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A Review on a Method of Integration of Additive Manufacturing Technology with CNC Machining

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ABSTRACT

For industries in industrialized nations, reducing manufacturing costs and overall in-process time is essential to preserving competitive advantage. High added value manufacturing is also necessary at the same time. The manufacturing sectors in high-wage nations that are at a competitive disadvantage will find it more and more difficult to survive in the future if this issue is not resolved. A Hybrid Multi-tasking machine tool has been developed by adding Laser Metal Deposition functionality to its already-existing integrated turning and milling capabilities in order to meet these criteria by opening up new possibilities for machine tools. A further development of Done-in-One processes is made possible by the idea of a hybrid multitasking platform, which allows for the rapid generation of the net shape through high-precision finish machining operations after near-net shape components are constructed using additive manufacturing. It is especially suitable for small-lot fabrication of hard-to-cut materials, including high-hardness materials used in the energy industry, aerospace alloys, production tools and components, and high-precision, custom alloy designs frequently seen in the manufacturing of medical devices. With the help of application examples, this paper presents the Mazak Hybrid Multi-tasking machine tool's characteristics and highlights the opportunities and tasks for the next generation of production.

Keywords: Hybrid Multi-tasking Machine Tool, Laser Metal Deposition, Additive Manufacturing, High Added Value Manufacturing, Done-in-One Processes, High-Precision Finish Machining, Production Tools and Components, Next Generation Manufacturing.

1. Introduction

Three types of metalworking processes can be distinguished. The first is removal processing, which includes laser cutting, polishing, grinding, and machining, among other techniques. The second is forming processes, which includes injection moulding, stamping, forging, casting, and so forth. AM, which is characterized by 3D printing, fast prototyping, coating, welding, jointing, and other processes, is the third technique that is receiving more attention. One of AM's benefits is that it makes it feasible to produce metal parts with geometries that were previously unattainable with conventional methods. Additionally, by cutting down on setup, material preparation, and production lead time, AM is a good technique for effective small lot production. Nevertheless, despite these benefits, the vast majority of AM is still not widely regarded in the manufacturing sector as a truly feasible substitute for the production process. There are several various causes for this, such as low productivity and accuracy of components manufactured with AM technology. Furthermore, industrial-scale AM equipment continues to be a substantial capital expenditure. Another important factor is that, for components of comparable shape, AM construction is currently not cost-effective and is very sluggish when compared to traditional production techniques. As a result, several government-backed initiatives have been started recently to develop tools and materials for use on production lines to make parts in Japan and other countries.

However, in order to take advantage of the benefits of both approaches, AM has long been integrated with conventional technologies like CNC machining in academic and research settings. The idea behind hybridizing AM and CNC machining is to allow metal AM parts to be finished in-process, usually improving accuracy and surface polish right out of the machine. However, because these metal AM technologies have several duties for real-world applications, the hybrid concept systems' stated uses were constrained. Furthermore, the driving axe configurations of the majority of these hybrid concept systems platforms are primarily centered on additive manufacturing technologies.

As a result, they are not best suited for tasks like turning and 5-axis machining, which are essential for producing a large number of intricate parts in a single step for great production efficiency. Mazak created the INTEGREX i-400 AM, a hybrid multitasking machine, to address these issues and provide a new production method for the upcoming generation. This machine has improved and expanded the capabilities of the Done-in-One.

2. Hybrid Multitasking Machine

2.1 Development Background

The combination of additive manufacturing (AM) and conventional machining techniques has become a revolutionary development in the quickly changing field of manufacturing technologies. A major step toward more effective, accurate, and adaptable manufacturing solutions has been made with the development of hybrid multi-tasking machine tools, which combine well-established Computer Numerical Control (CNC) techniques with additive manufacturing capabilities like Laser Metal Deposition (LMD). This method tackles important issues facing the industry, such as lower costs, increased productivity, and the capacity to manage intricate geometries, especially in small-lot manufacturing. These innovations not only guarantee cost-effectiveness but also improve the caliber and reach of manufacturing as firms fight to stay competitive in high-wage nations.

