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A comprehensive design framework for additive manufacturing in the automotive industry: a case study

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ABSTRACT

Purpose: The work aims to propose a comprehensive design framework for additive manufacturing and apply it to a case study of the height adjuster handle of a car. The aim is to provide designers and engineers with a practical example of how the framework can be used to design a complex part for additive manufacturing. The article also aims to demonstrate the potential benefits of additive manufacturing in the automotive industry, such as improved performance, reduced times, and cost savings. Additionally, the article aims to compare the developed framework with existing design for additive manufacturing (DFAM) methodologies and highlight its unique features and advantages in designing the height adjuster handle.

Design/methodology/approach: The study used qualitative and quantitative data collection and analysis methods. The first phase of the study involved a systematic review of existing DfAM methodologies and a critical analysis of their strengths and weaknesses. Based on this analysis, a new DfAM framework is developed, which aims to address the limitations of existing frameworks and provide a comprehensive design approach for additive manufacturing. The second phase of the study involved applying the developed framework to a case study of a complex automotive part - a height adjuster handle. The design requirements of the height adjuster handle were identified based on the principles of DfAM, and the part was designed using computer-aided design (CAD) software and optimised topologically using ANSYS software. In the third phase, the performance of the height adjuster handle designed using the developed framework was compared with a part manufactured with injection moulding technology. The comparison was based on various performance criteria, including mechanical properties, dimensional accuracy, and production time and cost.

Findings: The findings of the study demonstrate the effectiveness of the developed design framework for additive manufacturing (DfAM) in producing a complex automotive part with improved performance characteristics and reduced lead time.

Research limitations/implications: Although the results of the study provide important insights into the effectiveness of the developed DfAM framework for producing a complex automotive part, there are some limitations to the research that should be considered, such as the case study involved the design of a single part, and the results may not be generalisable to other parts or applications. Further research is needed to validate the effectiveness of the DfAM framework for a broader range of automotive parts.

Practical implications: The findings of the study have important practical implications for the automotive industry. The developed DfAM framework can be used in the FDM technology. It can be used as a decision aid in the manufacturing of FDM parts in order to improve the efficiency and cost-effectiveness of the production process for complex automotive parts.

Originality/value: The value of the study is the development of a novel DfAM framework and the demonstration of its effectiveness in a case study. The proposed framework can be used as a reference for future research. It can also provide practical guidance for industry professionals seeking to improve the efficiency and cost-effectiveness of their additive manufacturing processes.

Keywords: Additive manufacturing, Design for additive manufacturing, DfAM, FDM technology

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Additive manufacturing is a crucial component in the growth of Industry 4.0; it can be used in a smart factory environment to produce on-demand, highly customised products with increased flexibility, efficiency, reduced waste and responsiveness to customer needs. The integration can be achieved using digital design tools, automated production processes, and real-time monitoring [1,2]. AM allows the creation of products by constructing them layer by layer from a 3D model, yielding complex internal and external shapes that cannot be produced using traditional techniques [3]. It offers several advantages over traditional manufacturing methods, such as design freedom, reduced waste, and shorter lead times [4]. Despite its advantages, additive manufacturing also has limitations such as size constraints, material limitations, and limitations in part quality [5]. The growth of additive manufacturing significantly impacts both industry and academic fields, and ongoing efforts are aimed at improving the process, materials, and design. The utilisation of additive manufacturing frequently leads to questions about its benefits over traditional processes and technologies, including whether manufacturing is cheaper [6].

On the other side, designers often face difficulties exploiting the full potential of additive manufacturing, leading to growing attention towards the Design for Additive Manufacturing (DfAM) [7]. The term Design for Additive Manufacturing (DfAM) is not consistently used by researchers [8]; it refers to the design approaches that take advantage of the unique capabilities of additive manufacturing while considering the limitations of the specific AM technology process [9]. However, a clear differentiation between the various design methods used in additive manufacturing is essential, including those that change the production process, alter the shape for better fit, and completely re-design forms and functions for AM compatibility.

The proposed DfAM framework integrates various design considerations such as part geometry, material selection, topology optimisation, and process simulation to achieve optimal design solutions that meet the performance and design requirements of the automotive industry. The framework also includes multiple objectives, such as manufacturability, performance, and cost, into the design process to provide a comprehensive approach to designing and producing complex parts using AM technologies. While previous studies have proposed similar DfAM methodologies, our paper proposes an approach that underlines the importance of design for manufacturability and incorporates a lot of considerations.

