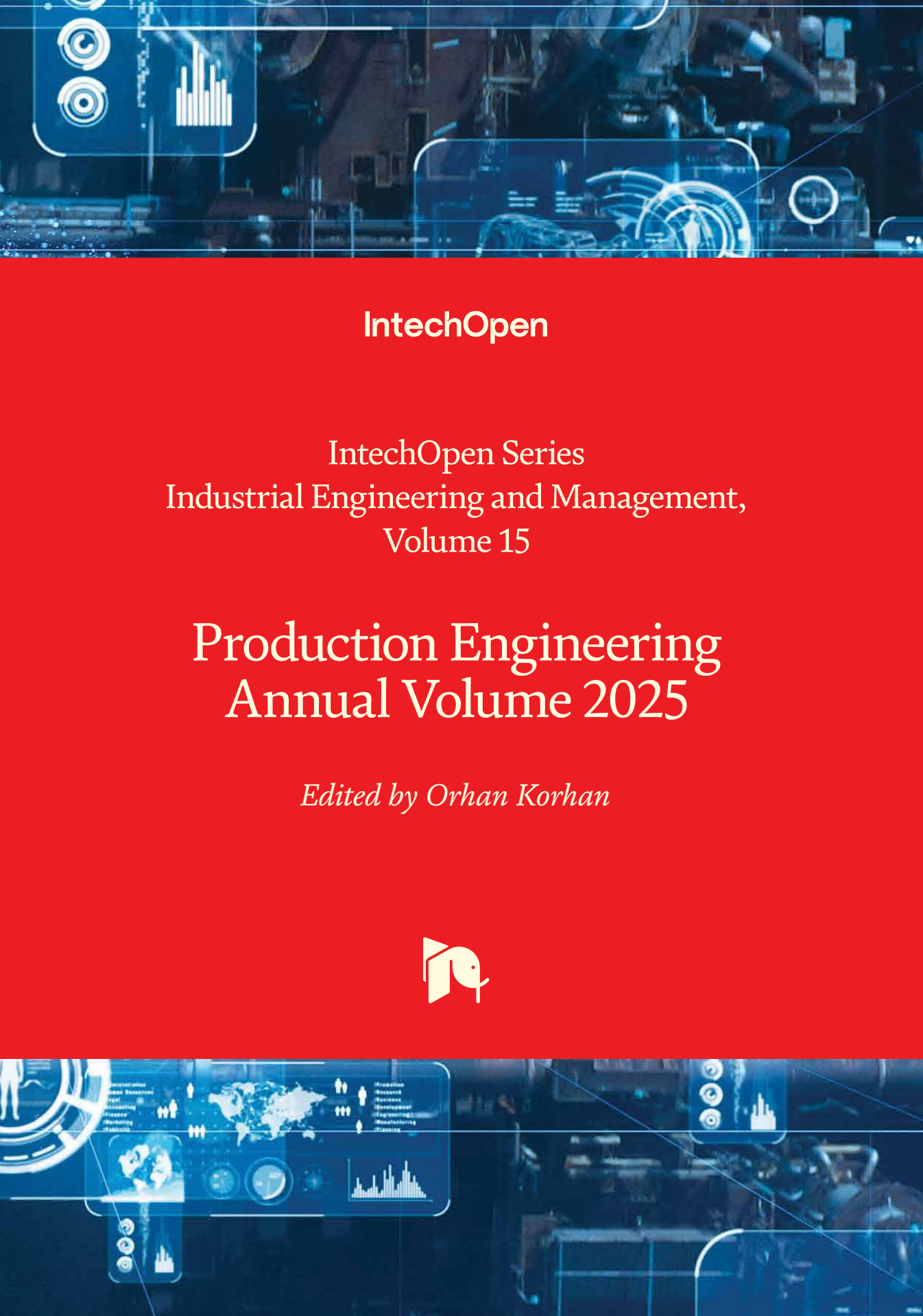




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Volume 15

Aims and Scope of the Series

Industrial Engineering and Management (IEM) is a discipline that focuses on optimizing complex processes and systems within various industries. It involves the integration of engineering, business, economics, mathematics, and behavioral sciences to improve efficiency, productivity, quality, and overall performance in organizations. Key aspects of Industrial Engineering and Management include: Process Optimization; System Analysis and Design; Quality Control and Management; Supply Chain Management; Operations Management; Human Factors and Ergonomics; Project Management; Cost Analysis and Financial Management; Decision Analysis.

Overall, Industrial Engineering and Management aims to optimize resources, improve processes, enhance productivity, and ensure the effective and efficient utilization of all elements involved in the production or delivery of goods and services. It is crucial in today's competitive business environment for organizations to stay efficient and competitive.

Production Engineering and Operational Excellence are fields of study and practices that focus on optimizing and improving the manufacturing and production processes within an organization. It combines principles from engineering, management, and operational strategies to enhance productivity, efficiency, quality, safety, and sustainability in the production of goods and services.

Here are the key components of Production Engineering and Operational Excellence: Process Optimization; Operational Excellence; Manufacturing Systems Design; Quality Management; Supply Chain Optimization; Production Planning and Scheduling; Automation and Technology Integration; Health, Safety, and Environmental Management; Cost Management; Performance Measurement and Key Performance Indicators (KPIs); Continuous Improvement and Innovation. Production Engineering and Operational Excellence are crucial for organizations aiming to stay competitive in the global market by achieving high levels of efficiency, quality, and customer satisfaction while optimizing resources and minimizing waste. It is a multidisciplinary approach that encompasses engineering principles, management strategies, and the effective use of technology to drive operational success.

Meet the Series Editor



Fausto Pedro Garcia Marquez is a Full Professor at UCLM, Spain, with accreditation since 2013. He also holds the position of Honorary Senior Research Fellow at Birmingham University, UK, and serves as a Lecturer at the Postgraduate European Institute. In addition to these roles, Fausto has experience as a Senior Manager at Accenture from 2013 to 2014. He earned his European Ph.D. with the highest distinction. Throughout his career, Fausto has received numerous awards and honors. These include the Nominate Prize (2022), Gran Maestre (2022), Grand Prize (2021), Runner Prize (2020), and Advancement Prize (2018), as well as Runner (2015), Advancement (2013), and Silver (2012) by the International Society of Management Science and Engineering Management (ISMSEM). He was also the recipient of the First International Business Ideas Competition 2017 Award. Fausto's contributions extend to academic publishing, with over 242 papers to his name. Notably, his work has been recognized in journals like "Applied Energy" (Q1, IF 9.746, Best Paper 2020) and "Renewable Energy" (Q1, IF 8.001, Best Paper 2014). His affiliations include the editorial and authorship roles in more than 50 books, with publications through respected publishers such as Elsevier, Springer, Pearson, Mc-GrawHill, IntechOpen, IGI, Marcombo, and AlfaOmega. He has authored over 100 international chapters and holds 6 patents. Fausto serves as the Editor of 5 International Journals and is a Committee Member for more than 70 International Conferences. His research portfolio encompasses being the Principal Investigator in 4 European Projects, 8 National Projects, and participating in over 150 projects involving universities and companies. His areas of expertise and research interests span Artificial Intelligence, Maintenance, Management, Renewable Energy, Transport, Advanced Analytics, and Data Science. Fausto is a recognized Expert in the European Union in AI4People (EISMD) and ESF. He also serves as the Director of www.ingeniumgroup.eu, holds the status of Senior Member at IEEE since 2021, and has been honored as an Honorary Member of the Research Council of the Indian Institute of Finance since 2021. Fausto is also the Committee Chair of The International Society for Management Science and Engineering Management (ISMSEM) since 2020.

Meet the Topic Editor



Orhan Korhan graduated with a BS from Eastern Mediterranean University (EMU), Northern Cyprus, in 2000, an MS from the University of Louisville, USA, in 2002, and a Ph.D. in Industrial Engineering from EMU in 2010. He has been working at EMU since 2009. He became an Assistant Professor in 2010, an Associate Professor in 2014, and a Full Professor in 2020. He is a member of scientific committees at several international conferences and has published several books, book chapters, and papers. He established the Industry 4.0 Research Center in EMU. He is also a certified specialist in occupational safety and health. His current research interests include Industry 4.0, work-related musculoskeletal disorders, cognitive ergonomics, and facilities planning and design.

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Preface

Production engineering is a dynamic and multidisciplinary field that blends manufacturing technology, engineering sciences, and management principles to optimize complex systems, processes, and organizations. It is dedicated to the comprehensive understanding and practical implementation of engineering techniques to improve manufacturing methods, enhance efficiency, ensure quality control, and reduce production costs—ultimately making products more competitive and marketable.

At its core, production engineering focuses on the development, improvement, and integration of systems involving people, knowledge, information, equipment, energy, materials, and finances. These systems are analyzed and optimized using tools derived from mathematics, the physical and social sciences, and engineering design methodologies to predict and evaluate the performance of both existing and emerging manufacturing systems.

This book is a curated collection of current research, innovations, and practical applications in production engineering. It brings together a diverse set of contributions that reflect the ongoing transformation within the industry, driven by technological advancement and digital integration.

Among the topics explored are:

- **Forming 1050 Aluminium Alloy by Implementing SPF Concept**, which showcases advanced material forming techniques for lightweight and high-performance applications.
- **The Application of 3D Printers in Textile**, demonstrating how additive manufacturing is revolutionizing traditional industries through customizability and sustainability.
- **A New Approach to Calculate the Maintenance Period for Industrial Robots to Increase Efficiency in Manufacturing Industry**, offering intelligent predictive models aimed at minimizing downtime and enhancing manufacturing efficiency.
- **Intelligent Systematization for Operational Excellence through Software for Efficient Cost Management in Enterprise Assets**, which introduces digital tools for smarter decision-making and resource allocation in production environments.
- **Rotary Robotic Additive Manufacturing: Type Synthesis, Process Planning, and Applications**, providing insights into the fusion of robotics and additive manufacturing for complex, scalable production.

- **Advancements in Enhancing Structural Reliability and Functional Properties in 3D Printed Materials**, addressing the challenges and opportunities in improving material performance for critical applications.

Each chapter is designed to provide valuable perspectives on both theoretical frameworks and practical implementations, offering insights for researchers, practitioners, and students alike. The content reflects the rapidly evolving nature of production engineering, where digital technologies, automation, and sustainability converge to define the future of manufacturing.

We hope this book serves not only as a reference but also as a source of inspiration for ongoing innovation and excellence in the field of production engineering.

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Chapter 1

Forming 1050 Aluminium Alloy by Implementing SPF Concept

Mohammad Reza Allazadeh

Abstract

AA1050H14 sheets with commercial identification of Al1050 are formed by implementing superplastic forming technology for industrial applications. Numerical simulations are modelled via built-in Bailey-Norton creep law material model in ABAQUS. The published uniaxial test data on Al1050 are utilized in the FEM (finite element methods) simulations for AA1050 flow stress curves at different uniaxial loading strain rate and testing temperature conditions. The strain rate sensitivity of AA1050, published by the author, was implemented in the numerical models to adopt the SPF (superplastic forming) concept. The pressure cycles were extracted from the outcomes of the FEM simulations to determine the loading condition in the SPF press to blow the AA1050 sheets into the die cavity by hot gas pressure. The simulation mimics the formation of the SPF part in the press for both aspects of geometrical and formation time, which in turn captures the material flow rate using creep model. The outcomes of forming trials confirm that the lead time for the stretching AA1050 sheets via SPF is suitable for forming AA1050 complex boxes used in food industry or the relevant sectors.

Keywords: AA1050, superplastic forming, SPF, sheet forming, creep model, ABAQUS, Aluminium

1. Introduction

Superplasticity is usually defined as the condition of some material undergoing large elongation with low flow stress at elevated temperature and low strain rate plastic deformation. SPF (superplastic forming) method is usually suitable for manufacture of aluminium components and parts with complex shapes and geometries to reduce the manufacturing cost, number of components, number of joints, and the overall weight of the product [1].

Aluminium alloy 1050 is a relatively cheap and very popular aluminium grade with standard designated and commercial identification of AA1050 and Al1050, respectively. It has several applications in sheet metal work due to its high ductility, excellent corrosion resistance as well as highly reflective finish [2], however, it has poor machinability because of its strength [3]. Typical industrial applications of AA1050 are in lamp reflectors, food industry containers, chemical process plant equipment, architectural flashings. It is reported that there is potential application for AA1050 in vehicle industry since it has better corrosion resistance in acidic environment

compared to aluminium alloys 5xxx and 6xxx [1]. Wang et al. [4] suggested micro-electro-mechanical system device application for AA1050.

H14 in AA1050-H14 refers to the typical tempering process for commercial AA1050 sheets. The temper H14 indicates that work hardening, via rolling process, instead of annealing process was implemented to increase the hardness of rolled aluminium sheets by the half of sheets' initial hardness [2]. The work hardening modifies the strain history of the material, and therefore, results in altering thermo-mechanical properties of the material. AA1050-H14 has very good cold workability attribute; however, it has breaking elongation not more than 12%, which is low for the material property demands of many industrial products [5].