This development's history stems from AM technology's potential drawbacks and benefits. Even though additive manufacturing (AM) may create complicated geometries and shorten lead times in small-lot productions, problems like sluggish processing rates, high costs, and poor precision have prevented AM from becoming a widely used manufacturing technique. By fusing the advantages of CNC and AM machining, hybrid solutions fill these gaps. For example, the INTEGREX i-400 AM incorporates LMD technology, a variation of laser cladding that is frequently used for coating and repair applications, into a multipurpose machine structure, allowing the creation of highly functional and intricately designed components.

The development of manufacturing technologies toward integrated systems that address cost, efficiency, and functional requirements is best illustrated by the hybrid multitasking machine. Its evolution highlights the industry's move toward implementing cutting-edge strategies to stay competitive in international marketplaces. The successful application examples demonstrate the hybrid machine's potential to redefine conventional manufacturing, offering sustainable solutions with reduced material costs, tooling consumption, and overall production complexity.

Mazak chose to concentrate on LMD technology because of its adaptability and track record of successfully integrating various metals and alloys, which makes it appropriate for use in sectors like energy and oil as well as the medical manufacturing industry. In addition to minimizing material waste, the hybrid machine provides a reliable and flexible production solution by utilizing LMD for material coating, repair, and near-net shape manufacture. Multiple LMD heads for accurate and fast operations are part of the machine's sophisticated design, which increases its adaptability to a range of industrial requirements.