The value of the paper is in the application of the methodology to a case study of a handle adjuster, which demonstrates the effectiveness of our approach in attaining significant improvements in design efficiency and cost reduction. Our contribution to the field is the development of a comprehensive DfAM methodology that considers both technical and economic aspects of additive manufacturing. We demonstrate the effectiveness of our approach through a case study on the handle component, which significantly reduced weight and production costs while maintaining or improving performance. Our work provides practical implications for the automotive industry. It contributes to advancing technically sound and economically feasible additive manufacturing research, which has practical implications for the automotive industry and other manufacturing sectors.

2. State of the Art of Design for Additive Manufacturing (DfAM)

"Design for Additive Manufacturing" is a well-known term in literature; it describes various design techniques and tools optimised for functional performance and critical aspects of the product life cycle, considering the characteristics of additive manufacturing technologies [10]. It includes manufacturability, reliability, and cost [11]. DfAM also accounts for the constraints of the additive manufacturing technology employed in producing the product [9].

DfAM is a subgroup of "Design for X" (DFX), (DFX) regroups methods for integrating different issues into the design process [11]. For instance, "Design For Manufacturing and Assembly" (DFMA) refers to the standards for "Design For Assembly" (DFA) and "Design For Manufacturing" (DFM). Design for Additive Manufacturing (DfAM) is the new name for the DFM concept in AM. It is a design strategy that minimises development costs and time while enhancing performance, quality, and profitability [9]. It is done by considering both design objectives and production limitations, such as user and market demands, materials, processes, assembly and disassembly techniques, maintenance requirements, and other factors [10].

2.1. The necessity for DfAM

The DfMA concept encompasses all processes, including AM processes. However, DfAM distinguishes itself from traditional DfMA by requiring different design knowledge, tools, rules, procedures, and methods [12].

Additive manufacturing overcomes the limitations of traditional methods by producing more complex parts with better functionality [9]. It offers designers numerous possibilities due to its distinctive features. The identified capabilities of additive manufacturing are detailed below:

- Freeform shapes and materials: The flexibility in design complexity provided by additive manufacturing enables designers to create any desired shape [13].
- Multiple materials: The capability to print multiple materials simultaneously is a critical aspect of additive manufacturing. The feature allows composite objects with dynamically changeable topographies to be created [8,13,14].
- Internal freeform geometry: By utilising additive manufacturing, it's possible to create complex internal features like compliant cooling channels, fluid channels, and air ducts, which can enhance the performance of a component [8,13].
- Thin and small structures: The smallest possible feature size is primarily determined by the x-y resolution of the 3D printer, enabling additive manufacturing to produce delicate and miniature features like thin walls, tiny holes, and pins [13].
- Textured surfaces: Textured surfaces have become increasingly popular in recent years due to their ability to improve the look and feel of a product. With the help of additive manufacturing (AM) technology, it is now possible to produce textured surfaces on a wide range of consumer goods, including plastics, metals, and ceramics [9,13].
- Topology optimisation for additive manufacturing: The advanced capabilities of AM technology allow the creation of parts with optimised topologies [7,15]. It is made possible through the use of Topological Optimisation (TO), a numerical method that adjusts the arrangement of materials within a design to meet specific performance goals, as well as finite element analysis (FEA), which is often utilised in research for topology optimisation in additively manufactured parts [13].

Although AM has many possibilities, it also has certain restrictions. In order to effectively utilise AM, designers must consider constraints such as those in CAD, anisotropy, porosity, support structures during production, and orientation [4,8, 16-18].

2.2. Design methods for AM

The literature describes several design methods for additive manufacturing [19,20]. However, the bottom-up approach using the functional surface method [16] is the most effective. Such a method requires a strong connection between design and finite element analysis (FEA) for optimal results.

The methodologies described in the literature are summarised in Table 1.

The crucial steps for AM design are described in Figure 1.

However, the described methodologies present limitations, which are regrouped in Table 2.