Cepeda-Jimé Nez et al. have found that AA1050 has discontinuous recrystallization at 465 °C during the thermomechanical processing [6], therefore, the formation up to 500°C is targeted in this chapter. Despite all, there is limited investigation of part formation of AA1050 sheets through SPF process. This chapter is continuation of such investigation by the author, which could be beneficial to introduce new applications for AA1050 sheets. For this purpose, several FEM (finite element model) simulations were developed and few SPF trials were planned.

The geometric measurement of parts was not in the scope of this investigation, and therefore, the evaluation of the FEM model was performed by comparing the shape of the formed part to the FEM simulation models. The outputs of the FEM simulations were employed to generate SPF pressure profile at target temperature and strain rate. The suggested pressure cycles were tailored to produce different SPF trial plans to bulge the sheets in the die cavity.

2. The FEM simulation

The concept of superplastic forming is to achieve large strain throughout the formation of a body via a controllable applied strain rate, or more precisely, by maintaining the deformation strain rate within limited tolerances.

The three-dimensional FEM simulations were modelled in ABAQUS and the material models were based on the built-in mathematical models for material behaviour in ABAQUS. Researchers have shown that the general termination reason for superplastic flow is internal cavitation at pre-existing particles and the growth and the interlinkage of such cavities [7–11]. The density and type of the inclusions (e.g., second phase particles) and high energy boundaries increase the cavitation nucleation as well [12]. In this chapter, the FEM simulations are with assumption of the continuum material with no dislocation or lattice defects. Applying back pressure is one way to reduce cavitation at inter-granular sites by means of introducing the hydrostatic pressure equal to the pressure difference of the over and under the sheet [13]. Nevertheless, the FEM simulations ignore the cavitation formation and growth, and therefore, the back pressure was not included in the FEM simulations.

Sizes of the grains and grain size distribution are other important factors, which determine the SPF behaviour, since the formation mechanism is mainly governed by the grain boundary sliding during the SPF process [12]. The formation mechanism is not only controlled by the grain size of the flat sheet but also with the metallurgical events, such as recrystallization and recovery, which change the grain size and microstructure of the part being formed during the SPF process. Previous research detected the discontinuous recrystallization for aluminium alloy 1050 during the thermomechanical processing about 465°C. [6].

The mentioned metallurgical processes are not embedded in the numerical simulations in this chapter. The models simulate the formation of a sheet, with material model defined by the output of the uniaxial test, against the three-dimensional scan image of the die.

The purpose of the FEM modelling is to develop the pressure-time cycle for each trial conditions considering the SPF parameters as well as the part's and dies' geometries. However, the SPF pressure cycles were adjusted and optimised during the trials based on the experiences.

To build the numerical models, which define the material behaviour during forming, it is crucial to determine all the parameters of the applicable model in ABAQUS. Strain rate sensitivity, also known as m-value, is obtained from the author's past publication [14].

The FEM simulations were accomplished in ABAQUS software package. The objective of the simulations is to control the applied pressure during trial time to manufacture the aluminium alloy component in the shortest possible time ensuring the designated superplastic strain rate at each point of the material. The three-dimensional scanned image of the die was used for the simulation without attempt to produce CAD drawing file based on the scanned image. The flow stress curves were extracted from the author's publication on this topic [15].

For the FEM models, the principle of symmetry was implemented to simplify the die part in order to reduce the cost of the simulation. Hence, the die part was represented in the simulation with only quarter portion of the die profile. **Figure 1** shows the quarter size of geometry of the models and the loading condition in the models using symmetry concept. The loading was designed similar to the loading of the sheet during the SPF trials by applying gas pressure from top side.

To have a commercial value for the trial results, it was attempted to plan the trial test at critical parameters for quick plastic forming (QPF) defined as testing at temperatures between 400 and 500°C and strain rates between 0.001 and 0.1 s⁻¹ [16]. Author has produced **Table 1** in [15] to show the temperatures and strain rates of the uniaxial tests for the tested specimens.

Partition option of the ABAQUS was used to optimise the FEM meshing. The material model in ABAQUS was the creep mode, which is Bailey-Norton creep law with time hardening option or strain hardening in some cases. The equation constants were calculated based on the SPF uniaxial tests and m-value results explained in the publications [14, 15].

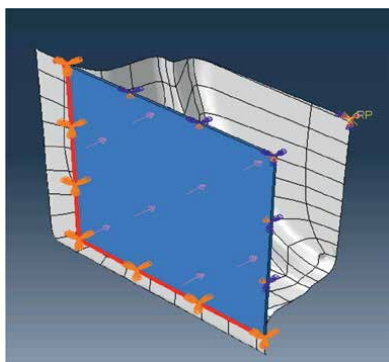


Figure 1.
The die geometry and the gas pressure loading model in the FEM simulations.

Uniaxial test coupon ID	Testing Temperature [°C]	Strain Rate [s ⁻¹]	Rolling Direction [degree]
J	100	0.005	90
I	200	0.001	90
H	200	0.0005	90
E	200	0.0001	90
K	300	0.001	90
L	300	0.0005	0
O	300	0.0005	45
G	300	0.0005	90
M	300	0.0001	0
N	300	0.0001	45
F	300	0.0001	90
T	400	0.0001	90
S	500	0.001	90
D	500	0.005	90
Q	500	0.0005	90
R	500	0.0001	90
P*	500	0.005	90
C*	200	0.0001	90

Uniaxial tests with ^{SC82} were performed under argon environment.

Table 1.
Uniaxial tests' specifications for the experiments [15].

The quarter sheet model for the numerical simulation was considered to be 2 mm thick with the dimension of 200 in 180 mm for the length and the width of the sheet.

Two numerical methods are available in ABAQUS/Standard to retain controlled strain for superplastic forming the aluminium alloy sheets via SPF process. These numerical methods are introducing the SPF loads by tabular and solution-dependent amplitude methods, which are corresponding to the pressure-time cycle calculations through the uniaxial tests' stress-strain curve and by creep strain rate control computations. Creep strain rate control option is a controlling algorithm, which calculates the maximum value of the ratio of the equivalent creep strain rate to the target creep strain rate ($r_{\max}$) for any integration point in a specified element set for each increment of numerical analysis.

Both loading approaches must keep the strain rate for all points in the material during forming near or less than the designated strain rate for the simulation to adopt the material behaviour of the uniaxial test results. In case of solution-dependent loading method, ABAQUS/Standard defines the loading magnitude for new time step (p) based on the loading magnitude of previous time step (p_{old}) such that $p = p_{\text{old}}$ for $0.2 > r_{\max} > 3.0$, $p = (2.0 p_{\text{old}})$ for $r_{\max} < 0.2$, and $p = (2.0 p_{\text{old}})$ for $r_{\max} > 3.0$.

3. Selected flow stresses for the numerical models

Although all the strain rates in **Table 1** are within the SPF-controlled strain rate defined by Ghosh [17], the material properties of the uniaxial tests for some of the samples were selected for the numerical models. The analytical calculation was discussed in the other publications of the author [15].

Figures 2–4 are the curve fitting for the selected samples. The elastic material properties were also calculated from the stress-strain graphs.

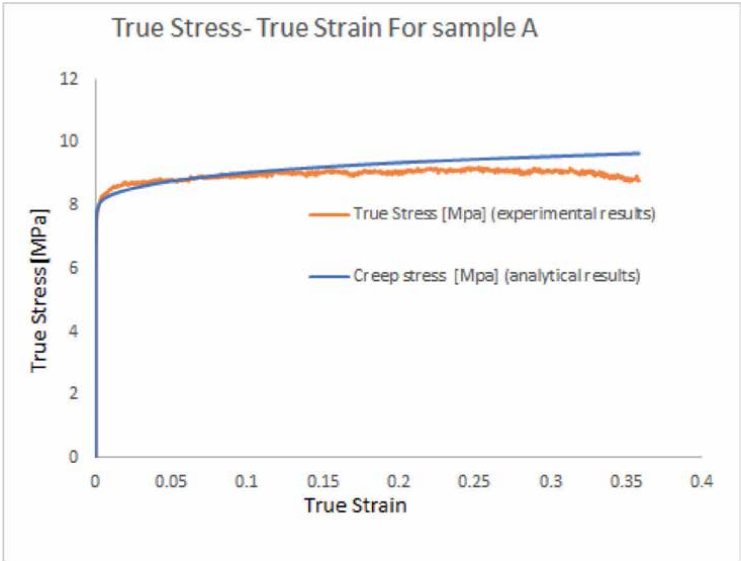


Figure 2.
Stress versus strain graph for sample A.

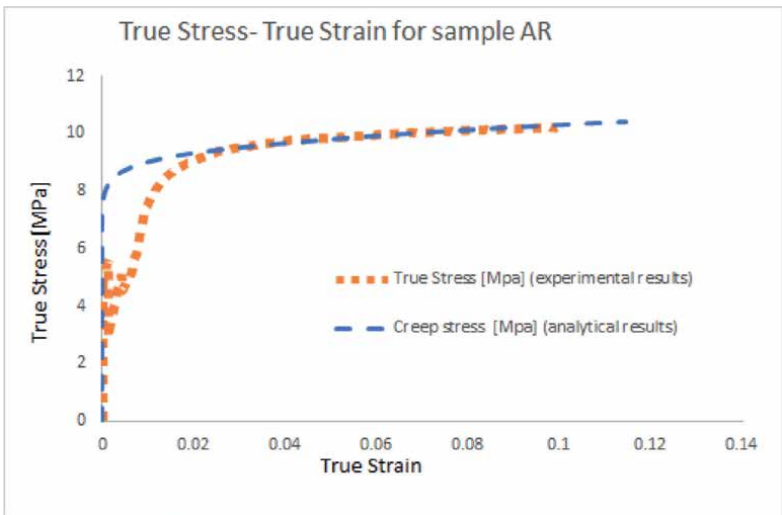


Figure 3.
Stress versus strain graph for sample AR.

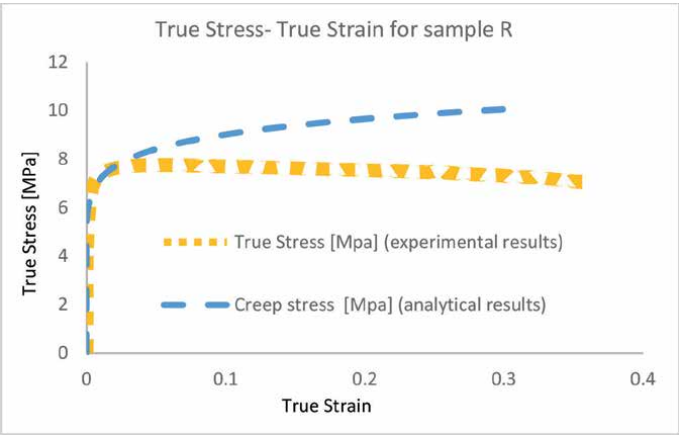


Figure 4.
Stress versus strain graph for sample R.

4. FEM simulation results

The pressure profile for the trial plan was constructed by considering the simulation results from both pressure profile computations. **Figures 5–9** show the stress flow after full formation of aluminium alloy sheets based on the m-value and stress flow for uniaxial testing conditions of coupons R, D, and Q using both tabular and solution-dependent computation methods.

Graphs in **Figures 10–12** show the pressure cycle suggested by the FEM simulations for forming aluminium alloy sheets 1050H14 at 500°C with strain rate 5×10^{-3} (D-sample), $5 \times 10^{-4} \text{ s}^{-1}$ (A-sample for argon testing atmosphere and Q-sample for air testing atmosphere), and $1 \times 10^{-4} \text{ s}^{-1}$ (R-sample). It can be observed that the slop of the loading increment is higher for the forming with larger strain rate target. It was taken into consideration that the strain rate of each individual node should not exceed the designated value for the simulation. The major advantage of

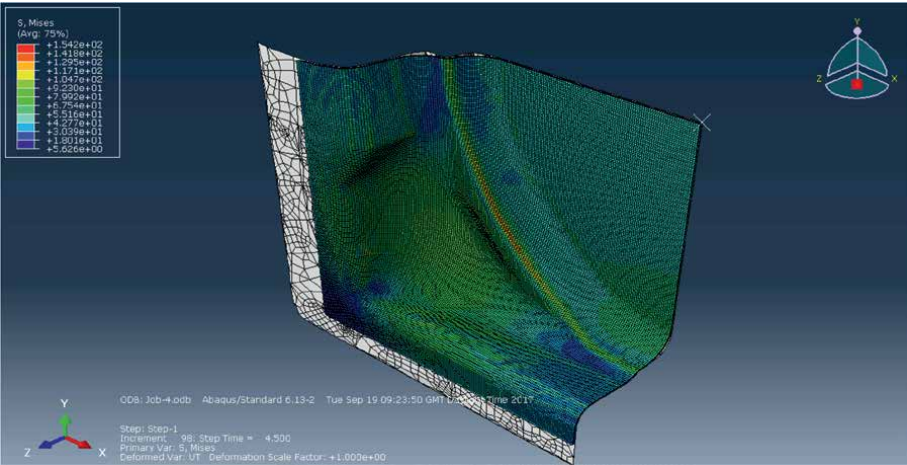


Figure 5.
Von mises stress flow with tabular loading computation method for strain rate of 0.0005 at 500°C (Q-sample).