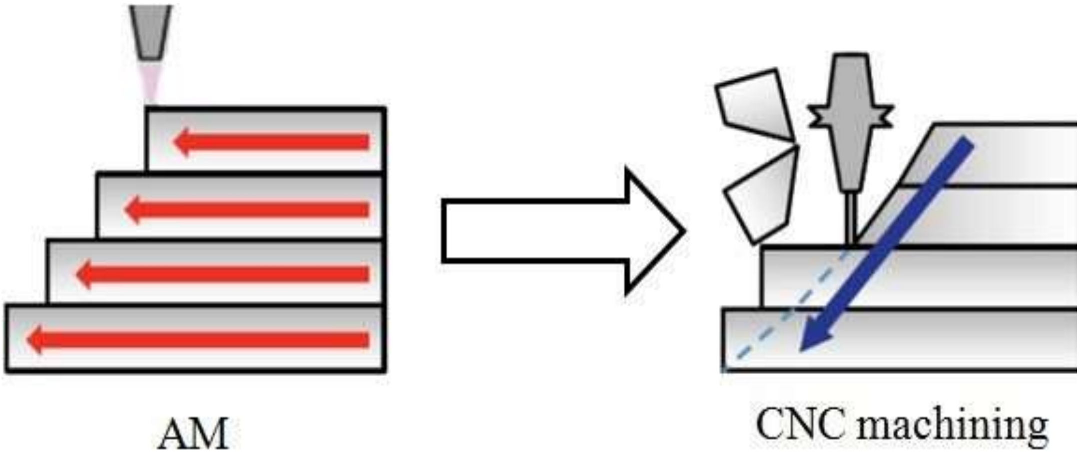


Fig.1. Concept of hybridizing AM and CNC machining

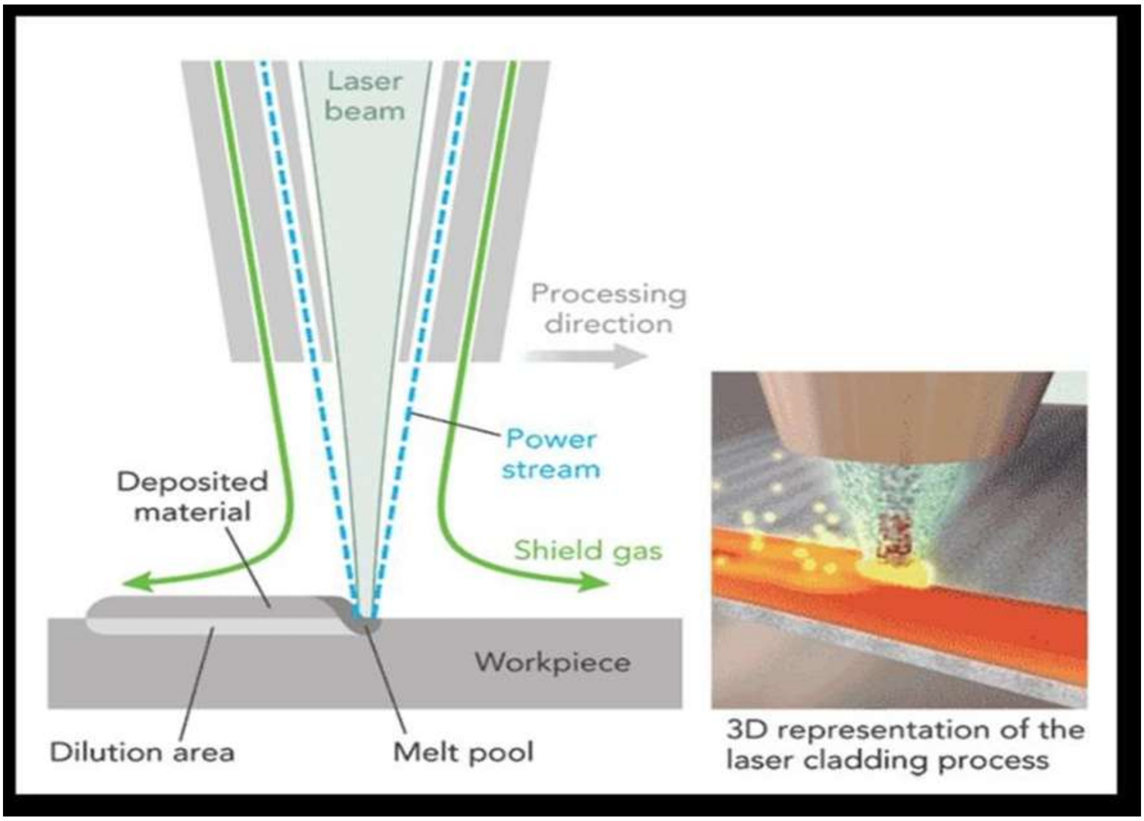


Fig.2. LDM Mechanism

2.2 Introduction of INTEGREX i-400 AM

By combining additive manufacturing (AM) and conventional CNC machining, Yamazaki Mazak Corporation's INTEGREX i-400 AM marks a substantial advancement in hybrid multi-tasking machine tools. The urgent industrial need to cut production costs and processing times while preserving high precision and added value is what this breakthrough aims to solve. Fundamentally, the INTEGREX i-400 AM makes use of 5-axis machining capabilities in conjunction with Laser Metal Deposition (LMD) technology, a directed energy deposition (DED) technique. By increasing productivity and decreasing waste, this synergy makes it possible to produce near-net form components that are then completed with high precision in a single setup.

The machine is specifically made for applications that call for intricate geometries and materials that are challenging to manufacture. The system allows small-lot manufactures of medical devices, aerospace alloys, and energy sector components by integrating LMD. The machine's capacity to respond to a variety of needs is improved by the employment of two separate LMD heads: "Fine" for detailed features and "High-speed" for efficient deposition. An automated tool changer (ATC) allows these heads to be easily incorporated into the process and simply stored in the normal tool magazine.

The oil and energy industry's hybrid processes are a notable use case for the INTEGREX i-400 AM. For instance, the LMD process is used to cover stainless steel substrate components, such as cylinder shafts, with nickel-based alloys, such as Inconel 718. By combining the advantages of additive and subtractive manufacturing, this method drastically lowers the cost of materials and tools. The hybrid process saves a significant amount of money by using fewer raw materials and producing less waste, even though the cycle time may not be very different from traditional processes. This is a significant benefit for producing high-value components.

