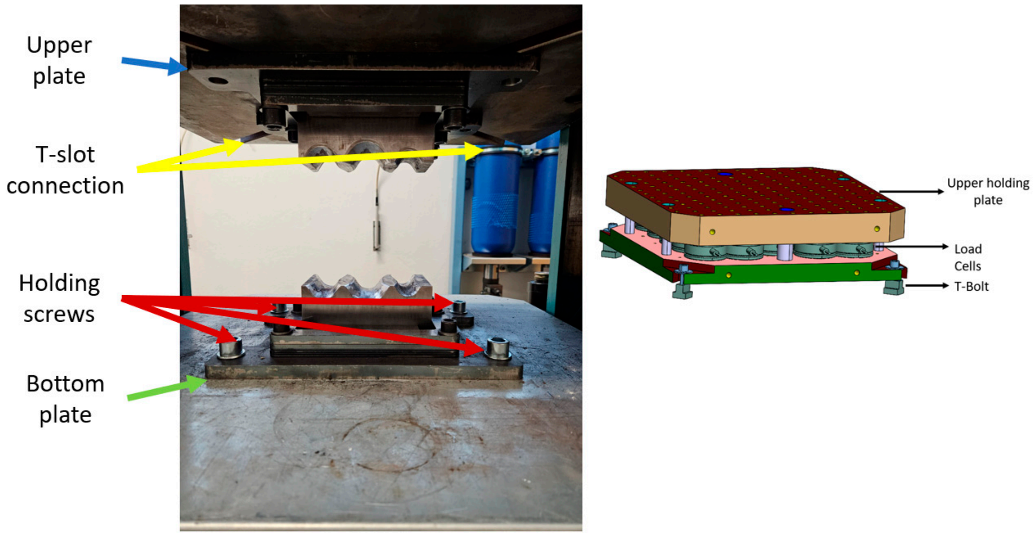

Figure 2. The physical twin of the holding assembly with its corresponding digital twin CAD model.

2.3. Design Requirements

The forging die must be constructed based on the requirements to perform the consolidation step [17]. Forging dies are subjected to high cyclic loads, leading to high levels of internal pressure, stress concentrations in the die cavity, localized deformation, and the pre-mature failure of dies [18]. They must be held by a holding device that must fit into the hydraulic press described above. The design solution should allow for the very fast replacement of the active part of the equipment, forging dies, and the intensive overflow of the bar from the developed composite material, without the unnecessary time delays or temperature drops that normally occur during hot forming. The final design of the equipment consists of two main sections: the forging dies and the die-holding assembly.

2.4. Forging Dies

The engineering design of the forging dies is based on the abovementioned requirements. The die assembly includes two mirrored shaped dies containing three holes with different diameters and radiuses, as shown in Figure 3.

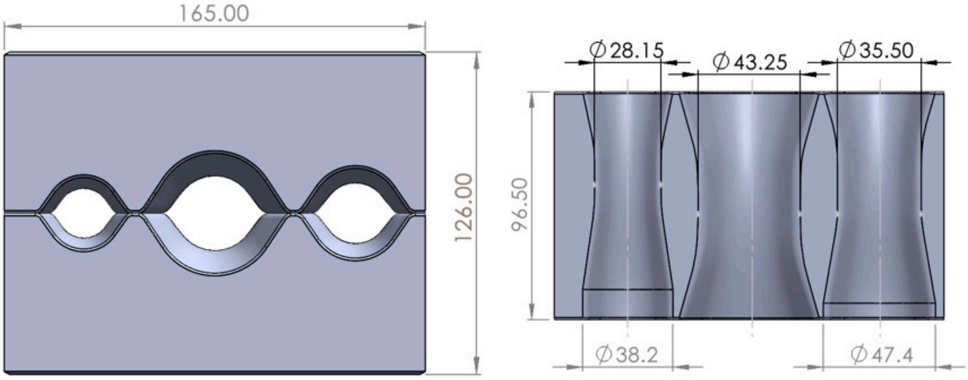

Figure 3. (**Left**): CAD model of forging dies. (**Right**): top view of the bottom die.

The engineering design of the dies is a crucial aspect of the forging process, as it determines the quality and efficiency of the final product. In the case of circular bars, the dies are specifically designed to allow for continuous forging, which reduces their volume to the minimum diameter of the individual holes. This reduction in diameter is a critical step in the process, as it ensures that the bars meet the desired specifications for their final use. However, the reduction in diameter also results in a deformation of the volume of the bars. This deformation, in turn, creates a significant amount of friction between the bars and the dies during the forging process. The resulting friction can cause various issues, such as material sticking to the die, a poor surface finish, and even die failure. Therefore, it is essential to address this issue to achieve high-quality forgings.

To mitigate the problem of friction, the holes in the dies are gradually narrowed down, as depicted in Figure 4. This design allows the deformed material to have enough space to flow without causing excessive friction between the bars and the dies. As a result, the forging process is smoother, and the final product has a better surface finish and dimensional accuracy. Moreover, reducing the friction also reduces the wear and tear on the dies, increasing their lifespan and ultimately saving costs in the long run. Hence, the careful engineering design of the dies is critical to achieve a successful and efficient forging process, with minimal friction between the bars and the dies.

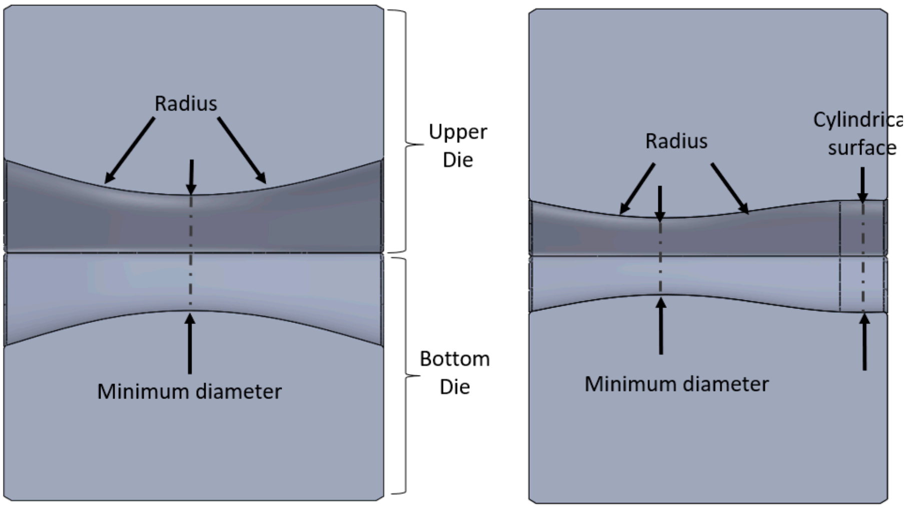

Figure 4. (**Left**): cross-section of the middle hole. (**Right**): cross-section of the side hole.