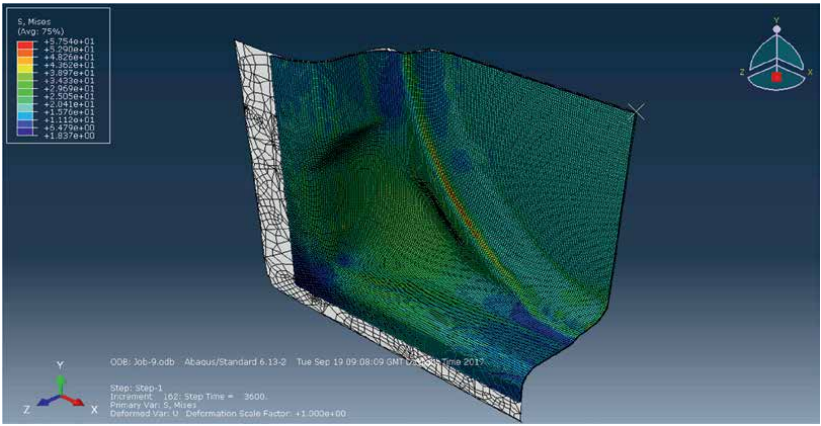


Figure 6.
Von misses stress flow with tabular loading computation method for strain rate of 0.0005 at 500°C (A-sample).

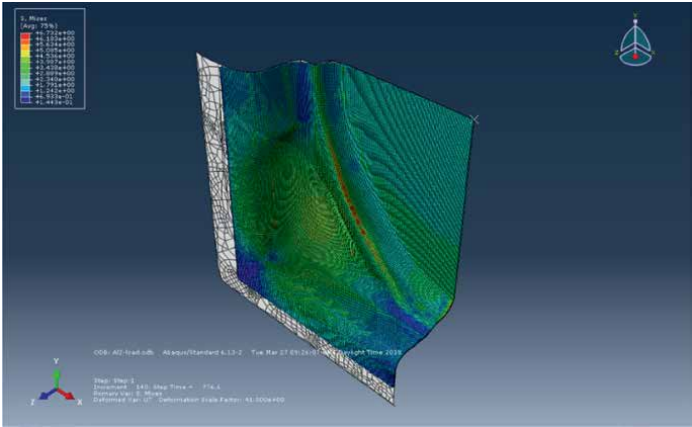


Figure 7.
Von misses stress flow with tabular loading computation method for strain rate of 0.005 at 500°C (D-sample).

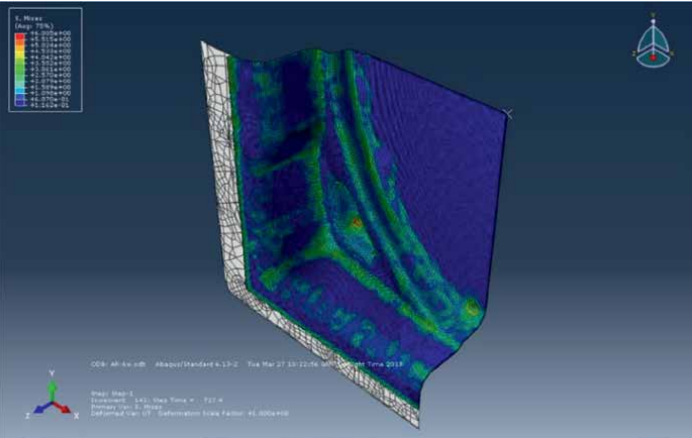


Figure 8.
Von misses stress flow with strain rate control computation method for strain rate of 0.005 at 500°C (D-sample).

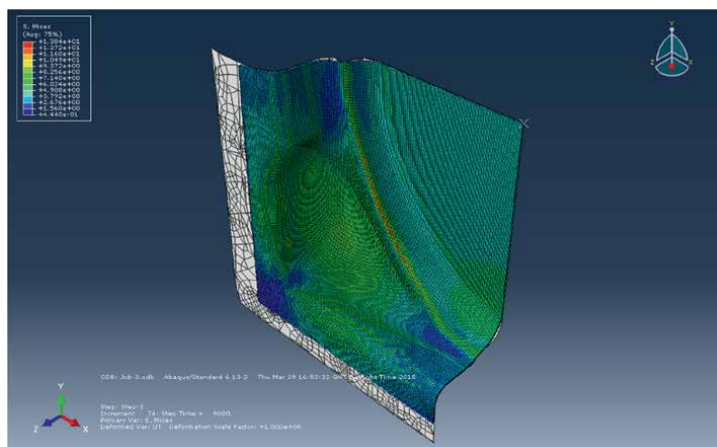


Figure 9. Von misses stress flow with tabular loading computation method for strain rate of 0.0001 at 500°C (R-sample).

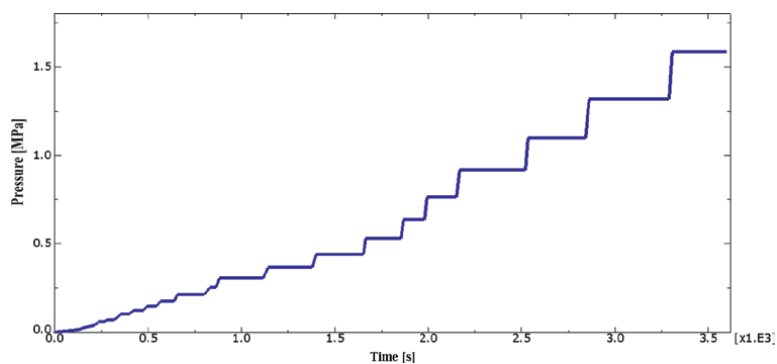


Figure 10.
Pressure profile suggested for forming Al1050H14 alloys at 500°C and at $5 \times 10^{-4} \text{ s}^{-1}$ (testing condition coupon a for argon atmosphere).

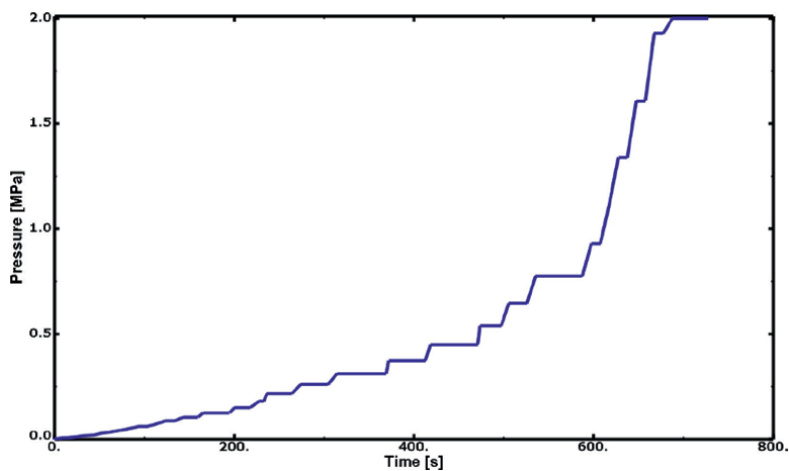


Figure 11.
Pressure profile suggested for forming Al1050H14 alloys at 500°C and at $5 \times 10^{-3} \text{ s}^{-1}$ (testing condition coupon D).

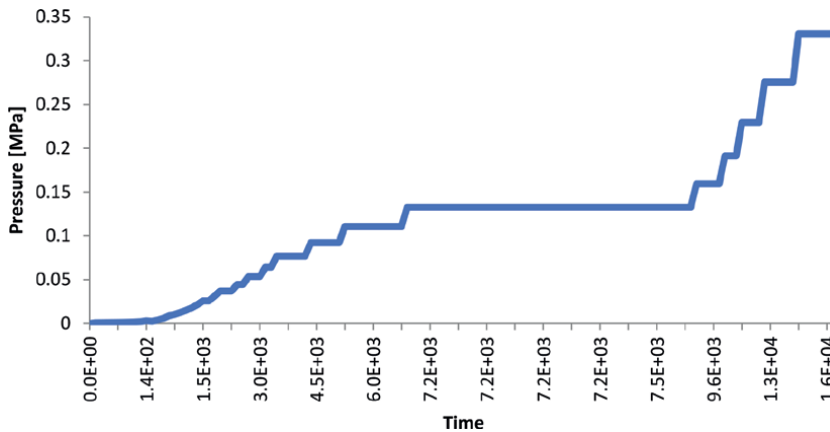


Figure 12.
Pressure profile suggested for forming Al1050H14 alloys at 500°C and at $1 \times 10^{-4} \text{ S}^{-1}$ (testing condition coupon R).

control keyword method over the tabular loading method is its automatic maintaining of the strain rate lower than the designated strain rate for the simulation at each individual node. To examine this, critical nodes with different strain in the FEM models were selected as sample to examine the strain rate variation during the FEM simulation. **Figure 13** shows the elements selected for the solution-dependent loading approach, whilst **Figure 14** shows the selective element in the simulation using the tabular loading condition. **Figure 15** presents the positions of the selected elements in the formed sheet.

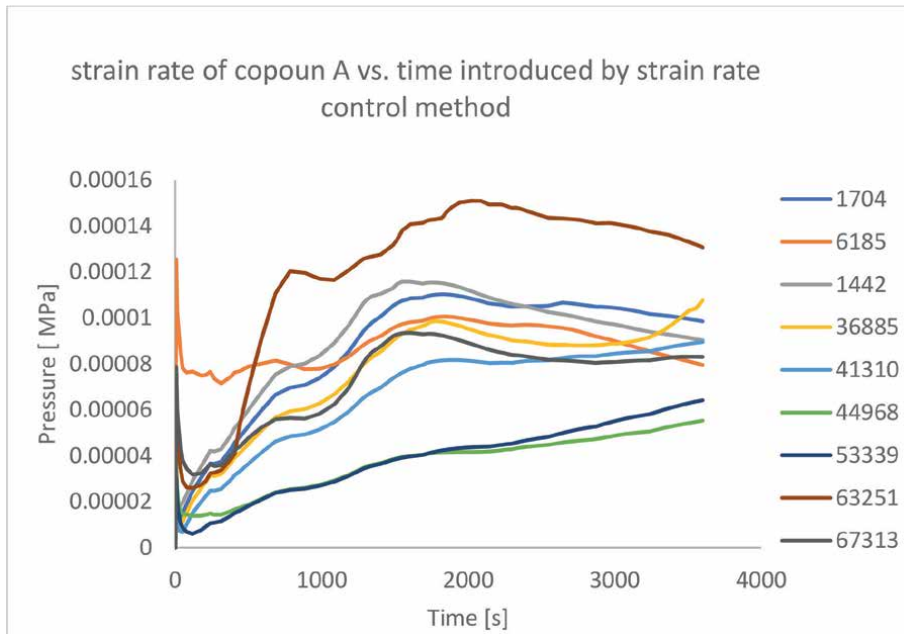


Figure 13.
Solution-dependent strain rate imposed to the FEM simulation of forming sample Q condition.

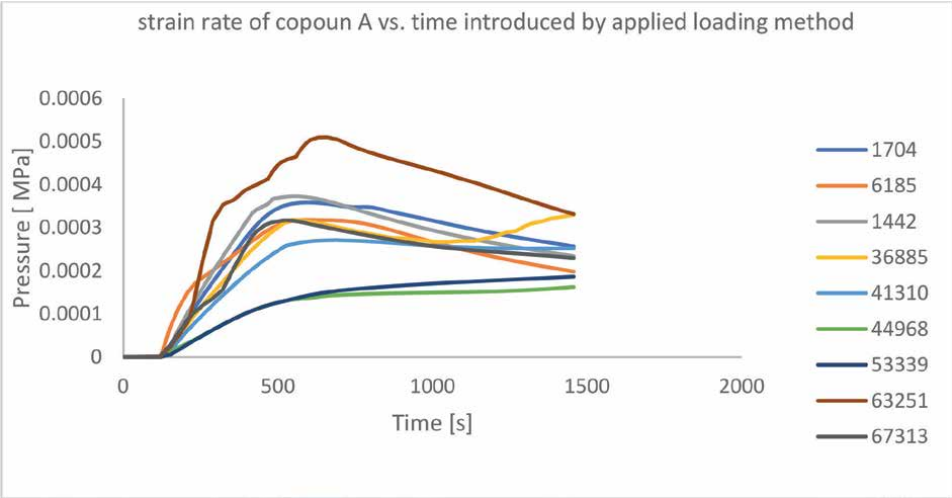


Figure 14.
Tabular loading method imposed strain rate to the FEM simulation of forming sample Q condition.