Notable are the machine's usability and safety characteristics. For operator safety, it has mineral glass windows, interlocked doors, laser protection coverings, and a fume extraction system to control flying metal particles. Lights positioned ergonomically guarantee operator visibility while working. These characteristics emphasize the importance of environmental and operator well-being factors in addition to productivity.

Fig.3. INTERGEX i-400 AM

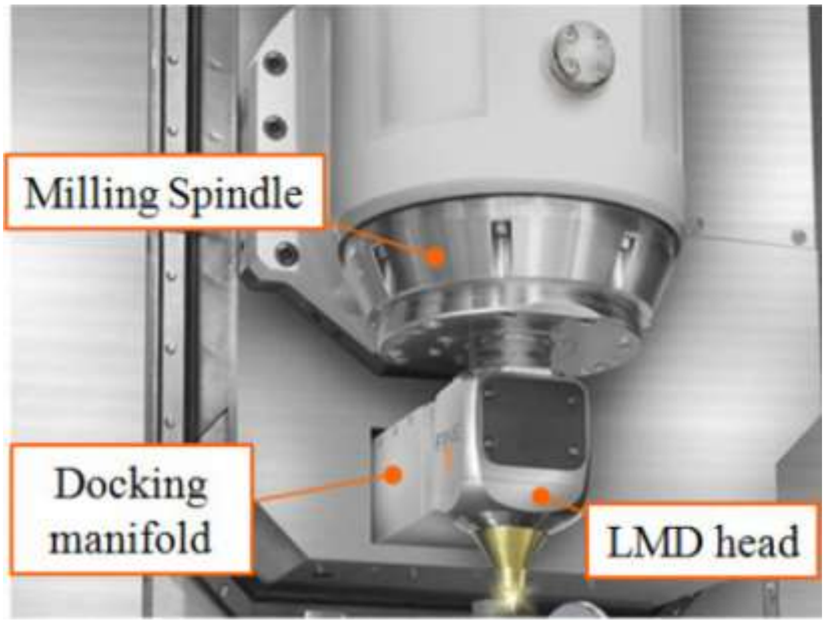


Fig.4. LMD head and docking manifold

3. DEVELOPMENT METHODOLOGY

The creation of a hybrid multipurpose machine tool that combines CNC machining with additive manufacturing (AM) technologies to satisfy the needs of high-wage nations for high-value, cost-effective production. This creative method seeks to improve the "Done-in-One" production concept by fusing traditional turning and milling processes with Laser Metal Deposition (LMD) technology. For small-lot production, complicated aerospace alloys, high-hardness energy sector materials, and specialist medical device manufacture, this hybrid approach is especially useful since it allows for the synthesis of near-net form components using AM and achieves high-precision final machining.

The development history emphasizes that AM has drawbacks such as low precision, high prices, and slower processing rates when compared to conventional technologies, even while it has the potential to produce complex geometries and shorten production lead times. The hybrid technique addresses these problems by combining AM and CNC machining, guaranteeing accuracy and quality right out of the machine. Because it can effectively fuse various metals and alloys, the selected LMD technology, a type of Directed Energy Deposition (DED), is particularly well-suited for applications like material coating, near-net shape creation, and component repair.

The design of the INTEGREX i-400 AM hybrid machine has advanced technologies such as two interchangeable LMD heads for fine or high-speed deposition, multi-axis motion control, and a supplementary spindle for enhanced productivity. This technology ensures versatility in handling a range of activities, from delicate detail work to high-speed manufacturing. Enclosed processing rooms, advanced fume extraction, and ergonomic enhancements are features that put safety first while ensuring operator protection and usability.

The hybrid machine bridges the gap between the precision of CNC machining and the inventive potential of AM, marking a revolutionary advancement in production. Adoption could drive efficiency and sustainability while revolutionizing industries like aerospace, energy, and medicine that depend on high-performance parts.