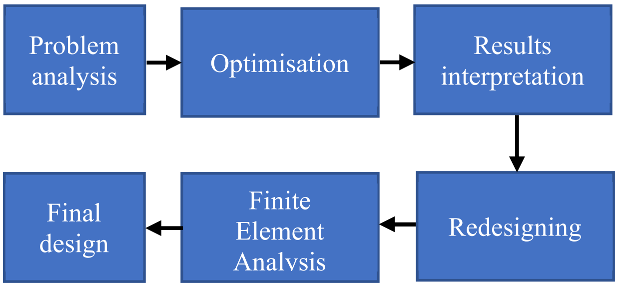

Fig. 1. Crucial steps for AM design

Table 1.
Different DfAM methodologies exist

Resource	Methodology	Steps
[21]	Design methodology for additive manufacturing, application to powder projection	• Definition of a design space • The definition of the final theoretical geometry of the product • The definition of the corresponding practical geometry • Geometry estimation because for the same initial conditions
[22]	Global methodology for AM	• Problem definition • Part consolidation • Identification of the failure mechanisms • Part optimisation
[23]	Design for additive manufacturing application to EBM technology	• Generation of an initial shape • Part optimisation • Choose the orientation • The initial geometry is adapted • Validation of the part
[24]	Methodology for Designing Pieces for Additive Manufacturing.	• Create a basic geometry • Suggest an optimised geometry • Ensure the manufacturability of the part
[7]	Global methodology for a multi-mechanical systems	• Specification • Optimisation • Conception • Validation

Table 2.
Limitations of the reviewed methodology

Limitation	Description
Incomplete design stages	The methodologies do not cover all stages of the design process for additive manufacturing.
Technology-specificity	Some approaches may be effective for certain technologies but not necessarily for others.
Limited capacity	Some approaches are not open to all capacities of additive manufacturing.
Support generation	The generation of supports, which is done by the slicing software, is not addressed.
Domaine particularity	Some approaches are focused on a particular objective, domain, or application, limiting their applicability to other areas.
Orientation limitations	The orientation of the part is based only on the machine space and may not consider other factors.
Material selection	No information is provided on the selection of materials, which is an important consideration in additive manufacturing.

3. Methodology

After examining the advantages and limitations of previous design methods, it seems there is a need for a new framework that combines the benefits of additive manufacturing (AM). This section introduces a new design technique that considers the benefits of AM in component design.

The objective of the methodology is to create the optimal design that meets the client's needs while taking advantage of the specific advantages of AM technologies. The process starts with problem definition and finishes with the validated final design, presented as a flowchart in Figure 2. The methodology is further explained in each section below.

The methodology proposed in Figure 2 provides a structured approach to developing an effective DfAM methodology, highlighting the importance of testing and refining the design in order to obtain a final design that respects the specifications and profit of the capabilities of the AM technology. It underlines the importance of considering the design problem and application, selecting the appropriate additive manufacturing process and material, and optimising the design. By following this framework, designers and engineers can develop additively manufactured parts with quality and performance.

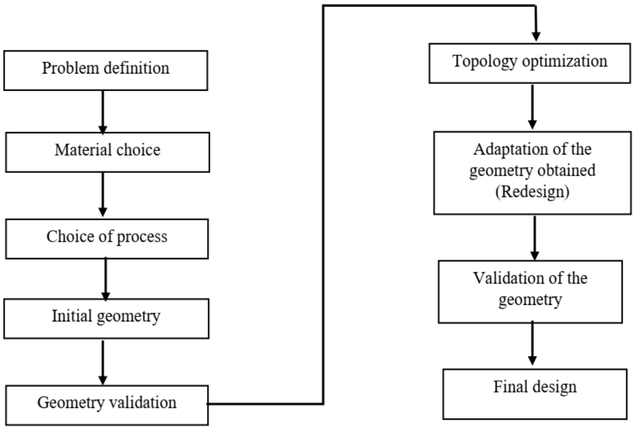

Fig. 2. Different steps of the methodology proposed

4. Validation of the proposed methodology

In order to evaluate the proposed methodology, a height adjuster handle for a car made using the injection moulding process is analysed. To demonstrate the effectiveness of our approach, a comparison is established between the part designed to be produced by the injection moulding process and a part to be produced by the additive manufacturing process while taking advantage of the benefits offered by this technology.