2.5. The Manufacturing Method of the Forging Dies

The method of manufacturing the dies plays a crucial role in producing high-quality forging dies that can withstand the high stresses and temperatures of the forging process while maintaining their dimensional accuracy and surface finish. Among the materials commonly used for forging dies, tool steel stands out due to its high strength, toughness, and wear resistance. The manufacturing process begins with the hot and warm forming of the steel, followed by a critical step of heat treatment through tempering. Tempering is a crucial stage in the manufacturing process, as it enhances the toughness and ductility of the steel. To achieve this, the steel is heated to a specific temperature and kept there for a set period, followed by slow cooling. The temperature and time of tempering depend on the type of tool steel and the desired properties of the final forging die.

After heat treatment, the contours of the working and bearing surfaces are machined to the desired dimensions using a machining center. The machining process entails removing excess material and shaping the die to the desired specifications. The working contour is a critical component of the die, as it determines the shape and dimensions of the final product. The contour is optimized based on previous research, and the selected shape is scaled for individual cross-sections to ensure the final product meets the required specifications and is of high quality. The approximate weight of each die is around 1.5 kg, making them easy to handle during the forging process despite their critical role in ensuring the accuracy and consistency of the final product (Figure 5). The use of high-quality materials and precise manufacturing methods is essential in producing forging dies that can withstand the high stresses and temperatures of the forging process while maintaining their dimensional accuracy and surface finish. After the machining process, the surface of the forging die is coated to further enhance its properties. Nitriding is used to increase the die's hardness, wear resistance, and overall performance during the forging process. The coating process is carefully selected based on the intended use of the die and the type of material being forged, ensuring that the final product meets the required specifications.

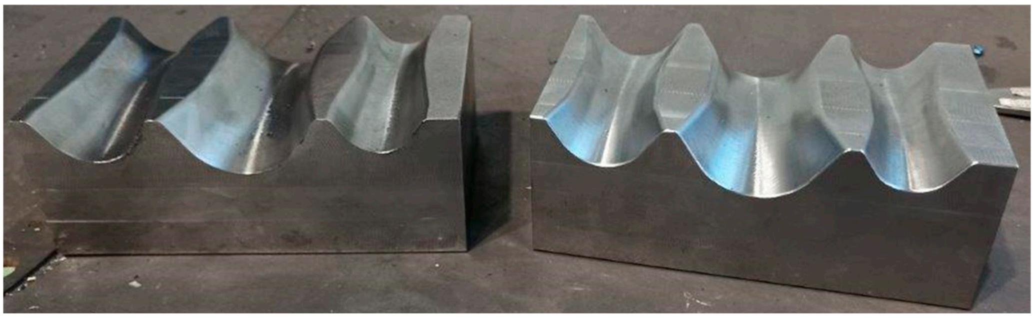

Figure 5. Manufactured Forging Dies.

3. Implementation of the Digital Twin

This section presents a systematic process for creating a digital twin of the holder from its physical counterpart. The process of creating a digital twin from a physical twin, such as the magnetic forging holder and support tools, is a significant contribution of the research. Once the physical twin is identified, a software analogue can be used to create a digital twin that simulates the internal processes, technical characteristics, and behavior of the physical twin. Engineers and developers can identify potential problems in the physical device before they arise by running simulations based on real-time data gathered through IoT sensors with the help of digital twins. Manufacturing industries that produce complex machinery and equipment often require a holding equipment assembly (HEA) to facilitate manufacturing. Therefore, the digital twinning process of the HEA, using various technologies and techniques, is described here. The digital twinning of the HEA can be achieved using a combination of technologies, such as 3D scanning, computer-aided design (CAD), and so on. Our focus is on using SOLIDWORKS to create the digital twin.

3.1. *Digital Twin of the Holding Equipment Assembly*

The digital twin of the HEA consists of five main plates of varying thicknesses and a design that holds a single die. Figure 6 depicts the digital twin of the die-holding assembly. The same assembly is mirrored for holding the upper die. This means that the digital twin of the HEA is designed to hold the upper and lower forging dies in place during the manufacturing process using magnetic force.

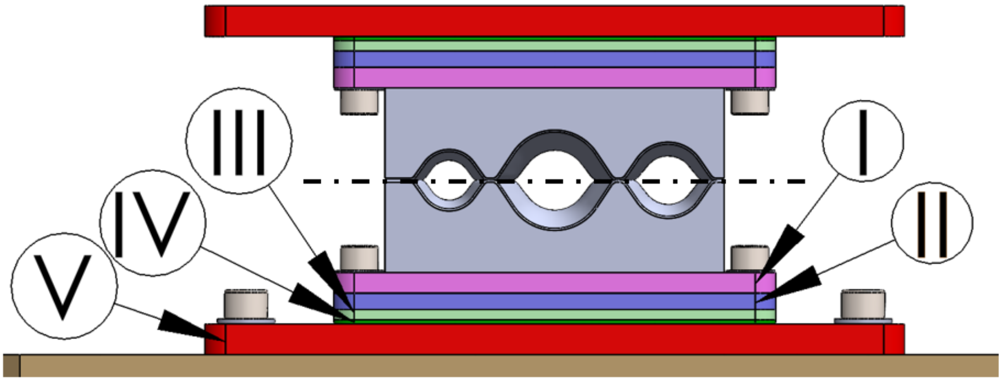

Figure 6. The digital twin of the die-holding assembly.