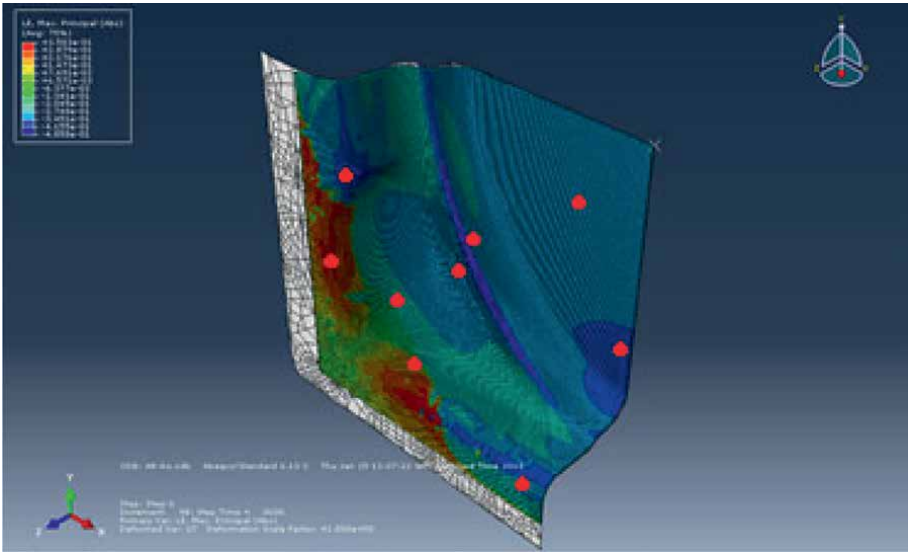


Figure 15.
Position of selective element to examine the strain rate of the elements in the model for forming sample Q condition.

The same analysis can be done in the extended manner for simulation with each forming condition suggested in **Table 1** to approve the forming strain rates within the designated strain rate of other models. ABAQUS provides the $r_{\max}$ ration in the case of the controlled strain rate simulation method. **Figures 16** and **17** depict the $r_{\max}$ values for simulation of forming aluminium alloy sheet using R-sample and P-sample conditions in **Table 1**, respectively.

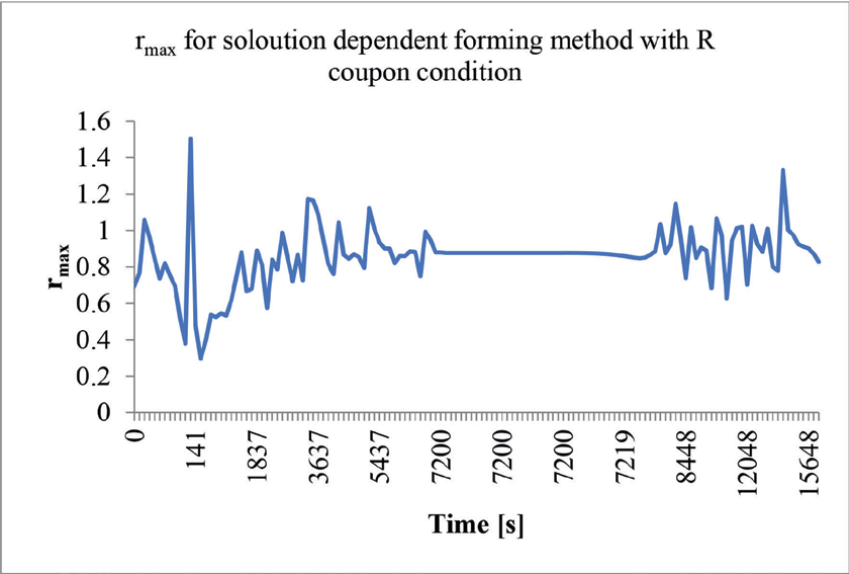


Figure 16.
 Variation of r_{max} in the model using R-sample condition.

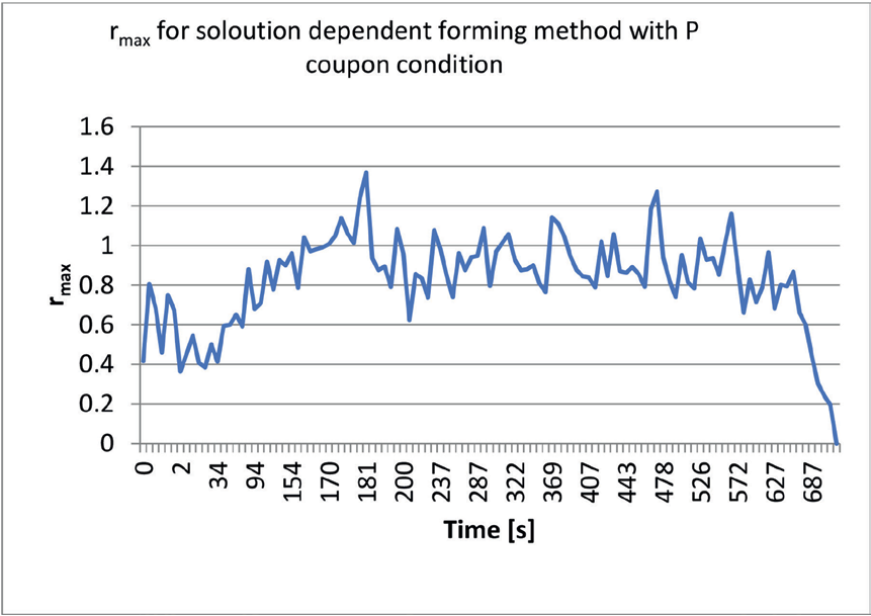


Figure 17.
 Variation of r_{max} in the model using P-sample condition.

Figure 18 depicts the stress flow versus material flow at a point in the deepest region of the cavity of the formed part. It can be seen that strain reaches 50%, whilst the maximum stress is less than 9 MPa.

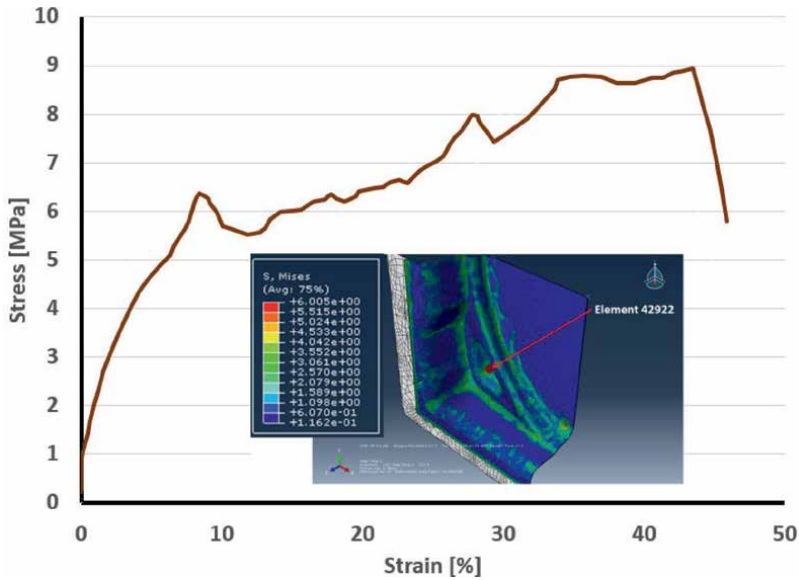


Figure 18.
Stress flow at element 42,922 for SPF forming at 500°C and 0.005 strain rate.

5. SPF trials' results and discussion

The SPF trials were performed in ACB 200 T superplastic forming press designed to validate FEM models and optimal pressure cycles for forming sheets. Explaining the SPF technology is not within the scope of this chapter.

The first trial plan was developed for forming at a strain rate of 0.0005 1/s at 500°C and the data were extracted from A-sample uniaxial test for better adjustment of the forming parameters. Since there is some uncertainty for the press temperature control during loading the flat sheet which may overshoot the furnace temperature near to the melting point, the furnace of the press was set to the temperature regulation on platen rather than tool. This led to a reduction in the trial temperature to 490°C. The press was set for 10 minutes preheating of the sheet before triggering the forming pressure cycle specified for this trial. The sheets were held with mechanical over tonnage of 300 t between two dies to seal the gas leakage from the gap between two parts of the die in closed position in the press. The first trial was set based on the simulations for A-coupon as the error for the input data of uniaxial test was revealed afterward. The pressure cycle was simplified with less steps and optimised to make sure that different material zones would not have strain rate higher than the designated one. **Figure 19** illustrates the pressure cycle applied for trial-1 SPF experiment. **Figure 20** depicts the photo of the formed part for the trial 1. The second trial plan was developed using the same forming conditions for the temperature and strain rate but using uniaxial data for Q-coupon where the m-value was corrected.

The material properties were defined based on the graph in **Figure 21**. **Figure 22** presents the graph which was introduced to the SPF press for the applied pressure cycle of trial 2. However, the trial had to be terminated after 19 minutes of the pressure cycle of the trial for the safety reason due to high inlet gas flux which indicated possible leakage during forming process. **Figure 23** shows the extent of the forming

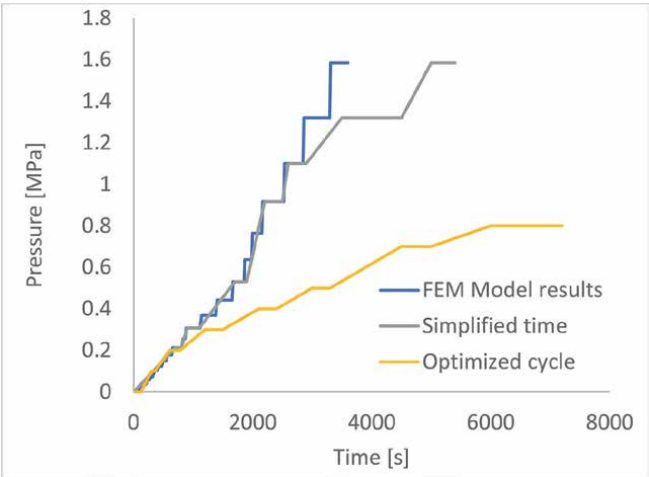


Figure 19.
Applied pressure cycle for SPF trial 1.



Figure 20.
Photos of the formed part of the SPF trial 1.

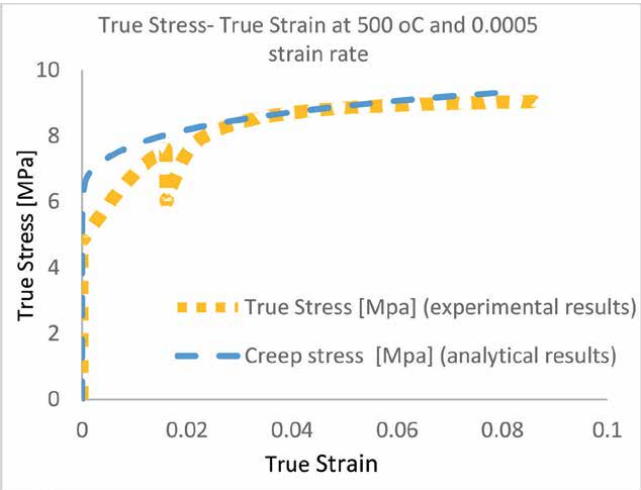


Figure 21.
Material properties used in creep law material model in ABAQUS for the SPF trial 2.

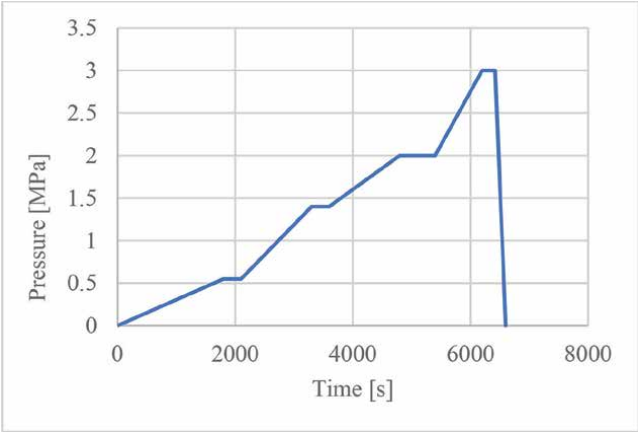


Figure 22.
Pressure-time cycle for SPF trial 2.



Figure 23.
Photos of the formed part in trial 2.

part up to the stopping of the SPF trial 2 for the project. **Figures 24** and **25** are two comparisons between the dome part formed in the SPF press after 19 minutes and simulation of the part formation after 1111 seconds step time.

Figure 26 shows the depth of the dome-shape formed from the flat sheet in the SPF trial and the formation of the sheet part in the ABAQUS simulation. It can be seen from the two images adjacent to each other in **Figure 26** that whilst the ruler indicates a depth 5 centimetre for the formed shape in right side of the image, the distance between two elements highlighted from the simulation of the formed part in the left side of the image is 5 centimetres as well. Consequently, the simulation validity is approved by the formation of the SPF part in the press for both aspects of proceeding in geometrical formation and time, since the model captures the material flow rate using creep model.