4.1. Case study

The considered case study is a Height Adjuster Handle, a lever used to adjust the height of the driver's seat. It is typically located on the side of the driver's. Based on an existing handle, the preliminary design is established using CAD software and given in Figure 3.

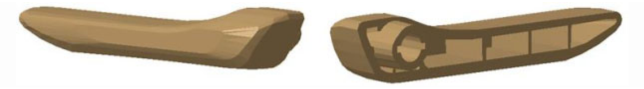

Fig. 3. Initial geometry of the handle

The purpose of this study is to use the entire potential offered by additive manufacturing processes in order to improve the design of the handle. The results of this case study will provide insights into how well the proposed DfAM methodology performs in optimising the design of a complex part that will be manufactured by FDM technology.

4.2. Problem definition

The purpose of this initial step is to define the context of the design process and comprehend the issue for that:

- Identify the problem: The problem, in this case, we want to solve is to design a height adjuster handle, which is a plastic component located on the car seat, using FDM technology.
- Define the scope: The scope includes the size, shape, and material requirements for the height adjuster handle. It also includes functional requirements, such as the ability to adjust the higher seat's height. We also need to consider constraints like being more user-friendly, ergonomically designed, and easy to operate, providing a safe and comfortable ride for all passengers, and manufactured using FDM technology.
- Identify constraints: We must identify any constraints that must be considered in the design process. Constraints may include production cost, material availability, printing capabilities, and durability requirements.

We also need to ensure that the design can withstand certain forces and stresses that arise during the normal use of the car.

The requirements for a height adjuster handle for a car are described in Table 3.

Table 3.
Height Adjuster Handle specifications

Component	Height adjuster handle
Primary function	Allow the user to change the height of a car seat
Other functions	Functionality, appearance, durability, cost, easy to instal, environment, ergonomic
Dimensions	L120*W22*D30 mm

4.3. Material choice

During the given stage, the selection of materials to compose the part is made. The additive manufacturing process heavily depends on the material, which influences the type of machine utilised, the amount of work required, and the potential form and mechanical strength of the final product [24].

PLA, ABS and PETG are the most popular materials used in FDM technology [25], and each has its own properties [26]. In our case, the choice between those materials can vary depending on the design and manufacturing process and the following requirements: mechanical strength, density, cost, availability, surface quality, durability, printing time, environment, and post-treatment.

Taking into account those requirements and using data provided by the material database CES EDUPACK, the ABS metal is the best choice for our case study; the characteristics of the ABS used are given in Table 4.

Table 4.
Material proprieties

Density	1.03 e^3 kg/m^3
Young's modulus	1.628 e^9 Pa
Yield strength	2.744 e^7 Pa
Tensile strength	3.626 e^7 Pa

4.4. Process choice

Once the material for the part has been selected, certain processes incompatible with the chosen material can be eliminated. It means only compatible machines from the available options must be considered.

According to ASTM F2792, Additive manufacturing processes are classified into seven groups: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization [3]. Those processes differ depending on the material type or the state where the initial material is presented [3].

In our case, in order to make a process choice for producing the handle, factors to be considered are, for example, the required production volume, the desired surface finish, the dimensional accuracy required, the complexity of the part geometry, and the available production equipment and resources, for all that, as the height adjuster handle is a plastic part. According to step 2, ABS is the material to use; for that, Fused Deposition Modelling (FDM) is the perfect choice to produce our part while respecting the exigences of the part. Such a technique consists of depositing material by layer; it generally uses a filament of polymer material, which is melted in a liquid state in a liquefaction head and extruded through a nozzle [3].

4.5. Initial geometry

In the given step, a first model is generated using computer-aided design (CAD) software (Catia V5) or scanned using a 3D scanner for existing parts. The model will serve as a starting point for the topological optimisation stage while considering the machine and material information.

The initial model of the handle is presented in Figure 3.

4.6. Validation of the geometry

Before moving forward, performing a static analysis using Ansys software (see the results in Fig. 4) to evaluate how the part behaves mechanically is important. This analysis provides areas of the design that have the maximum stress and strain and that the design should not exceed. Then, the structural analysis of the model was performed by ANSYS as follows:

- Mesh the part,
- Apply the boundary conditions,
- Apply load case,
- Analyse the stress by von-mises criterion (Fig. 4),
- Analyse strain as shown in Figure 4.