The design of the digital twin is based on the physical HEA, and it is created so that it functions in the same way as the physical assembly, while also providing a means for testing and analysis before the physical assembly is created. The digital twinning process using SOLIDWORKS is an important step in the manufacturing process for the HEA, as it allows a digital replica to be created that can be tested and optimized before the physical assembly is built. This can help to save time and resources, while also ensuring that the final product is of high quality and meets the required specifications. Figure 7 (left) illustrates Plate No. I in the digital twin of the proposed device, which is specifically designed to limit the lateral gaps of the forging die in the physical twin. It prevents the die from moving sideways or slipping during the forging process, which could cause defects or inaccuracies in the final product. Figure 7 (right) depicts the digital twin of Plate No. II. In the physical twin, Plate No. II is a plate with a gap that holds Plate No. I in place. Plate No. II provides additional support and stability to Plate No. I, which is responsible for limiting the lateral gaps of the forging die in the press. Together, Plate No. I and Plate No. II form a critical part of the digital twin of the HEA, as they help to ensure that the forging process is accurate and precise for virtual management.

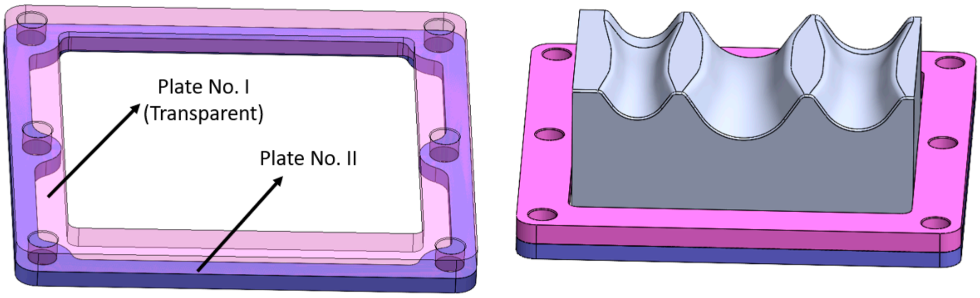

Figure 7. The digital twin of Plates Nos. I and II (**left**), the digital twin of II. Plates Nos. I and II holding the forging die (**right**).

Based on the physical twin described in the previous section, there are two other plates, Plate No. III and Plate No. IV, which are designed to hold seven neodymium magnets. The digital twin of these plates is shown in Figure 8. The plates have seven concentric holes to hold the neodymium magnets. The fact that the plates are designed to hold these magnets suggests that they are part of a larger system intended to utilize their magnetic forces for the press.

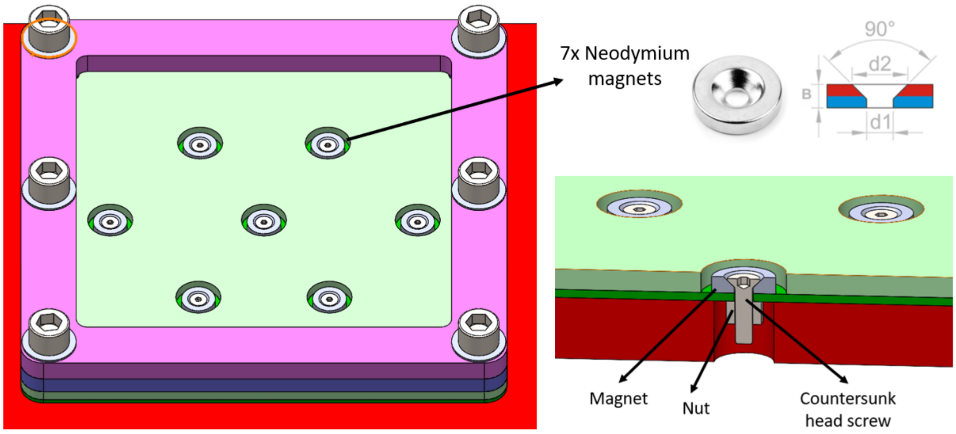

Figure 8. The digital twin of the die-holding assembly plates with neodymium magnets.

Neodymium magnets possess exceptional strength due to their composition of neodymium, iron, and boron. These magnets are commonly utilized in applications that require a strong magnetic field in a small space, such as in motors, headphones, and computer hard drives. One of the main advantages of neodymium magnets is their ability to generate significant magnetic force proportional to their size. This feature enables small neodymium magnets to hold objects that are considerably heavier than their own weight, making them highly suitable for supporting forging dies that can be quite heavy. In the specific design mentioned, a particular type of neodymium magnet, the N35, was selected. This magnet has a hole for a countersunk screw (ISO 10642) and can maintain its magnetic properties up to a temperature of 80 °C. The choice of magnet emphasizes the significance of selecting the appropriate type of neodymium magnet for a particular application, as different types may have distinct magnetic properties and temperature limitations. Their high magnetic force and small size make them an adaptable and inventive solution to various engineering and design predicaments.

In the physical twin, Plate No. III has seven holes with diameters slightly larger than the outer diameter of the neodymium magnet. This was duplicated in the digital twin. This design allows the magnet to fit snugly into the hole and remain securely in place. The slightly larger diameter provides enough room for the magnet to be inserted without too much resistance, but not so much room that it can move around freely. In contrast, the holes on Plate No. IV have the same size as the inner diameter of the neodymium magnet. These holes are designed to hold the connecting screw that joins the two plates together. The magnet holds the screw in place, preventing it from falling out. Once the magnet and screw are in place, the connecting screw is then fixed in a through-hole in Plate No. V. This final step secures the plates in place and ensures that the neodymium magnets hold the plates together with a strong magnetic force. The use of neodymium magnets and connecting screws provides an efficient and innovative way to join the plates together, creating a sturdy and reliable structure. Plate No. II has ten straight slots designed for welding in the physical version. This is why, in the digitalization, these slots are constructed in a way that allows for the welding of Plate No. IV to Plate No. III and Plate No. V from both sides. The neodymium magnets used in the physical twin are highly resistant to demagnetization, making them an ideal choice for this application. The connecting screws used in the digital twin, according to the physical twin model, are also made of high-strength steel to withstand the high loads and stresses placed on them during use. This combination of materials and design provides a durable and long-lasting connection between the plates. This design ensures that the plates are joined together securely and stably. Figure 9 provides a digital representation of the plates.