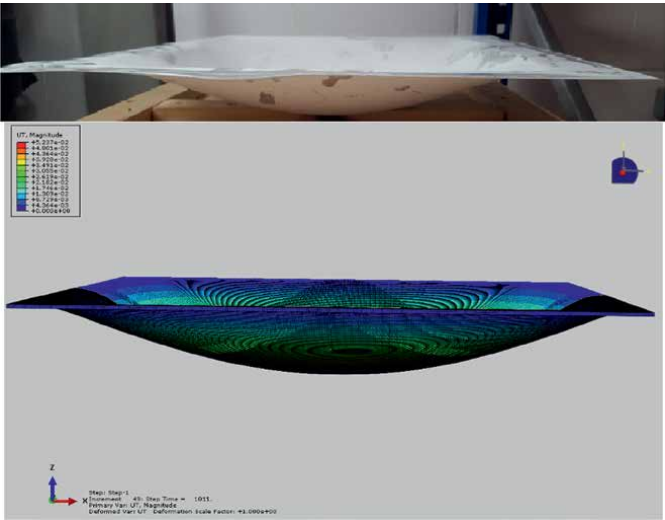


Figure 24.
Comparison between the formed part with the simulation results at 19 minutes time of formation and simulation time.

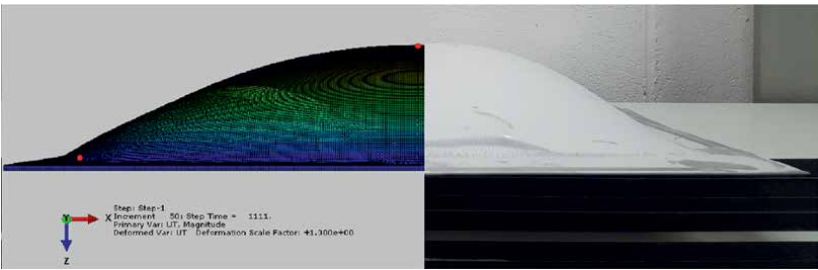


Figure 25.
View of comparison of the half of the formed part in the press after 19 minutes with the half part SPF simulation in ABAQUS at time step 50 and 1111 seconds of simulation time.

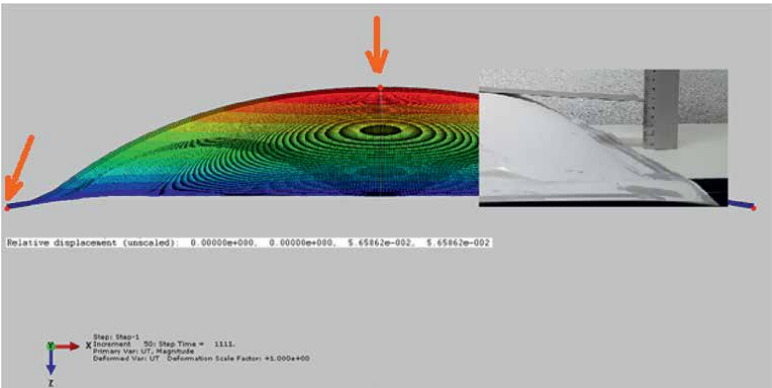


Figure 26.
Comparison of the height of the dome between the FEM simulation results and SPF forming results after 19 minutes.

6. Conclusion

Previous publications data for the uniaxial tests of AA1050 were utilised to list the strain rate and temperature on the flow stress in AA1050 sheet for all specimens. Some specimens with the best results according to E-2448 standard were selected for developing three-dimensional numerical analysis models in ABAQUS.

The strain rate sensitivity (m -value) and flow stress curve in the FEM models were obtained from the author's publication on this topic. For this purpose, the creep material model built-in was employed in the FEM models to predict the material behaviour during forming.

The data extracted from the numerical analysis were scrutinized to estimate the material flow of AA1050H14 sheet into the cavity of the die during formation. The formation of the sheet part in the ABAQUS simulation was compared to the depth of the dome-shape formed from the flat sheet in the SPF trial. The outcome of the analysis validated the material flow rate using creep model for both aspects of geometrical of the formed sheet and the SPF formation time.

It was found that the elongation of AA1050 sheets via SPF was within the limitation reached in the uniaxial test results published by the author. Analyses of numerical results show that there is direct relationship between the slope of the loading increment and the target forming strain rate. It can be concluded from FEM simulations that full formation of AA1050 sheets in the die cavity demands for at least 50% strain under 9 MPa loading.

It is fair to claim that SPF technology may offer a suitable lead time in manufacturing complex boxes from AA1050 sheet for food packaging industry or relevant sectors.

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Chapter 2

The Application of 3D Printers in Textile

Mohammad Amin Rahiminia

Abstract

The development of new technologies such as 3D printers and their application can increase the level of human knowledge in various sciences. Cases like the high production speed, the quality of the manufactured part, and the selection of different materials for making the part increase the use of 3D printers. According to the stated cases, the use of this method in textile sciences can also bring many applications. To use 3D printers in the production of textile textures, many things must be considered. One of these cases is choosing the right design software for designing textile textures, because textile structures have unique complexities. According to the stated cases, this chapter examines three subsets of innovation, design software, and mechanical tests in textile. The use of fabric that is produced by 3D printing is one of the important cases in investigating this issue. After the studies conducted on various researches, appropriate findings can be obtained in this field. These findings help the researcher to take a newer step by receiving the knowledge obtained from the researches of others. Eventually, progress in this knowledge will become much faster.

Keywords: selection of 3D design software, design of textile textures, selection of 3D printer, used materials, application of textures after manufacturing

1. Introduction

Scientific and research advances in the field of construction of additive structures allow users to produce 3D objects with high accuracy and low cost. Diversity in design, material selection, and structure construction in this method increases the research in this field for the production of textile fabrics. There is a lot of progress in this field, but many things and points should be taken into consideration. According to these items, the basic requirements are examined first. The most important things to consider in the production of a fabric with 3D printers are softness, stretchability, breathability (passage of air through the fabric), and flexibility. In this part of the chapter, the researches that have succeeded in designing, producing, and using the fabric obtained by the 3D printing method are discussed. This is divided into three subsets: innovation, design, and mechanical testing.

2. First part: Innovation

In textile, there are different ways to produce fabric, and then, the fabric is used in different places. The method of fabric production traditionally depends on its application. This makes the choice of production process important. Such as the selected raw materials that are used, the machines that convert the raw materials into fabric, and how the produced fabric is used, in the places where it is consumed. The new method of using 3D printers to make fabric and its application in different cases is very different and diverse. This technology helps the researchers to shorten the whole process of the traditional method and take advantage of newer ones as well.

One of these methods is the use of making small parts as repeating units, which can be separate and then connected together or can be produced integrally during production (**Figure 1**). The method of using 3D printers makes it possible to recycle materials much easier than traditional methods. Also, this method allows personalization for each person or item or to the user [1].

The process of using the 3D printer method in the production of textile products consists of: initial idea for design, design by suitable software, selection of suitable 3D printer for design production, selection of raw materials, making prototype. In this method, this task is achieved by controlling the nozzle of the device. A view of the samples made with the new method by the 3D printer is shown in **Figure 2** [2].

In this research, using a method, it was possible to produce a soft and flexible fabric with a 3D printer of fused deposition modeling (FDM). The subject of this research is to describe the options that 3D printing can provide for fabric production. The practical part consists of developing an application for printing 3D fabric design. The program provides several predefined types of elements with modifiable properties. These elements are used to produce laces similar to textiles. A view of the printed lace-shaped samples, which are similar to the fabric structure, is shown in **Figure 3** [3].

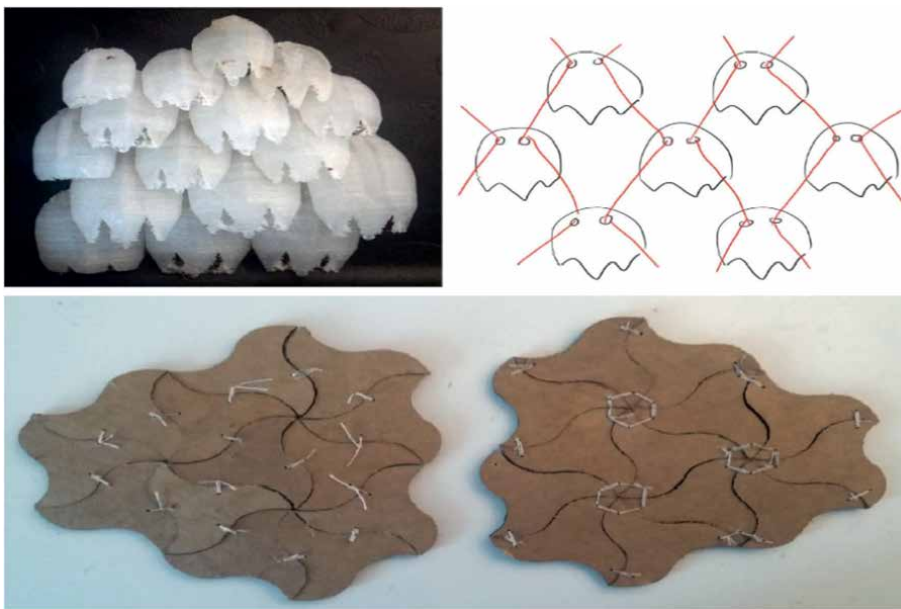


Figure 1.
A view of the printed pieces that are joined together to form the fabric structure [1].

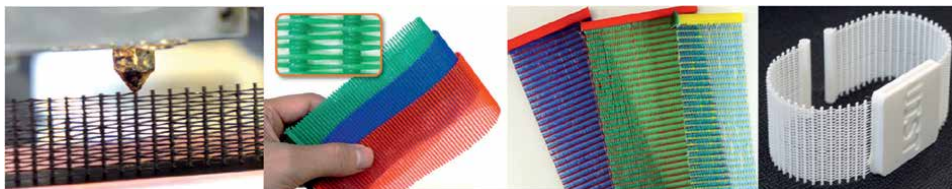


Figure 2.
A view of samples similar to woven fabrics produced by the nozzle control method of a 3D printer [2].

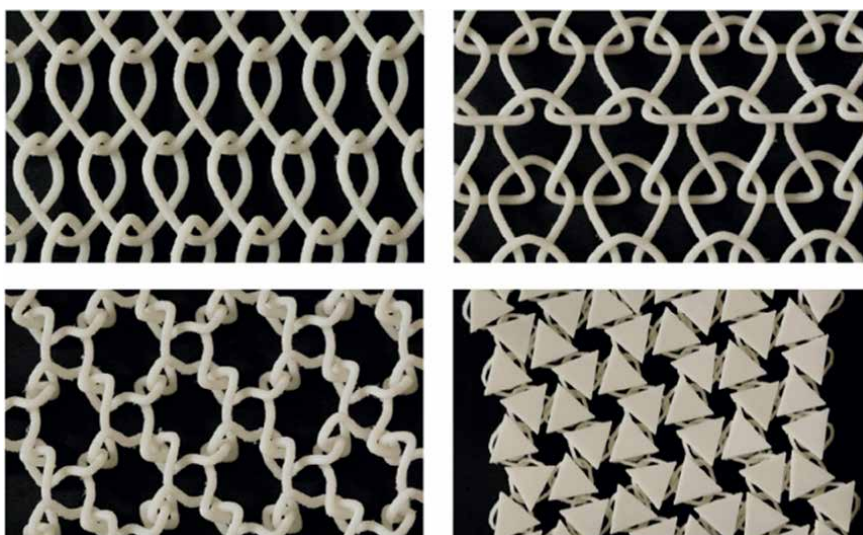


Figure 3.
A view of printed lace samples that resemble the structure of fabric [3].

By coding and digitizing textile textures, it is possible to find a relationship between textile textures and their 3D printed samples in the texture's structure behavior and the effect of consumables on them. A view of the fabric structure that is digitally coded is shown in **Figure 4** [4].

FDM 3D printing methods with soft and hard materials were used to produce clothes, which are mostly used in fashion structures. Then by surveying people, they concluded that the production of this model of clothes is mostly used by fashion users, and still work and research should be done in this field so that the clothes produced by 3D printing are equal to the clothes produced by traditional methods. A view of the fabric production process with a 3D printer is shown in **Figure 5** [5].

An experiment for the commercialization of clothing production with 3D printing has been carried out, and the result of which is obtaining samples that can be used in the fashion industry [6]. The application of 3D printers in the textile industry has been studied and investigated, so that the different methods of 3D printing to use this method in the textile industry are more focused on the issue of fashion and fabric (**Figure 6**). Successful and practical examples are shown in different structures, and their applications are also explained [7].