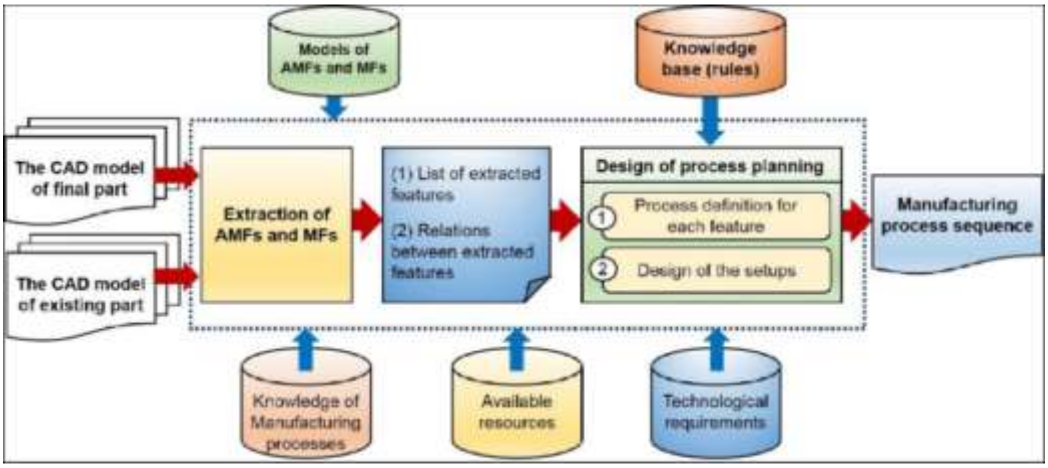


Fig.5. Hybrid manufacturing development

3.1 Sequential Hybrid

This method sequentially combines traditional machining techniques with Additive Manufacturing (AM). It is distinguished by building near-net-shaped components using the AM method first, then achieving the required accuracy and surface quality through precision machining. This technology addresses issues like poor accuracy and surface polish that are inherent in solo AM methods while utilizing the strengths of each process. It is especially well-suited for uses requiring intricate geometries and expensive materials, enabling economical tooling and effective material use.

3.2 Concurrent Hybrid

In this setup, machining and AM operations are either done concurrently or in stages that are closely related within the same system. By removing intermediary procedures, this contemporaneous integration allows for increased productivity and reduced cycle times. It is accomplished by using certain equipment and setups that enable smooth transitions between material removal and deposition. This configuration ensures greater precision and shorter processing times, making it advantageous for applications like coating and repair that call for instant post-processing of additively built parts.

3.3 Hybrid Machines

Advanced multitasking platforms that combine several production processes, like turning, milling, and AM, into a single machine are referred to as hybrid machines. The INTEGREX i-400 AM, which blends conventional CNC machining with Laser Metal Deposition (LMD), is one example. These devices offer flexible ways to produce intricate parts in a single configuration, increasing productivity and cutting down on material waste. They work especially well for producing high-performance materials in small quantities for sectors including energy, medical devices, and aerospace.

4. BENEFITS AND CHALLENGES

4.1 Benefits

1. Efficiency and Cost Reduction: The hybrid machine significantly lowers production costs and material waste by integrating additive and subtractive manufacturing, especially for expensive materials like Inconel 718.

2. Improved Capabilities: The integration makes it possible to build complicated and high-precision geometries in a single setup, increasing accuracy and cutting lead times.

3. Material Versatility: The technique allows for the combination of various materials, allowing for specialized uses such as near-net form fabrication, coating, and repair.

4. Applications in Various Industries: For sectors like aerospace, energy, and medicine where high-precision and high-value manufacturing are essential, the machine is very helpful.

5. Increased Productivity: It incorporates operational safety measures and makes it easier to produce high-value parts with fewer tooling and process steps.

4.2 Challenges

1. High Initial Costs: Adoption in cost-sensitive environments may be constrained by the hybrid machines and AM technologies' substantial initial costs.

2. AM Limitations: Problems like slow build rates and expensive AM materials (such metal powders) continue to be obstacles to wider use.

3. Complexity of Integration: To guarantee functionality and compatibility, extensive engineering is needed when developing systems that combine AM and CNC capabilities.