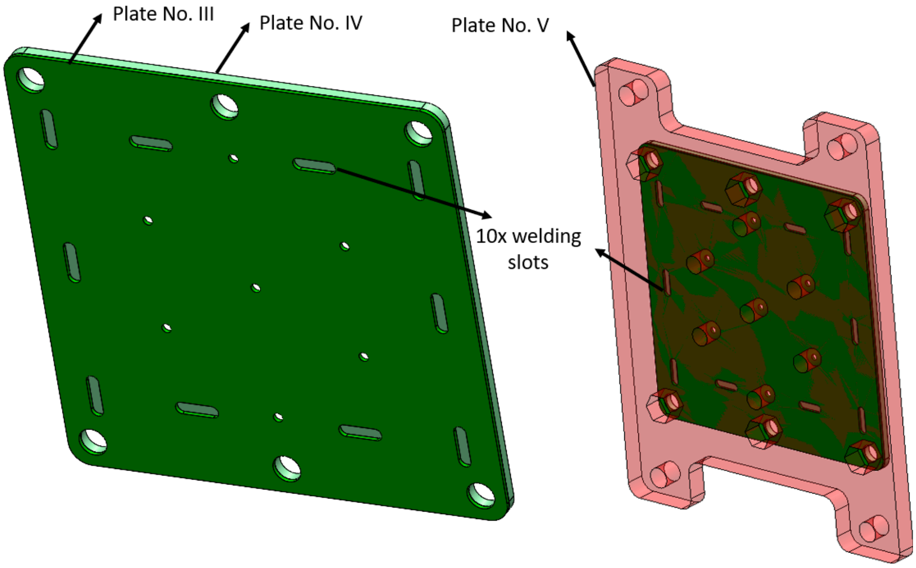

Figure 9. The digital twin of the die-holding assembly plates with welding slots.

Plate No. V, also known as the base plate, plays a critical role in the overall structure of the assembly. It serves as the foundation on which all the other plates (from No. I to No. IV) are mounted, providing stability and support for the entire system. This is demonstrated in Figure 10. The plate is designed with six through-hex-holes that allow for the mounting nuts to sit securely on Plate No. IV, preventing any potential rotation during operation.

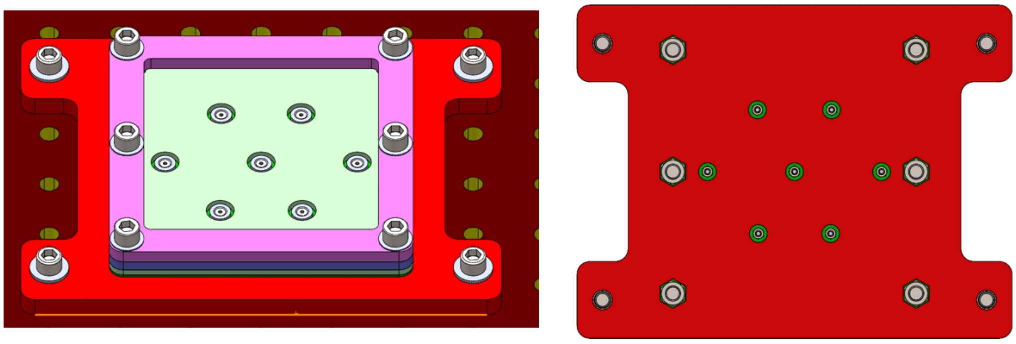

Figure 10. Die-holding assembly.

The through-holes on Plate No. V are precisely located and spaced to ensure the proper alignment and balance of the entire assembly, retaining it securely in place during the forging process. Plate No. V is fixed to the hydraulic press with four screws. These screws are strategically placed to provide maximum stability and prevent any unwanted movement or vibration. Its thickness is optimized based on the expected forces, stresses generated during the forging process, ensuring that it can withstand the expected loads without deforming or failing. In addition to its role as the foundation of the assembly, Plate No. V also plays a critical role in distributing the forging forces evenly across the entire structure. The six M12 bolts (ISO 4762) that connect all the plates are strong enough to withstand the high forces generated during the forging process, ensuring that the entire assembly remains stable and secure.

Figure 11 illustrates an additional feature of the proposed digital twin. The forging dies are secured in place by two rectangular inserts located in the gap between the die and Plate No. I. These inserts limit the front and rear gaps and prevent the dies from moving in these directions. Neodymium magnets are strategically arranged to secure the dies in place. Three magnets are directly beneath the center of the forging dies, while the remaining four magnets are partially beneath the dies. Half of the surface of these magnets holds the dies in place from the edges, and the other half secures the inserts. The inserts have small holes on each side to facilitate their removal if necessary.

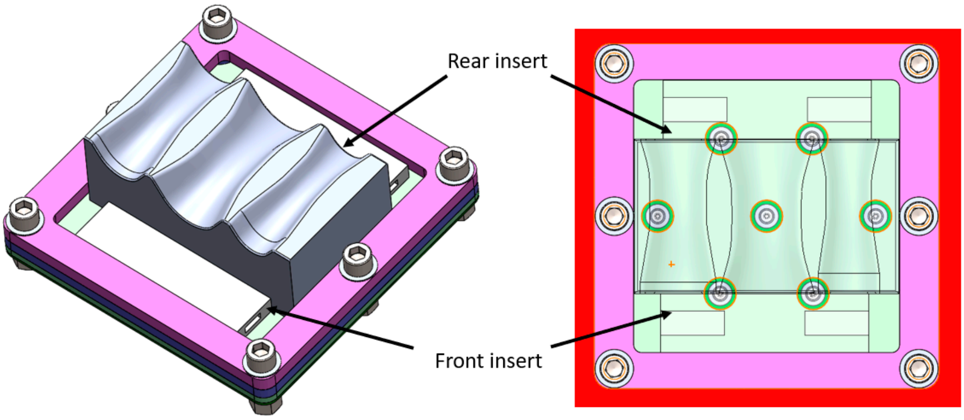

Figure 11. The digital twin of the die-holding assembly with front inserts for displacement blocking.

The digital twin of the mechanism, shown in Figure 12, provides a comprehensive understanding of the behavior of the components. One crucial aspect of the physical twin is the axial bending of elongated semi-finished products during forging, which necessitates straightening between operations. The development of straightening props in the physical twin makes this process easier and less complicated. To ensure the accurate monitoring of the component, it is essential to replicate this aspect in the digital twin. Thus, the digital twin includes the straightening props and their interaction with the equipment.