Otherwise, we might reach a point where we cannot proceed further during the topological optimisation process.

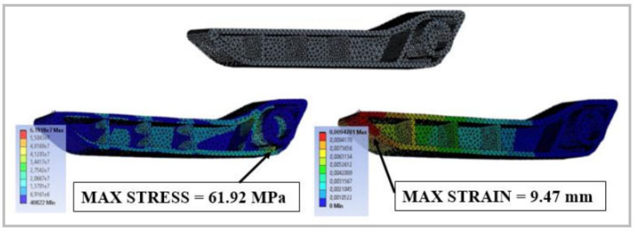

Fig. 4. Static analysis results of the handle

4.7. Topology optimisation

The handle ensures topological optimisation during the given stage to reduce weight, cost, and production time. The topology optimisation is performed to the handle using ANSYS software. Based on the static analysis, the structure can be divided into design and non-design. The non-design space cannot be modified, whereas the design space can be modified through iterative design until the objective of minimisation of 30% is attained after six iterations, as described in Figure 5. The CAD model of the handle requires some geometrical parameters to be checked, such as the thickness of the walls, which ranges from 0.6 to 2.5 mm. It is also important to consider overhangs in order to optimise the manufacturing process. Additionally, the holes must be checked based on their print orientation to ensure the part's quality [8].

According to the results listed in Table 5, the validation analysis indicates that the stress and strain values are below

Table 5.
Review of the results obtained for different percentage

	Original part	Optimised part					
		30%	40%	50%	60%	70%	80%
Mass, g	42.3	12.7	16.9	21.2	25.4	29.6	33.9
Volume, m^3	3.71E-5	1.11E-5	1.49E-5	1.86E-5	2.23E-5	2.6E-5	2.97E-5
Sterss, MPa	61.9	51.4	47.6	34.1	37.7	34.1	35.0
Strain, mm	9.47	6.31	2.63	2.28	2.14	2.09	2.03

the specified prescribed limits. As a result, the 30% lattice density-based part is the preferred geometry as it has achieved approximately 70% mass optimisation. The stress concentration is observed on the fixation support. At the same time, the highest strain level is identified at the end of the handle, which is similar to the behaviour of the original part. Figure 6 demonstrates these findings.

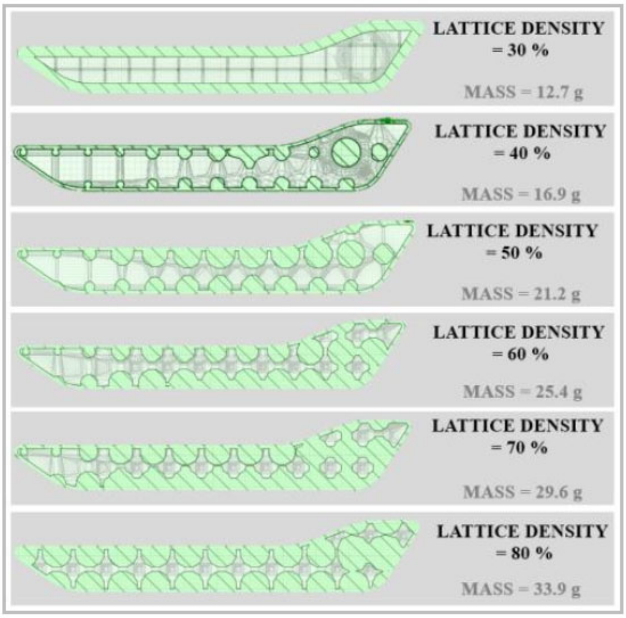

Fig. 5. Lattice topology optimisation results

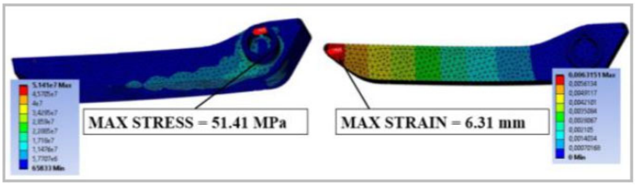

Fig. 6. Static results of the optimised part

The validation analysis reveals that part has a 17% reduction in stress concentration and the strain is reduced by 34% in the part.