The use of 3D and 4D printing methods for fabric and clothing production was investigated in different researches. Some successful methods, examples of which

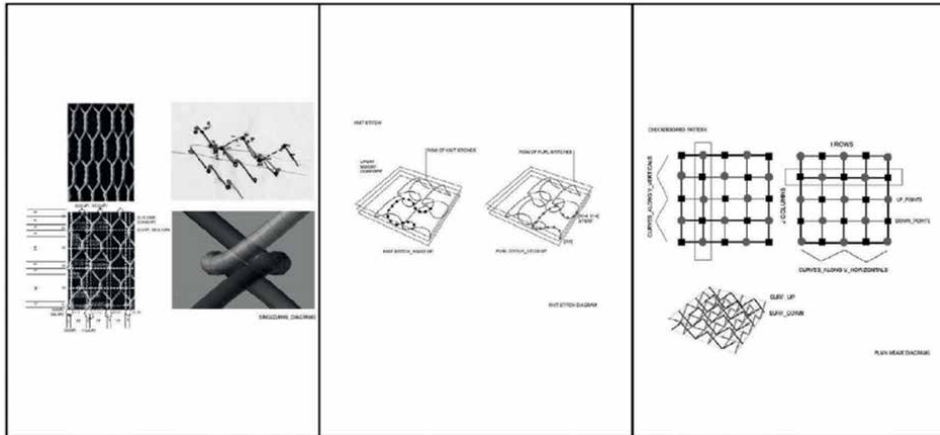


Figure 4.
A view of the fabric structure that is digitally coded [4].

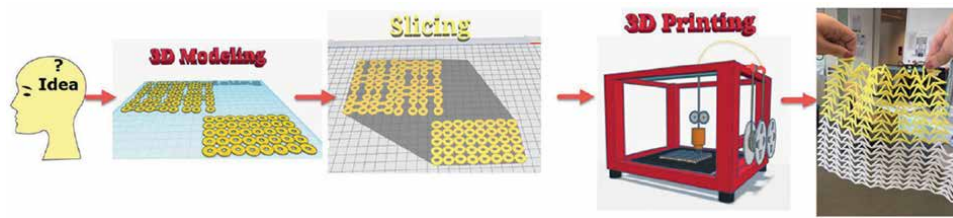


Figure 5.
A view of the fabric production process from design to prototype production with an FDM 3D printer [5].

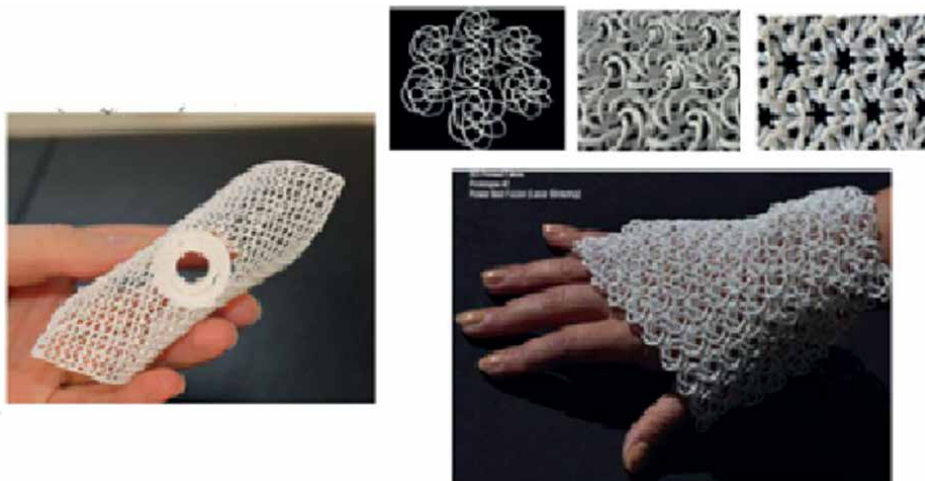


Figure 6.
A view of the integrated fabric produced by 3D printing and its application in the fashion industry [7].

are presented in **Figure 7**, show that this production method can be an alternative method for clothing production over time and after further research. The use of devices and the selection of suitable materials and patterns are very effective in the

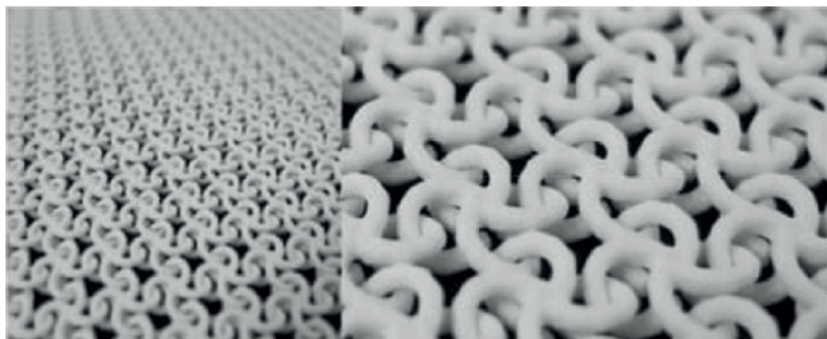


Figure 7.
A view of the highly flexible, integrated fabric made by the 3D printer [8].

method of using 3D printers. These samples have high bending and flexibility due to the structure designed in the fabric [8].

In this research, the research activities have been carried out with the 3D printing method for the production of clothes, shoes, and hats. One of the most important results of this research is the reason for the slowness of the research on the composition of clothes and the development of materials using 3D printing technology in the clothing industry. There are limitations in using 3D printing technology in clothing.

One of these limitations is the reproduction of the fabric structure produced by 3D printing, which cannot replace existing clothes produced by traditional methods due to the lack of diversity in consumables such as filament, resin, etc. These variables are not easily possible for 3D printers that want to be an alternative to fabric production in the traditional way.

The second limitation is the output size of the product produced by the 3D printer method, which has dimensional limitations. Therefore, in order to make more use of 3D printer technology for the production of clothes, there is a need for more research and development on different fabrics, in order to be able to produce fabric with the quality of the traditional method [9].

3. Second part: Design software

The use of appropriate design software can help research in advancing the goal of producing a higher quality product. First, to have a suitable pattern, you should use suitable software for fabric design. These steps are carried out until the prototype is printed, the output of the device is checked, and then the initial design is modified or optimized if needed. This method is a fixed path for fabric production with 3D printers, but there are other methods, which can be a combination of designing and setting the input codes to the machine to produce the fabric. Finally, the most important factor for having a suitable fabric is having the right software and the right pattern of fabric structure. The mentioned items can help a lot in the production of a fabric produced with a 3D printer that is close to traditional fabrics.

In this research, using a method, it was possible to produce a soft and flexible fabric with a 3D printer of FDM. In this method, this task was achieved by controlling the nozzle of the device. In this method, warp threads are printed vertically, and in each layer of warp threads, a weft thread passes through them, so that the nozzle

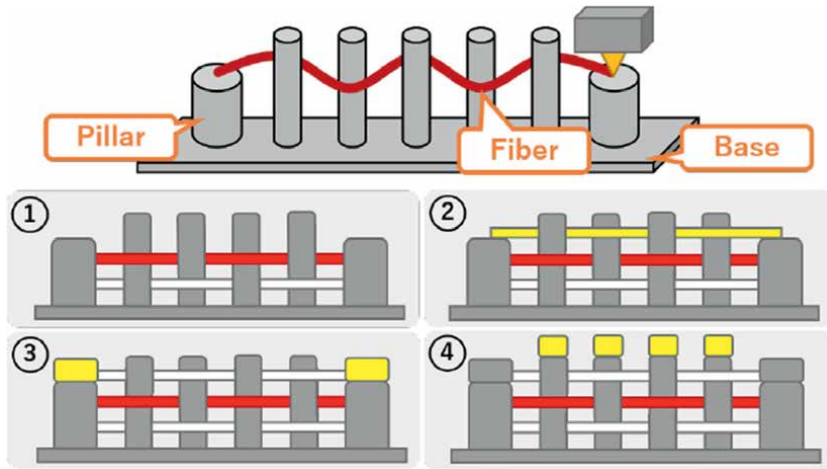


Figure 8.
Schematic view of the nozzle movement control process by the software [2].

continues to inject the material continuously to create the weft thread. And the nozzle is produced by passing through the warp threads and quickly cooling the fabric structure layer by layer (**Figure 8**). Although the precision in new printers has increased, which has made the quality of printing samples higher, still 3D printing of fabric by 3D printers is a challenge [2].

In this research, a software program developed for fabric design was used, which can produce laces like fabric. In this chapter, the limitations of the work are also described. Finally, the analysis of the made textile structure is done. The mobility of the fabric produced by the 3D printing method has been done by creating grid structures, this work creates an environment to adjust the appearance of the produced grids with the help of the developed program, and finally the result of this program shows that the change in design can affect the amount of fabric movement (**Figure 9**). In order to create flexibility in the structure, the diameter and thickness of the filament at the tip of the nozzle should be reduced. One of the disadvantages of fabrics produced in this way is their hardness and size [3].

In this study, by using design with appropriate software, different patterns of fabric production were produced by 3D printing method with FDM machine (**Figure 10**). Then the samples are examined in terms of comfort of covering and flexibility. Soft and hard materials have been used to produce fabric with structures that have different geometries, and finally, the samples were evaluated with an online survey [5].

In this research, by using the design and 3D printing machine, different patterns of clothes produced for fashion markets have been investigated. Also, the use of which 3D printer with which suitable consumable for which clothing pattern is also stated (**Figure 11**). Some areas of existing 3D printer technologies and their consumables need to be further improved to produce clothing with proper coverage, which can provide flexibility and comfort to the individual. One of the most important challenges of using 3D printer technologies is the long production time and the size of the structure [10].

In this research, 3D printed fabric has been produced using suitable pattern design and recycled polyester materials. The design of new structures was done according to the properties of recycled materials. The produced fabric was tested in the bending range at the wrist, and the bending result of the fabric was suitable for this area of the

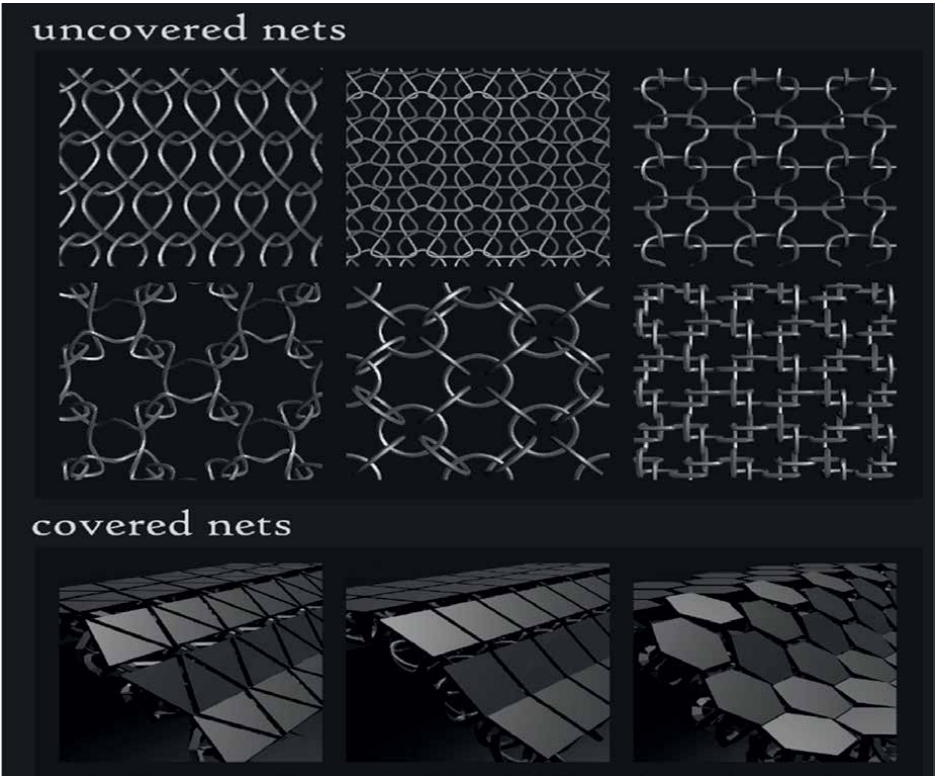


Figure 9.
A view of the integrated fabrics produced by the 3D printing method, which have different back and up on the surface of the fabric [3].

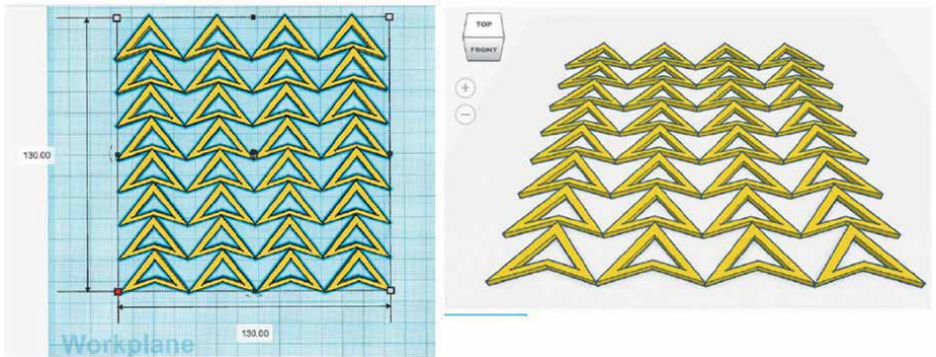


Figure 10.
A view of fabric design for production with a 3D printer [5].

human body. A view of the fabric produced with recycled materials by a 3D printer is shown in **Figure 12** [11].