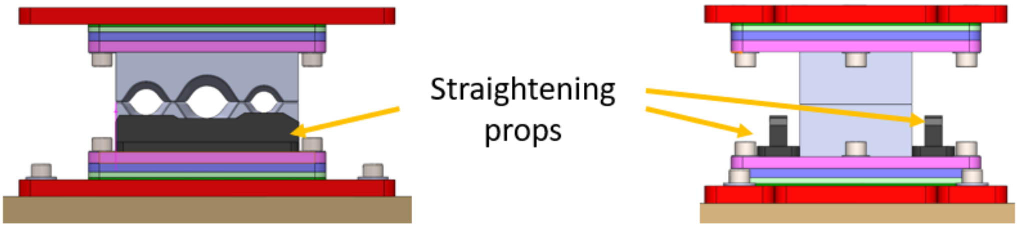

Figure 12. The digital twin of the die-holding assembly including straightening props.

The design of the straightening props in the physical twin is carefully considered to achieve the gradual straightening of the forged blank in the longitudinal axis. This design is accurately replicated in the digital twin. In three-point bending, two supports are placed symmetrically on both sides of the tool to make straightening as easy as possible. Such an arrangement enables the upper die to apply pressure against the props, resulting in the gradual straightening of the blank. By incorporating the straightening props in the digital twin, engineers and operators can better monitor and control the straightening process. They can also make adjustments as necessary to optimize the process and ensure that the component meets the required specifications. The inclusion of such critical components in the digital twin enables a more comprehensive understanding of the behavior of the mechanism, facilitating better decision making and problem solving.

The Manufacturing Method of the Holding Equipment

The fastening part of the equipment plays a crucial role in ensuring the overall stability and reliability of the equipment. To ensure the fastening part of the equipment is up to the task, the design was carefully crafted from sheet metal and laser-burned parts. The choice of weldable structural steel 11,373 was made based on its strength, durability, and ability to withstand the forces that the equipment is subjected to during operation. One of the unique features of the fastening part of the equipment is the use of ring-shaped neodymium magnets to hold the forging die. These commercially available flat magnets with tapered shoulders were carefully integrated into the design to allow for easy attachment with conventional screws, without the need to cut threads in the fixture. This approach not only simplifies the assembly process but also ensures that the cost of production is kept low. The design of the fastening part of the equipment also takes into account the various functional requirements, such as the attachment to the press and the definition of the position of the working element. Additionally, the production process was designed to be simple and cost-effective, with a limited number of welds used in the actual assembly, and only on two cuts. The structure was designed as a sandwich, allowing it to be easily screwed together with ordinary screws, and fixed to the press, thereby facilitating easy and quick replacement. This design approach also enables the replacement of damaged parts or parts requiring a flexible change in the dimensions of the active element of the die. All lasered plates used in the design are made from standard quality sheet metal, ensuring that the fastening part of the equipment meets the necessary technological aspects of production, simplicity, and low cost. The digital twin model of the fastening part of the equipment captures all of these critical features, making it an essential tool for optimizing and improving the equipment's performance.

4. Discussion

Digital twins are virtual replicas of physical objects or processes that provide real-time monitoring, analysis, and optimization capabilities [19–22]. With the ongoing development of cyber systems and intelligent technologies, such as Industry 4.0, the Internet of Things (IoT), cloud computing, and next-generation AI, digital twins have become an essential component of the manufacturing industry [23,24]. Furthermore, under the Industry 4.0 paradigm, scheduling should deal with smart and distributed manufacturing systems supporting novel and emerging technologies, such as digital twins, cyber-physical systems, and big data. Digital twins are of paramount importance for the effective functioning of smart manufacturing and cyber-physical systems in the Metaverse. These virtual replicas of physical objects, processes, and systems enable real-time monitoring, simulation, analysis, and optimization capabilities. In addition, digital twins are crucial for predictive maintenance in manufacturing systems, as they can provide insights into the equipment performance and health conditions. Moreover, by connecting digital twins to the Metaverse, it is possible for companies to design and test new processes using virtual simulations before implementing them in a physical environment. This can significantly reduce the costs and risks associated with changes to the manufacturing process. Therefore, the use of digital twins and cyber-physical systems is a necessary step towards the realization of smart manufacturing in the Metaverse. Moreover, the integration of digital twins and cyber-physical systems has ushered in a new era of sustainable smart manufacturing.

The rapid progress in information and communication technology (ICT) has captured the interest of numerous researchers who are eager to bring about a transformative revolution in modern industries [7,25]. This newfound fascination revolves around the cutting-edge idea of the digital twin. The concept of a digital twin entails a digital depiction of a physical object or system that can accurately replicate its physical behavior through real-time data exchange and interaction on various platforms. The integration of IoT within the power grid has resulted in a reliable means of accessing information, thereby enhancing its performance and providing a robust solution for real-time data management and analysis [7,26].

However, it is crucial to emphasize that cyber-physical systems (CPSs) possess an inherent susceptibility to security threats, demanding stringent measures to shield against lurking risks. Although our present research did not extensively delve into this particular aspect, we wholeheartedly recognize the indispensable role that security issues assume in the successful establishment and functioning of CPSs. Paramount considerations encompassing data confidentiality, authentication protocols, access control mechanisms, and fortification against cyber-attacks are imperative in the intricate tapestry of designing, implementing, and upholding secure CPS environments. Henceforth, forthcoming research should probe into these security concerns, ensuring the resilience and integrity of cyber-physical systems [27,28].