4. Qualifications & Requirements: New manufacturing techniques necessitate lengthy qualification periods and strict adherence to standards, especially in vital industries like aerospace.

5. Safety and Operator Training: When introducing cutting-edge technology, operators must receive specialized training and have strong safety measures in place to handle metal powders and lasers.

5. ADVANTAGES AND LIMITATIONS

5.1 Advantages

1. Lower Manufacturing Costs: Manufacturers can reduce material waste and tooling costs by combining AM and CNC processes, which lowers manufacturing costs.

2. Increased Production Efficiency: The "Done-in-One" technique made possible by hybrid machines shortens setup periods and facilitates seamless switching between additive and subtractive production processes.

3. Suitability for Complex Components: These machines are perfect for complex designs in sectors like aerospace, energy, and medical devices since they can use AM to create near-net form components and CNC machining to improve them.

4. Material Savings: By employing AM to apply material selectively, the hybrid technique lessens the requirement for extensive machining, especially in expensive alloys.

5.2 Disadvantages

1. Equipment compatibility: Making sure that AM and CNC systems integrate seamlessly.

2. Material compatibility: Handling variations in material characteristics between CNC and AM operations.

3. Process optimization: creating ideal parameters for AM-CNC operations that are coupled.

6. INDUSTRIALAPPLICATIONS

1. Aerospace: The hybrid machine's capacity to process hard-to-cut materials, such as high-strength metals used in airplane components, is advantageous to the aerospace industry. Near-net form production is made possible by AM, especially Laser Metal Deposition (LMD), which lowers material waste and boosts productivity. Given the high cost of materials and strict safety regulations in the aerospace industry, this is essential.

2. Automobile: The hybrid technique in automotive manufacturing facilitates the creation of intricate, lightweight, and high-performing components. Additionally, it facilitates remanufacturing and repair procedures, especially for expensive parts. Faster prototype and production are made possible by the "Done-in-One" idea, which reduces setup time.

3. Health Care: This technology is used by the medical sector to create high-precision parts using specialized metals. These materials are frequently found in implants and surgical tools. Custom and specialized medical equipment can benefit from the hybrid system's accuracy and small-lot production capabilities.

4. Power: High-value components are manufactured and repaired using hybrid machines in the energy sector, specifically in the oil and gas industry. Coating and repairing corrosion-resistant materials, such as Inconel 718, which is frequently used in hostile environments, are examples of applications. The hybrid method minimizes waste and tooling, which results in a significant cost reduction.

7. Application Example

One example of an application is the use of the INTEGREX i-400 AM hybrid multitasking machine to produce components for the oil and energy sector. The component's substrate material is stainless steel alloy (316S31), which is prized for its ability to withstand corrosion, and the deposited material is Inconel 718, a nickel-based alloy that is well-known for its resistance to oxidation, corrosion, and high temperatures.

The hybrid technique used CNC machining for precise finishing and laser metal deposition (LMD) for selectively adding high-performance materials. Creating a cylindrical shaft with spiral coatings, fins, flanges, and bosses using "High Speed" and "Fine" LMD heads was a crucial aspect of this application. For traceability, laser tagging was also used, guaranteeing that the procedure was finished in a single machine configuration.

Compared to traditional manufacture, which would have involved machining the entire component from a solid Inconel 718 block, this method produced notable material cost reductions and improved tool life. For example, the hybrid method required less than 10 kg of metal powder and a stainless-steel substrate, costing around $2,500, whereas a typical approach would need about 90 kg of Inconel 718 (at a cost surpassing $90,000). The example demonstrates how the hybrid machine may efficiently combine disparate materials to create high-value components at lower prices and with increased productivity.