The purpose of this research is to design a wearable garment produced by 3D printing. This example has practical, environmental, and experimental advantages. Samples are made monolithically from smaller components connected together (**Figure 13**). The two main factors that need to be improved before wearing printed



Figure 11.
A view of the fabric produced by the 3D printing method, which is similar to the weft knitted fabric [10].



Figure 12.
A view of fabric produced with recycled materials by a 3D printer [11].

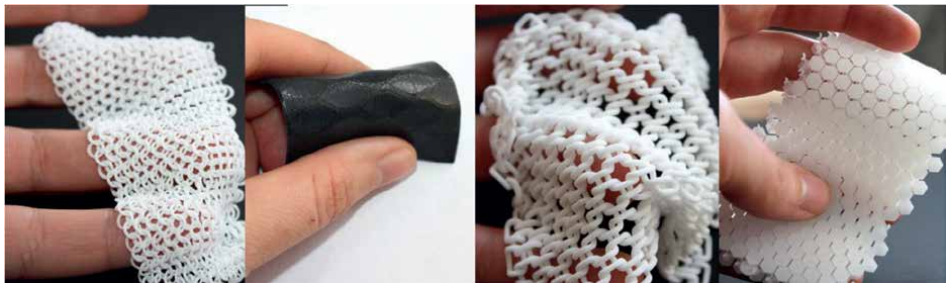


Figure 13.
A view of fabrics designed and produced with a 3D printer, which with the use of proper design have high flexibility and bending similar to traditional fabrics [12].



Figure 14.
A view of the fabric designed and produced by the 3D printing method for shoe production [13].

fabrics are the tear resistance and the softness of the material, which are essential if they are to be worn close to the skin.

The softness of the material can be suggested by using more compressible materials or materials with a softer outer surface, such as cellulose materials to improve the surface of the material. According to the components of the structure, the smaller these components are, the more the impact on the softness of the surface of the printed fabric will be, which is also suggested for the softness of the fabric surface [12].

In this research, 3D printing technology has been used in the design of new clothes (**Figure 14**). The designs were made by Rhino software. Different 3D printer devices have been used to print fabric, and each device has advantages and disadvantages, because the way they work and the materials used in them are different. As a result, different samples can be produced according to the design done for the fabric structure, the device used, and the material used. The quality of the produced fabric also depends on the mentioned factors. The design of 3D clothes produced by 3D printing is an important trend for future clothing design [13].

4. Third part: Mechanical tests

In this section, researches on fabrics produced by 3D printing on which mechanical tests have been performed will be discussed. These mechanical evaluations are very practical and used by other researchers for use in clothes or other cases. Knowing the fabric mechanics and how it works against the forces applied to it helps the researcher to design and produce a fabric with a suitable structure. Then the researcher checked these things with mechanical tests to find the disadvantages and advantages of the manufactured sample and to fix it.

In this research, the fabric produced by 3D printing method has been investigated to create flexible textile structures with tensile, shear, and bending properties. With CATIA software, the initial design of woven fabric has been done, and after printing the samples, they have been subjected to mechanical tests (**Figure 15**). The evaluation of the printed samples shows that it is possible to have the characteristics of the fabric structures produced in the traditional way in the 3D printing patterns [14].

In this research, the construction of new textile fabrics for use in clothing and industrial items has been investigated. The investigated fabrics are two types of

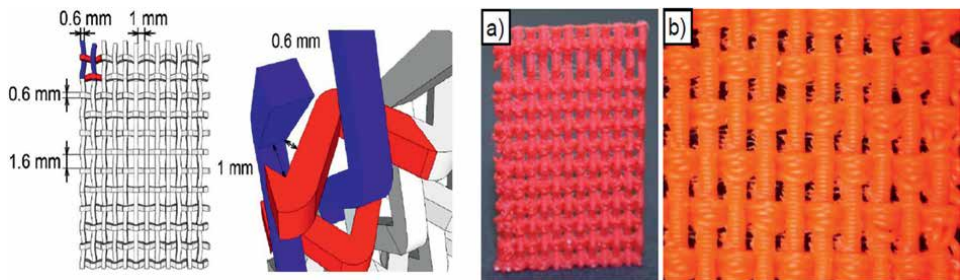


Figure 15.
A view of the sample designed by the software and printed by the 3D printer [14].

tubular fabrics with the construction of textile fabrics, which have been investigated in terms of internal pressure tolerance. These two types of tissue have high capabilities. In this research, the fabric surface was designed using a repeating pattern. The design of the samples was done in the Rhino software and the printing of the samples was done by the FDM printer; then, the internal pressure tolerance of the structure was checked by the mechanical test by the standard split-disk method (**Figure 16**). After performing the mechanical test, it was found that these fabrics show the same behavior as textile fabrics. Also, theoretical analysis was done by software on the samples, and the result of the analysis by the software showed a good correlation with the result of the mechanical test [15].

In this research, the behavior of reinforced composites with tubular fabrics printed on the basis of textile construction was investigated. In this research, the fabric surface was designed using a repeating pattern. The samples were produced

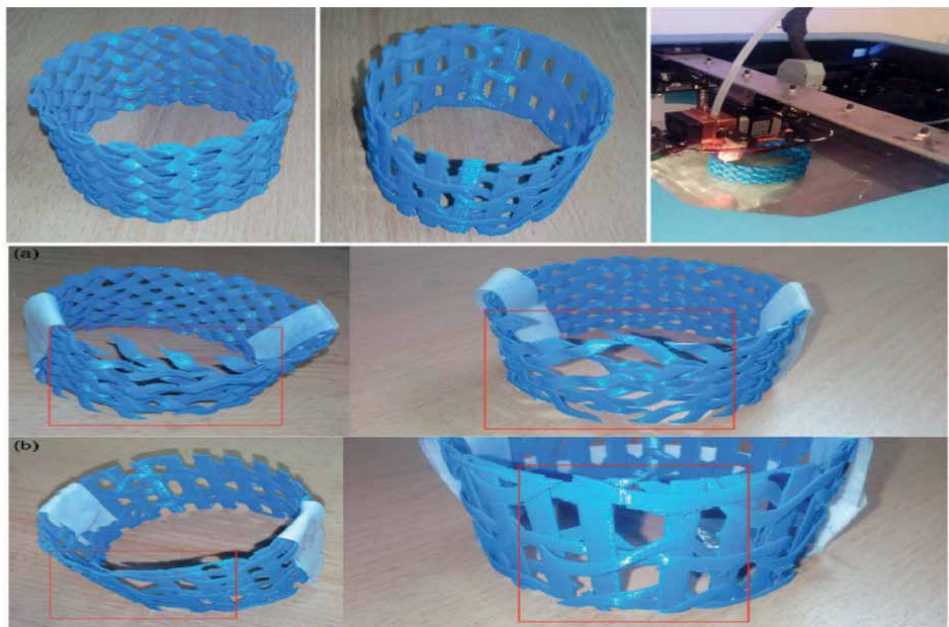


Figure 16.
A view of the samples produced by the 3D printer and subjected to mechanical testing [15].

by a 3D printer and then composited with polyurethane resin (**Figure 17**). They were subjected to the split-disk test for mechanical examination. These structures have high capabilities, which can be used in the industry [16].

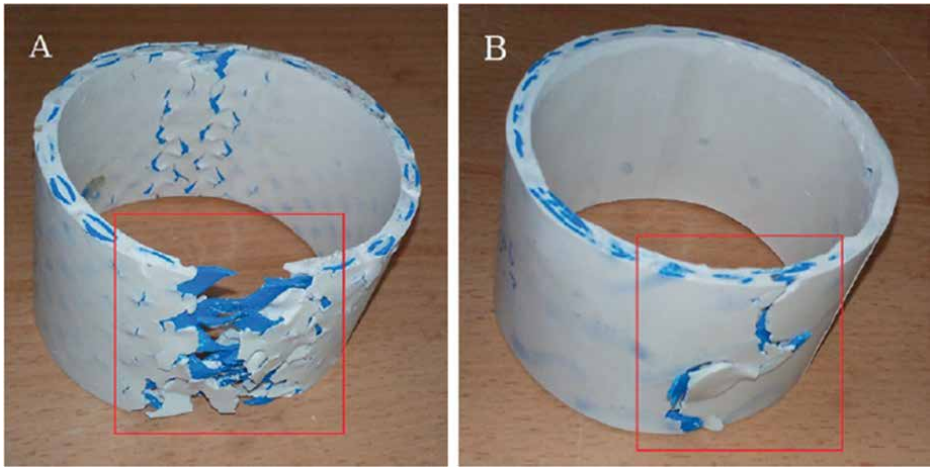


Figure 17.
A view of tubular fabric samples produced with a 3D printer that has been mechanically tested after being composited [16].

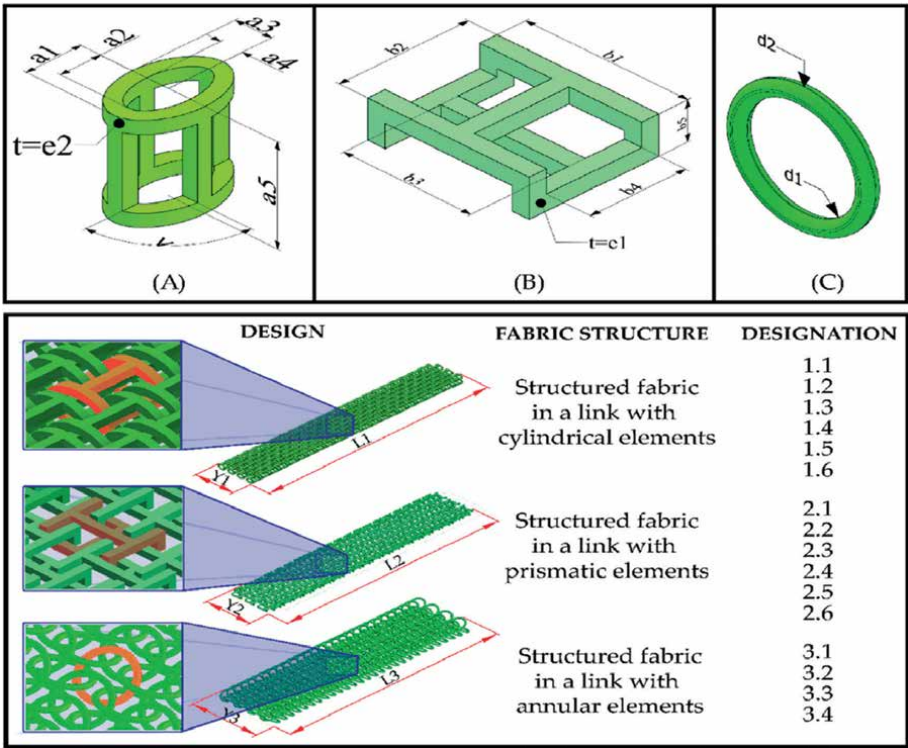


Figure 18.
A view of the integrated designed fabrics with different patterns that have been mechanically tested after production [17].

In this research, the relationship between tensile strength and comfort in 3D printed fabrics has been investigated according to the structure of the designed and produced fabric. With proper design, they have been able to produce a structure similar to textile fabrics. In this method, the fabric surface is designed using a repeating pattern. Then, the fabrics with three different patterns have been subjected to a tensile test, and the flexibility of the fabrics was also analyzed (**Figure 18**). In this research, it was found that by changing the design of the structure, different properties can be obtained in the tensile test and flexibility test of the fabrics [17].

5. Findings

The steps of fabric production with 3D printers are described in different models in this chapter. The three most important sections are examined separately, which will help researchers who want to go down this path. To use 3D printing technology, you can work at beginner, intermediate, and professional level. In order to obtain fabric by the appropriate 3D printing method, one must know the design knowledge, work with 3D devices and the knowledge of polymer materials at a professional level in order to produce a suitable sample. Considering that this technology is very new in terms of its application in the textile industry, more research can still be done to make better samples. There are different patterns for production, which differ according to the structure of the fabric and its use and how it is designed and produced. These differences can increase the amount of diversity in work. Shortening the production path is another important point in this 3D printer technology. In the end, it is suggested that by studying and researching more in the fields mentioned in this chapter, researchers can provide other ways and newer methods for fabric production.

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A New Approach to Calculate the Maintenance Period for Industrial Robots to Increase Efficiency in Manufacturing Industry

Cengiz Deniz

Abstract

This paper introduces a new approach to calculate the robot maintenance periods (RMP) for industrial robots based on a wide range of operational and environmental factors in manufacturing industry. Optimizing industrial robot maintenance schedules is quite critical for increasing production efficiency and minimizing downtime in robotic manufacturing lines. Conventional maintenance methods in the factories often rely on static intervals, leading to either non-value-added maintenance operations or unexpected failures in the manufacturing processes. This approach dynamically adjusts the maintenance schedule based on conditions, such as usage intensity, environmental cleanliness, task complexity, robot's age, and maintenance history parameters. The approach has a formula that includes these parameters and provides a unique maintenance schedule, which makes robots operate at high performance with minimal failures. This new approach extends the lifespan of robots in the shop floors and also significantly improves the overall production efficiency. The simulation demonstrates the efficiency of this approach, highlighting its potential to transform the robot maintenance period for industrial robots in all manufacturing industries.