The aim of this paper is to present a practical approach to implementing digital and physical twins of a magnetic forging holder, allowing for the continuous monitoring, simulation, prediction, and optimization of its performance. Figure 13 illustrates the final digital twin of the holder. The holder benefits from a special design and implementation, making it a user-friendly and powerful tool in materials research, specifically for the thermomechanical influencing of the structure and final properties of materials under development. The combination of smart manufacturing, Industry 4.0, and the Metaverse can lead to sustainable productivity in industries. However, the digital twinning of devices or physical twins to realize reliable implementation is necessary [29]. Digital twin technology has emerged as a breakthrough technology in the field of engineering and manufacturing, offering significant advantages, such as reduced development costs, optimized performance, and enhanced maintenance capabilities. The digital twin of the magnetic forging holder presented in this paper enables engineers and operators to monitor and simulate the equipment's behavior in real time, identify potential issues before they occur, and evaluate design changes in a risk-free environment. Moreover, the integration of digital twins with cyber-physical systems and advanced sensors can provide an excellent opportunity to capture and analyze data in real time, which can be used to enhance situational awareness, operational flexibility, and energy consumption. In addition to the practical implementation of digital twin technology, this paper presents a new type of creep-resistant composite material based on Fe, Al, and Y. This physical twin, which is a magnetic forging holder, consolidates powder material to form a solid state after mechanical alloying. Bars from the powder are produced using a forging process in which extreme grain coarsening occurs after the final heat treatment, leading to very high resistance to creep at high temperatures. The application of this process could have significant implications for the development of new materials with enhanced properties. Furthermore, this paper highlights the importance of the design of the forging equipment and tools for achieving the desired shape of the product without compromising the material's cohesion. The engineering design of the forging equipment requires extensive knowledge of and experience in forging technology to effectively meet a product's shape requirements. The development and implementation of digital twinning technology can assist in optimizing the performance of the forging equipment and tools.

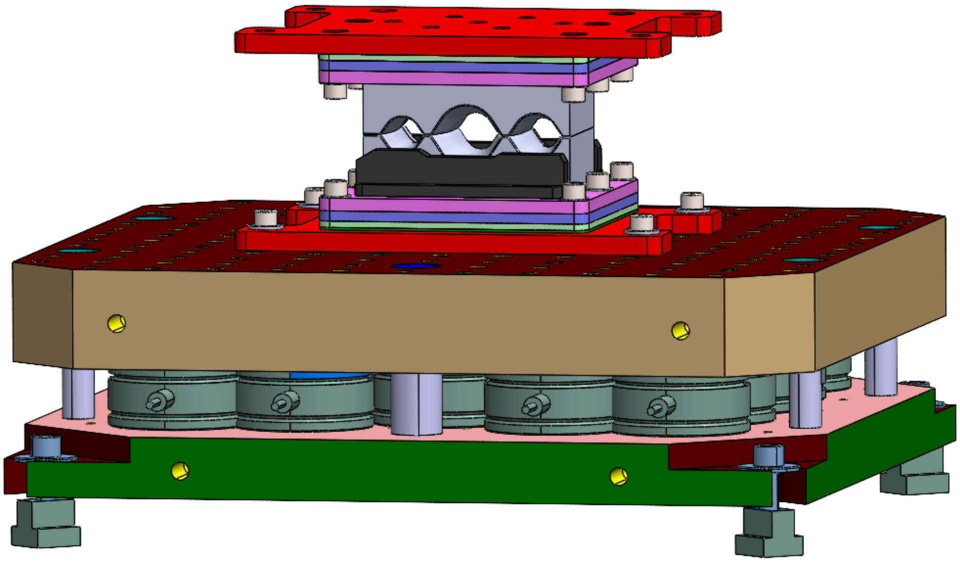

Figure 13. Final digital twin of the holder.

Through this digital representation, the DT provides real-time insights into the operational parameters, performance metrics, and overall condition of the holder. This includes vital factors, such as temperature, pressure, and mechanical stresses, which can be continuously monitored and analyzed.

To facilitate this monitoring process, an array of sensors is necessary to capture and transmit data from the physical holder to its digital twin. These sensors include temperature sensors, strain gauges, pressure sensors, and other specialized sensors tailored to the specific system requirements. The data collected by these sensors are then integrated into the digital twin, enabling a comprehensive understanding of the system's state and health.

The use of simulation methods, such as the Finite Element Method (FEM), provide a valuable tool for generating additional data and enhancing the digital twin model. FEM simulations can be used to virtually test and analyze the behavior of the magnetic forging holder under various conditions. This enables us to gain valuable insights into its performance without relying solely on physical experiments. Through FEM simulations, we can predict important parameters, including structural deformations, stress distributions, and material responses. These simulated results can then be compared and validated against the data obtained from the physical twin model. This process ensures that the digital twin accurately represents the behavior of the physical counterpart. By aligning the digital and physical twin models, we can identify any discrepancies or inconsistencies and refine the digital twin accordingly. Integrating simulation methods into digital twinning expands our dataset and enhances our understanding of the magnetic forging holder's performance. The comparison and validation between the digital twin model and the physical twin model serve as crucial steps in ensuring the fidelity and reliability of the digital twin. This iterative process of simulation, comparison, and validation contributes to the continuous improvement in and optimization of the digital twin model.

By incorporating sensor data into the digital twin, manufacturers and researchers gain a holistic view of the magnetic forging holder's performance and condition. This comprehensive perspective enables them to detect potential issues, anticipate maintenance needs, and optimize the thermomechanical process. Moreover, the availability of real-time data from the digital twin facilitates informed decision making and enables proactive measures to ensure that the system operates within the desired parameters. Hence, the digital twin not only enhances the design and manufacturing aspects, but it also serves as a means to continuously monitor and evaluate the system's performance. It facilitates the ongoing assessment of critical factors, leading to improved efficiency, reduced downtime, and increased productivity.

A simple comparison of die-holding methods is given for a better understanding of the engineering design method and its achievements.

The comparative assessment aims to scientifically evaluate the die-holding assembly in comparison to prior art alternatives commonly employed in the industry. Key factors, including the structural design, functionality, ease of use, and performance, were meticulously analyzed to provide an objective assessment of the merits of the current die-holding assembly.

Structural Design:

The current die-holding assembly incorporates a digital twin comprising five main plates of varying thicknesses. These plates, designed to hold a single die using magnetic force, present a significant departure from the conventional mechanical clamping mechanisms or hydraulic systems typically found in prior art alternatives. The integration of a digital twin not only ensures the accurate replication of the physical assembly, but it also facilitates comprehensive testing, analysis, and optimization before the physical counterpart is produced.