Fig.6. Application example for hybrid process

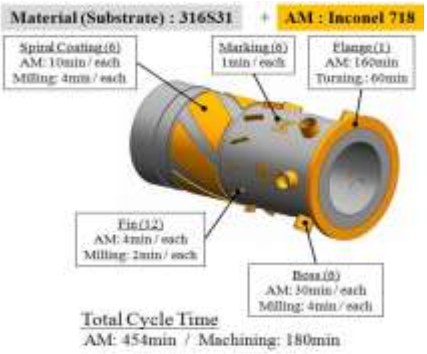


Fig.7. Total cycle time of the application

8. Case Studies

8.1 Oil-Energy Industry Application

316S31 stainless steel cylinder shaft substrate is covered with the nickel-based alloy Inconel 718. Both "Fine" and "High-speed" Laser Metal Deposition (LMD) heads are used in this hybrid technique. In order to achieve cost reduction and traceability within a single manufacturing setup, the procedure entails generating bosses, flanges, fins, spiral coatings, and laser marks. By using less costly solid materials like Inconel 718, this method drastically lowers material costs and tool wear as compared to traditional machining.

8.2 Mechanical and Microstructure Evaluation

The deposited Inconel 718 material performed similarly in strength tests to hot-rolled bars that were not heat treated. High reliability in material integration was demonstrated by the bond strength of Inconel 718-316S31 joints surpassing the tensile strength of 316S31. No joint flaws were found by microscopic examination, confirming the hybrid process's integrity.

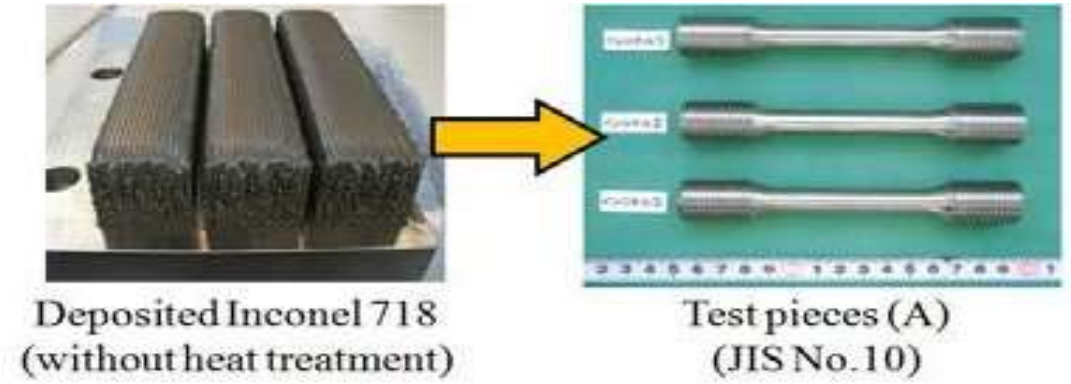
9.Results of LMD Process Evaluation

The study's assessment of the Laser Metal Deposition (LMD) technology yields encouraging findings for applications involving additive manufacturing. Test pieces were created using the same application conditions as the hybrid machine that was produced in order to do the assessment. Mechanical strength, hardness, and microstructural properties of (A) the deposited Inconel 718 material and (B) the jointed interface between Inconel 718 and a 316S31 substrate were the main criteria of this study.

The results show that the deposited Inconel 718's mechanical characteristics are on par with those of hot-rolled Inconel 718 bars that have not undergone heat treatment. Robust material deposition is indicated by the equivalence between the tensile strength and 0.2% proof stress values. Furthermore, consistent findings from hardness testing supported LMD's capability for creating long-lasting components.