4.8. Adaptation and validation of the geometry

The result of topology optimisation is often a complex geometry that may not be suitable for manufacturing. The given step involves modifying the geometry to ensure that it meets the design requirements while considering practical considerations such as manufacturability and structural integrity, which implies adding or removing features and adjusting the structure's shape.

Adapting the geometry after topology optimisation aims to arrive at a final design that meets the required performance and functionality while being manufacturable and useful.

4.9. Final design

After adaptation and validation of the geometry after optimisation, the final design refers to the modified completed design. It includes the optimisation process results and any necessary adaptations and validations to ensure the design meets the desired performance criteria. It also considers other factors such as ergonomics, aesthetics, and manufacturability. The final part of the handle is presented in Figure 7; such a design will be used in the manufacturing process.

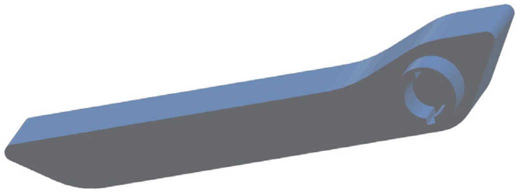

Fig. 7. The final part

The CAD model of the handle is prepared to manufacture the final design obtained using the FDM technology. This CAD model is then imported into the slicing software, which generates the toolpath for the 3D printer. The 3D printer is set up with the appropriate parameters, such as layer height and printing speed. The printer then starts building the part layer by layer.

5. Discussion

The proposed DfAM methodology gives a structured approach to designing parts for AM. Designers can follow the given methodology to build parts that fully utilise AM's capabilities, including complex geometries and lattice structures. The methodology allows designers to create optimised parts that meet functional requirements and constraints while reducing weight and material usage. The case studied is an automotive part; it is generally produced using the Injection Molding process, a popular manufacturing method for producing plastic components like our case [27].

In terms of the process, injection moulding and FDM are quite different. Injection moulding involves melting and injecting molten plastic into a mould [27], while FDM builds a part layer-by-layer by extruding melted plastic through a nozzle [3].

In terms of material, injection moulding allows the use of a wider range of materials, including high-performance plastics [28]. Injection-moulded parts also have a smoother surface finish and more precise dimensions due to the use of a mould. On the other hand, FDM is limited to various materials, and parts may have a rougher surface finish due to the layer-by-layer build process [3].

Regarding production time and cost, injection moulding can be more expensive upfront due to the cost of creating the mould but can be more cost-effective for high-volume production [28]. On the other hand, FDM has a lower upfront cost and can be more cost-effective for lower-volume production [25].

Using the FDM technology for our application presents some limitations, such as the surface finish of the printed part not being as smooth and precise as the surface finish of an injection-moulded part. It can affect the aesthetic of the height adjuster handle, particularly if the surface texture is an important aspect of the design; also, FDM technology is generally slower than injection moulding, which limits its effectiveness for producing the handles in large volumes. FDM printers also have size limitations, which can restrict the size of the handle that can be produced.

Despite those limitations, FDM technology offers design flexibility and quick iteration and can still be useful for producing Height Adjuster Handles for low volumes or prototyping purposes. It can also be a helpful process for producing extra parts.

6. Conclusions

The DfAM approaches are intended to assist designers in making design choices to meet functional needs, guarantee manufacturability in AM systems, and help manufacturers during part fabrication in those systems.

The paper describes a framework for a methodology to design for additive manufacturing with respect to the client requirements and the machines' performance, with additional value compared to the existing DFAM methods.

The main DfAM steps involved in this methodology are problem definition, material and process choice, topology optimisation and redesigning.

A case study of an automotive part is used to verify the methodology. The results show that by utilising additive manufacturing resources, engineers can improve their output efficiency regarding the mass and volume of the part while respecting the specifications of the clients and profiting from the benefits of additive technology; a comparison between the FDM process and injection moulding is discussed. It was found out that FDM is a suitable choice for producing simple and functional parts such as a height adjuster handle, where cost-effectiveness and quick production are important factors. However, injection moulding is a better choice for large production due to its ability to produce quality, durable parts in large quantities at a lower cost per part.

Additional information

The results obtained in the work were presented at the 15th Congress of Mechanics Morocco.

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