Functionality:

The digital twin of the die-holding assembly faithfully replicates the functional characteristics of the physical assembly. By securely holding the die in place during the forging process, it effectively limits lateral gaps, mitigating the risks of movement or slipping that may lead to defects or inaccuracies in the final product. The strategic arrangement of neodymium magnets within the plates enhances the assembly's holding capability, imparting stability and precision. In contrast, prior art alternatives often lack the intricate precision and adaptability offered by the current design, often relying on less efficient clamping mechanisms that may compromise the integrity of the forging process.

Ease of Use:

The current die-holding assembly presents notable advantages in terms of ease of use. The integration of a digital twin allows for comprehensive testing, optimization, and analysis, mitigating the risks of errors and optimizing resource allocation. The utilization of ring-shaped neodymium magnets simplifies the attachment process by enabling easy integration with conventional screws, eliminating the need for intricate thread-cutting procedures. Prior art alternatives may require complex and time-consuming setup procedures, potentially resulting in operational inefficiencies and increased production costs.

Performance:

The performance of the current die-holding assembly outshines prior art alternatives on several fronts. The design ensures the uniform distribution of forging forces throughout the structure, thereby enhancing stability and preventing unwarranted movement and vibrations. The inclusion of straightening props in the digital twin enables the precise monitoring and control of the straightening process, optimizing the quality of the forged components. The integration of high-strength neodymium magnets, along with judicious material selection, such as weldable structural steel and robust connecting screws, enhance the assembly's durability and reliability. In contrast, prior art alternatives may lack these features, potentially resulting in compromised precision, increased downtime, and diminished overall performance.

The comprehensive comparative assessment presented here underscores the significant advantages offered by the current die-holding assembly over prior art alternatives. Its innovative design, seamless integration of digital twin technology, improved functionality, ease of use, and superior performance position it as a highly promising solution in the industry. The scientific analysis accentuates the design's potential to streamline manufacturing processes, enhance product quality, and optimize overall operational efficiency. In order to further analyze the current design of the die-holding assembly and provide a comprehensive assessment, we conducted a multi-criteria decision analysis (MCDA). Due to its simplicity and logical approach, MCDA is a useful tool that can be applied to both simple and complex situations. It is a method for solving problems that characterizes an optimum choice.

In this comparison, the fixing of dies using traditional mechanical connections, such as bolts and screws, is presented as an alternative solution.

At the beginning of the analysis, MCDA requires that four main terms be defined [30]:

1. Goal: designing forging die with holder equipment;
2. Decision-makers: project coordinators and authors;
3. Evaluation criteria: simplicity, mounting assembly/disassembly, price;
4. Outcome: optimum solution that fulfils the goals.

In defining the terms, MCDA generally uses the next three steps:

- Dividing the decision into smaller and more understandable parts (Table 1);
- Analyzing each part (Table 2);
- Integrating the parts to produce a meaningful solution (Table 3).

The basic principle of this method is to compare multiple criteria. In the case of a criterion preference in a row, the value 1 is selected; otherwise, the selected value is 0. The number of its preferences is subsequently determined for each criterion, which is equal to the sum of units in the row of the considered criterion. Based on the sum of preferences, the weights of each criterion are determined according to the following relationship (Equation (1)):

$$V_i = \frac{K_i}{\sum_{i=1}^{n} k_i} \tag{1}$$

where the sum of the weights is always equal to 1:

V_i—the standard weight of the i-th criterion [-];
K_i—the non-standard weight of the i-th criterion [-];
n—number of criteria.

Table 1. Table of criteria and their values.

Criteria	Simplicity	Assembly/Disassembly	Price	Sum	Weight
Simplicity	X	1	1	2	2/5 = 0.4
Assembly/disassembly	1	X	1	2	2/5 = 0.4
Price	1	0	X	1	1/5 = 0.2

Table 2. Criterion value analysis for each variant.

Criteria	Simplicity	Assembly/Disassembly	Price	Sum	Weight
Simplicity	X	1	1	2	2/5 = 0.4
Assembly/disassembly	1	X	1	2	2/5 = 0.4
Price	1	0	X	1	1/5 = 0.2

Table 3. Final comparison of variants.

Variants/Criteria	Simplicity	Assembly/Disassembly	Price	Sum of Value	Order
Magnetic holding	3 × 0.4 = 1.2	3 × 0.4 = 1.2	1 × 0.2 = 0.6	3	1
Mechanical holding	2 × 0.4 = 0.8	1 × 0.4 = 0.8	3 × 0.2 = 0.6	2.2	2

Subsequently, for all criteria, the evaluation is determined for individual variants in the range of 1–3, where 1 is the worst, 2 is the average, and 3 is the best. In the last step, the weight and evaluation of the individual criteria are multiplied, and the values for all variants are added together to obtain the final evaluation.

As can be seen from the result of the MCDA in Table 3, based on this project's design requirements, magnetic holding is a more suitable solution than traditional mechanical connections. A general SWOT analysis is a compilation of the strengths, weaknesses, opportunities, and threats of the engineering design project. The main goals of a SWOT analysis are to develop a comprehensive awareness of the many factors involved in making a decision and to understand a specific variant. Figure 14 presents a general evaluation of the designed equipment as a SWOT analysis.

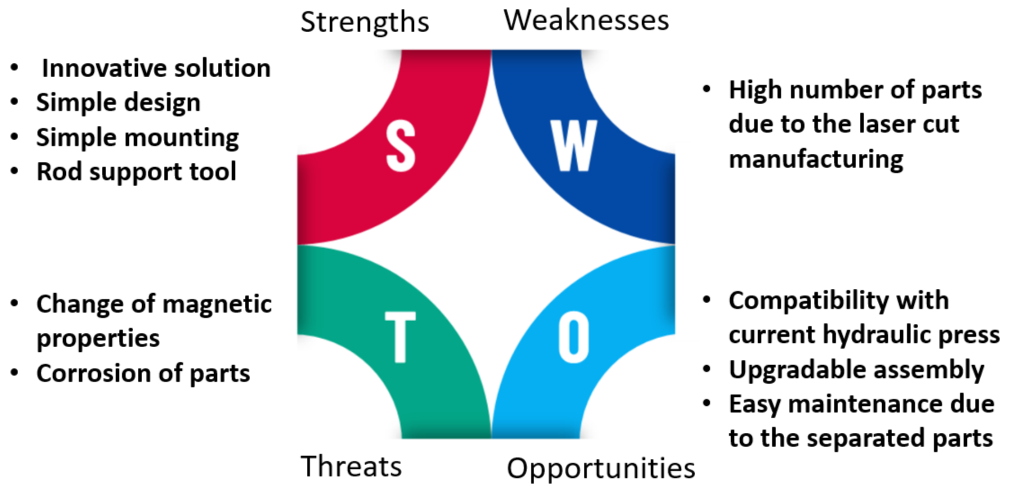

Figure 14. SWOT Analysis.