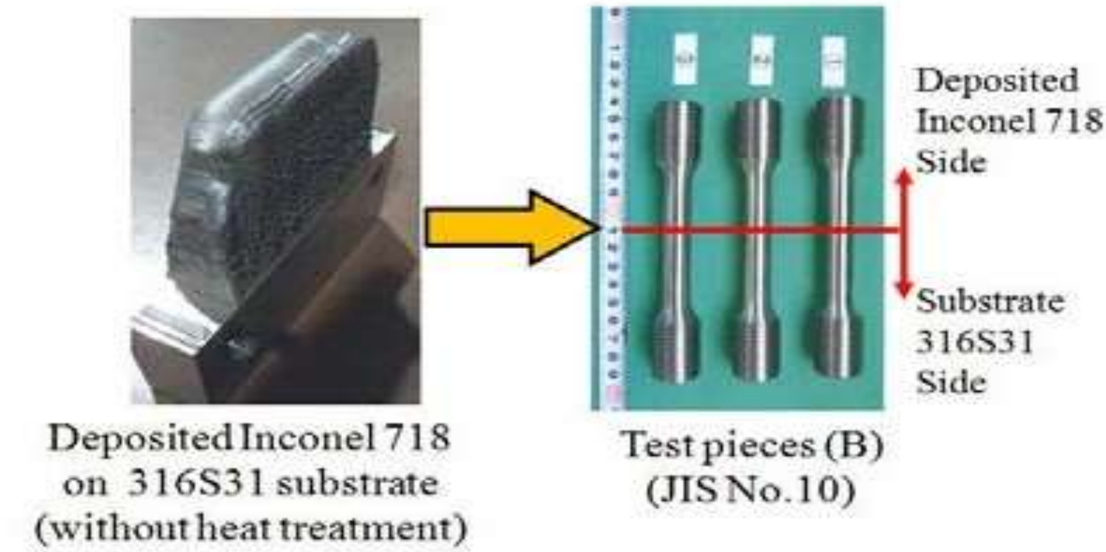
Tensile testing revealed that the 316S31 substrate, not the joint contact, was the rupture point for the junction between the deposited material and the substrate. This outcome shows that the joint strength is greater than the substrate material's intrinsic mechanical strength. This finding was corroborated by microstructural investigation, which revealed no flaws in the heavily deposited material and few areas of the substrate that were diluted or heated. The accuracy of the LMD process is responsible for these features.

The study comes to the conclusion that by permitting high-strength junctions between incompatible materials, LMD technology has the ability to completely transform traditional production techniques. This capacity could improve manufacturing efficiency and enable creative product designs. LMD's cost-effectiveness and material-saving benefits over conventional techniques are emphasized, with special attention paid to its useful applications in repair, coating, and near-net shape manufacturing. This development is a big step in the direction of combining additive and subtractive manufacturing methods for industrial processes of the future.



Deposited Inconel 718 (without heat treatment)

Test pieces (A) (JIS No.10)



Deposited Inconel 718 on 316S31 substrate (without heat treatment)

Test pieces (B) (JIS No.10)

Fig.8. Specimens for tensile strength testing

10. Future Research Direction

1. Enhancement of Hybrid Procedures:

Enhancement of Laser Metal Deposition (LMD) process control and its combination with CNC machining. Creation of cutting-edge methods to improve hybrid processes' precision, material use, and energy efficiency.

2. Research on Materials: Investigation of multi-material fabrication methods to improve hybrid systems' performance. Examining the characteristics of joined and deposited materials to guarantee mechanical performance and dependability

3. Increased Uses: Using hybrid systems for a range of sectors, including tooling, energy, medical devices, and aircraft. Pay attention to coating applications, near-net form production, and maintenance procedures.

4. Cost-Effectiveness:

Research to lower the high prices of hybrid systems and AM powders. Formulating plans to reduce material waste and tooling wear.

5. Improvement to the system:

Improvements in LMD head architectures for increased speed and accuracy. incorporating automation features, like improved fume extraction and ergonomic designs, to increase usability and safety.

6. Adoption in Industry:

Tackling the issues of hybrid process acceptance and qualification periods in vital sectors like aerospace. Gaining the trust of the industry requires exhibiting reliable and consistent performance.

11. Conclusion

Mazak created the Hybrid Multi-tasking machine tool with LMD function in addition to turning and milling capabilities because of the technological limitations of AM. By using this machine, it was discovered that there are numerous areas where a hybrid process offers a significant benefit over traditional manufacturing methods. Mazak simultaneously gave an example of how to use the hybrid process to create an industrial product with sufficient mechanical strength. This process is anticipated to gain popularity across a range of industries for coating, mending, and producing prototypes or high-value goods.

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