The digital twinning of the magnetic forging holder presented in this paper can have significant implications for the development of new materials with enhanced properties and the optimization of the performance of forging equipment and tools. The combination of smart manufacturing, Industry 4.0, and the Metaverse can lead to sustainable productivity in industries, and the practical implementation of digital twin technology can play a crucial role in achieving this goal. The digital twin for monitoring the condition of the magnetic holder was developed for this purpose. This offers several advantages; for instance, the digital twin provides a virtual representation of the physical system that can be updated continuously with real-time data from sensors and other sources. The proposed digital twin has several advantages for smart manufacturing. It allows for the real-time monitoring and analysis of the equipment's performance, which can help to identify potential issues and prevent downtime. It also enables predictive maintenance, allowing for proactive maintenance schedules based on data analysis rather than reactive maintenance based on equipment failure.

The development of this digital twin represents a significant contribution to the field of smart manufacturing, as it demonstrates the potential for integrating specialized equipment into a digital ecosystem. The findings of this study have practical applications in the manufacturing industry, particularly in the development of smart manufacturing systems. The digital twin approach can be applied to a wide range of industrial components, enabling their integration into smart manufacturing environments and facilitating the move towards Industry 4.0. This research showcases the use of Industry 4.0 technologies in the development of a tool for the hot/warm forging of a newly developed composite material, with a focus on user-friendliness and ease of maintenance.

Some future impacts of digital twins in industry include the following:

- The use of digital twins will continue to expand and gain popularity in different industries, including manufacturing, healthcare, and transportation, among others;
- The integration of digital twins into manufacturing processes has the potential to improve efficiency and reduce costs;
- Digital twins can help manufacturers to achieve higher levels of quality control by providing real-time data and insights into the manufacturing process;
- Digital twins can play a significant role in improving the quality and performance of physical objects by allowing researchers to tailor them to meet specific requirements and achieve desired properties;
- The use of digital twins will be increasingly integrated with the Metaverse, creating new possibilities for virtual and physical interactions.

In the future, the role of machine learning techniques in analyzing systems and their application in creating digital twins is expected to play a pivotal role [31,32]. Machine learning has demonstrated remarkable performance in various domains and has the potential to revolutionize the capabilities of digital twins. By leveraging machine learning algorithms, digital twins can effectively process and analyze vast amounts of data, enabling insights and predictions that enhance their functionality. Machine learning techniques offer the ability to identify patterns, correlations, and anomalies within complex datasets, empowering digital twins to make informed decisions and adapt to changing conditions [33]. These techniques can contribute to the optimization of manufacturing processes, predictive maintenance, anomaly detection, and even the enhancement of product design and performance. Furthermore, machine learning can aid in the development of advanced analytics models for digital twins, enabling the extraction of valuable insights from real-time data streams.

Ref. [34] states that by utilizing machine learning algorithms, digital twins can continuously learn and improve their understanding of the physical system they represent, leading to more accurate predictions and efficient decision making. In summary, the integration of machine learning techniques within digital twins holds tremendous potential for advancing their capabilities. By harnessing the power of machine learning, digital twins can leverage their data-driven analysis to optimize processes, enhance performance, and facilitate informed decision making, ultimately driving innovation and efficiency across various industries.

5. Conclusions

In recent years, the significance of digital twins has grown exponentially in various domains, including smart manufacturing, cyber-physical systems, Industry 4.0, and the emerging concept of the Metaverse. Digital twins enable the real-time analysis, simulations, and predictive maintenance of physical objects through virtual representations. In this study, we demonstrated a practical implementation of a digital twin for a magnetic forging holder, showcasing its potential within the context of Industry 4.0.

By creating a digital twin of the magnetic forging holder, our research aims to significantly enhance the quality and performance of this crucial component in the development of new materials, and specifically the creep-resistant composite material based on Fe, Al, and Y. The digital twin facilitates an improved consolidation of the powder material and enables the formation of a solid state after mechanical alloying. This demonstrates the pivotal role digital twins can play in advancing materials research and development. Through the customization and optimization of equipment and tools, digital twins empower researchers to meet specific requirements and achieve desired material properties more effectively. Moreover, the integration of digital twins in manufacturing processes has the potential to revolutionize efficiency, cost reduction, and product quality. By harnessing the power of digital twins, manufacturers can streamline operations, enhance predictive maintenance practices, and minimize downtime. This holds immense promise for various industries as they navigate the complexities of Industry 4.0 and aim to stay competitive in an increasingly interconnected and data-driven world. However, it is important to acknowledge the limitations of our study. While the demonstrated digital twin for the magnetic forging holder shows promise, further research and development are required to fully optimize its capabilities. Challenges such as data integration, model accuracy, and real-time synchronization with the physical counterpart need to be addressed. Additionally, the scalability and implementation of digital twins across diverse manufacturing processes and industries may present technical, organizational, and resource-related challenges. In conclusion, this study highlights the immense potential of digital twins in the context of Industry 4.0 and its broader applications in materials research and development. The integration of digital twins enables equipment and tools to be tailored precisely, optimizing manufacturing processes, improving efficiency, reducing costs, and enhancing product quality. As the field continues to advance, addressing the existing limitations and further exploring the capabilities of digital twins will be crucial to fully realize the transformative impact of this technology in the era of Industry 4.0.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Fe	Iron
Al	Aluminum
Y	Yttrium
IoT	Internet of Things
CAD	Computer-Aided Design
HEA	Holding Equipment Assembly
ISO	International Organization for Standardization
CPS	Cyber-Physical Systems
MCDA	Multi-Criteria Decision Analysis
SWOT	Strengths, Weaknesses, Opportunities, Threats

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