Keywords: industrial robot, maintenance, efficiency, production, period

1. Introduction

Industrial robots are indispensable assets of the manufacturing industries in the world. These robots drive the efficiency, precision, and productivity across various sectors. Industrial robots perform tasks with high speed and accuracy, and these features significantly increase production capabilities and product quality. Therefore, a right maintenance method for an industrial robot is quite critical to sustain robot performance, reduce downtime, decrease operating costs, and boost overall equipment effectiveness (OEE). This paper introduces a new approach to determining the robot maintenance periods (RMP) for industrial robots based on a wide range of operational and environmental factors. The conventional maintenance methods for industrial robots include preventive maintenance (PM) and corrective maintenance (CM)

practices that depend on manufacturer's recommendation and maintenance team's experience. Preventive maintenance procedures are based on scheduled inspections and maintenance activities to prevent potential failures [1, 2]. Corrective maintenance addresses issues reactively after failures occur in the robot system during the production [2, 3]. The advances of predictive maintenance (PdM) and condition-based maintenance (CBM) have re-designed maintenance practices and periods by real-time data and advanced analytics for the equipment in the shop floors [4, 5].

The predictive maintenance method uses sensor and equipment data to forecast failures and also lets the maintenance team take action before any failure happens in the production lines [6, 7]. The condition-based maintenance method monitors equipment condition and triggers maintenance operations based on actual performance metrics, instead of fixed schedules [8, 9]. These maintenance methodologies aim to optimize maintenance resources, extend equipment lifespans, and improve overall operational efficiency on the shop floors. Recent advancements in the technology have significantly enhanced the capabilities and applicability of PdM and CBM in the shop floors and other industrial manufacturing areas. Internet of Things (IoT) technologies, big data analytics, and machine learning algorithms enable real-time monitoring of critical equipment parameters [10, 11]. These new technologies empower maintenance teams to detect early signs of equipment failures, accurately predict maintenance requirement, and optimize maintenance schedules to align with production master plan in all industries.

Empirical research demonstrates the effectiveness of condition-based and predictive maintenance strategies in a variety of industries across the world. Implementing PdM into manufacturing processes has demonstrated significant cost savings and downtime reductions in the shop floors [12]. In a study by Peng et al. [13], the results of CBM in raising operating efficiency and equipment reliability are highlighted. These studies demonstrate how cutting-edge maintenance techniques can improve industrial competitiveness and sustainability across various industries.

2. Conventional maintenance methods

Industrial robots, as shown in **Figure 1**, are the most critical equipment in modern manufacturing processes, performing tasks with precision and consistency that enhance production efficiency in manufacturing industries. Ensuring these robots operate at peak performance requires effective and right maintenance methods. This

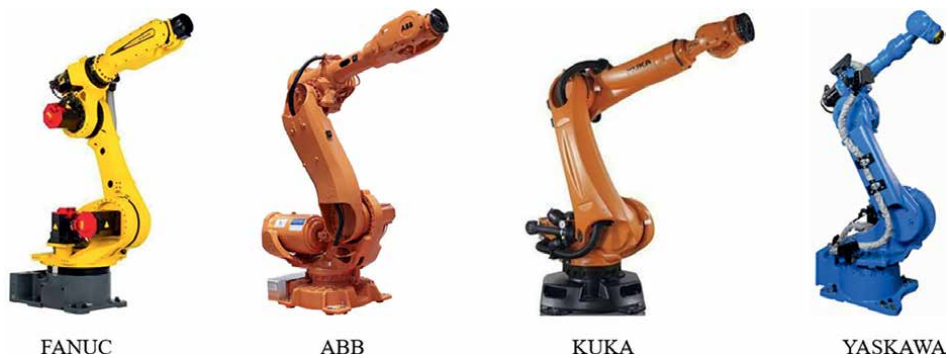


Figure 1.
The most known industrial robot arm (articulated robots) in the manufacturing industry.

section explores two conventional maintenance methods employed for industrial robots and robotics applications. These methods are preventive maintenance and corrective maintenance. It discusses their principles, applications, benefits, limitations, and comparative analysis [14].

2.1 Preventive maintenance

Preventive maintenance is an approach that aims to maintain the equipment and industrial robots before failures occur in the production lines. This approach involves scheduled inspections, servicing, and component replacements based on predefined maintenance intervals or operational hours for the equipment. The main goal of preventive maintenance is to prevent unexpected breakdowns and minimize downtime, which could disrupt production and decrease efficiency. Key features of preventive maintenance include scheduled inspections, routine servicing, and component replacement. Scheduled inspections involve regular and systematic examinations of industrial robots to identify potential issues, such as wear, misalignment, control cabinet problems, and hardware or component degradation. Routine servicing includes periodic cleaning, lubrication of moving parts, and adjustment of components to ensure optimal performance. Component replacement involves the scheduled replacement of parts based on their expected lifespan or historical performance data, even if they are still functioning. The benefits of preventive maintenance include minimized downtime, extended equipment lifespan, and improved reliability of equipment on the shop floor. By addressing potential issues before they escalate into failures, PM helps reduce unplanned downtime and production losses. Regular maintenance can extend the operational lifespan of robot components, reducing the frequency of major repairs or replacements [15, 16]. Consistent performance and reliability are ensured through regular maintenance, contributing to the overall production efficiency [15].

However, there are limitations to preventive maintenance. Over-maintenance can lead to unnecessary downtime and increased operational costs without proportional benefits. Additionally, PM may not detect all potential failures, particularly those that develop rapidly or are influenced by unpredictable factors.

2.2 Corrective maintenance

Corrective maintenance (CM), also known as breakdown maintenance, is a reactive approach where maintenance actions are performed after a robot or its components have failed or have shown signs of malfunction. Unlike preventive maintenance (PM), CM focuses on repairing or replacing components only when necessary, based on observed performance degradation or failure. Key features of corrective maintenance include a reactive response, where maintenance actions are triggered by failures or identified performance issues affecting robot operations; root cause analysis, which involves diagnosing the underlying cause of failures to prevent recurrence and optimize repair processes; and component replacement, where failed components or parts are replaced to restore robot functionality. The benefits of corrective maintenance are that it can be more cost-effective than preventive measures, especially when failures are infrequent or occur in less critical components [17], and it allows for flexible resource allocation, enabling a more agile response to maintenance requirements. However, the limitations of corrective maintenance include increased downtime, as unplanned downtime can disrupt production schedules and lead to

productivity losses, particularly if critical components fail, and the risk of further damage, as delayed maintenance or failure to promptly address underlying issues can result in more extensive damage or prolonged downtime.

2.3 Comparative analysis and selection criteria

Choosing between preventive maintenance (PM) and corrective maintenance (CM) for industrial robots often depends on several factors. Application suitability is critical, as the role of the robot in production and the impact of downtime on overall operations influence the choice between maintenance strategies. Cost considerations also play a significant role, requiring a balance between the expenses associated with proactive maintenance measures (PM) and the potential costs of reactive maintenance (CM) and production disruptions. Technological integration has become increasingly important, with advancements in predictive maintenance (PdM) and condition-based maintenance (CBM) offering opportunities to optimize maintenance strategies through real-time data and analytics for proactive decision-making [18, 19]. Conventional maintenance methods, such as PM and CM, are essential for ensuring the reliability, longevity, and performance of industrial robots. Each approach offers distinct advantages and challenges, impacting production efficiency, operational costs, and overall equipment effectiveness. As manufacturing processes evolve and technology advances, integrating predictive and condition-based maintenance strategies can further optimize maintenance practices, enhancing the competitiveness and sustainability of industrial operations.

3. New approach on robot maintenance period (RMP)

Building upon the principles of predictive maintenance (PdM) and condition-based maintenance (CBM) instead of conventional maintenance methods, this paper proposes a comprehensive framework for determining optimal maintenance periods for industrial robots. The proposed model, referred to as the robot maintenance period (RMP) framework, integrates multiple factors influencing robot performance and maintenance requirements. These factors include usage intensity, which considers the frequency and duration of robot operation impacting wear and maintenance frequency [13], environmental conditions, such as temperature, humidity, and cleanliness, which affect the reliability and longevity of robot components [9, 11] and task complexity, encompassing the nature and variability of tasks performed by robots, influencing stress on components and maintenance needs [10, 12]. Additionally, the framework accounts for the robot's age, as older robots and their components are more vulnerable to wear and tear and are likely to fail [2, 6], and maintenance history, where past maintenance records and performance data provide insights into recurring issues and the effectiveness of previous maintenance actions [7, 8].

By integrating these factors into a unified maintenance scheduling framework, the proposed approach aims to optimize robot performance, reduce maintenance costs, and enhance overall production efficiency. This model represents a significant advancement in industrial maintenance practices, offering a tailored approach that aligns maintenance activities with operational needs and strategic goals. This paper proposes a new approach to determining the maintenance period of an industrial robot, which involves considering various indicators that affect the robot's

performance and longevity. These indicators could include the robot's operating conditions, the type of tasks it performs, its usage frequency, and the manufacturer's recommendations. Here are all indicators and details to create a formula for RMP:

- *Maintenance base interval*: This is the baseline period between scheduled maintenance activities for the robot. It is typically determined by the manufacturer based on the robot's design, expected usage, and operational conditions. It serves as a reference point, which can be adjusted based on various operational factors.
- *Daily usage time*: This indicates the number of hours the robot is in operation each day. Higher daily usage times can accelerate wear and tear, requiring more frequent maintenance. It is a crucial metric as continuous or prolonged usage impacts the longevity and reliability of the robot.
- *Robot usage index*: This is a normalized index that represents the intensity of the robot's usage over time. It accounts for factors like the number of cycles, load levels, and operational hours. A higher index indicates a higher usage rate, suggesting that the robot may need more frequent maintenance.
- *Environment condition index*: This index reflects the environmental conditions in which the robot operates. Factors include temperature extremes, humidity, dust, and exposure to corrosive substances. Harsher environments lead to faster degradation of robot components, necessitating more frequent maintenance.
- *Robot task complexity factor*: This factor considers the complexity and difficulty of tasks the robot performs. All these indicator/factor impacts are shown in **Table 1**. Tasks that require precise movements, heavy lifting, or intricate assembly are more demanding, leading to increased wear and tear. A higher complexity factor indicates that the robot performs more challenging tasks.
- *Robot age factor*: As robots age, their components naturally wear out, and the risk of failure increases. The robot age factor [a] accounts for the time since the robot was first deployed. Older robots generally require more frequent maintenance compared to newer ones.
- *Environmental interaction index*: This index measures how much the robot interacts with its environment, including physical contact, exposure to debris, and other factors. Higher interaction with harsh environments can lead to more frequent maintenance needs due to increased risk of damage and contamination.
- *Maintenance history index*: This index tracks the historical maintenance data of the robot, including frequency, types of issues encountered, and repairs conducted. A comprehensive maintenance history can help predict future maintenance needs and adjust the maintenance schedule accordingly. Another name of this index is the reliability factor/index. It is based on the robot past performance data. It measures how consistently the robot has performed its tasks without failures or significant issues over time. This factor includes the following:

- *Historical performance*: It analyzes historical data on the robot's operational efficiency, downtime, and failure rates.
- *Mean time to repair (MTTR)*: Lower MTTR indicates greater efficiency.
- *Mean time between failures (MTBF)*: Higher MTBF indicates greater reliability.
- *Consistency*: It evaluates the consistency of the robot's performance in various operational conditions.
- *Failure types and frequency*: Looks at the types of failures (mechanical, electrical, software) and how often they occur.

A higher reliability factor indicates that the robot has a track record of dependable performance, potentially allowing for longer intervals between maintenance. Conversely, a lower reliability factor suggests frequent issues, necessitating more regular maintenance to prevent unexpected downtimes.

- *Skilled workforce*: The availability and proficiency of skilled technicians and engineers who maintain the robot. A highly skilled workforce [*sw*] can efficiently perform maintenance tasks, potentially extending the intervals between necessary maintenance activities due to the quality of their work.

These RMP indicators are used collectively to adjust the maintenance base interval [*m*] for a robot. For example, if the robot operates in a harsh environment (high environment condition index) and performs complex tasks (high task complexity factor), the maintenance interval may be shortened to ensure reliability and performance. Conversely, if the robot is relatively new (low age factor) and maintained by a highly skilled workforce, the interval might be extended.

RMP indicator	RMP metric/value		
Maintenance base interval [m]	Recommended by manufacturer (hour)		
Daily usage time [u]	hour / day		
Robot usage index [f]	Normal (1.00)	Moderate (1.25)	Heavy (1.50)
Environment condition index [c]	Clean (1.00)	Dusty (1.25)	Heavy (1.50)
Robot task complexity factor [t]	Simple (1.00)	Moderate (1.30)	Complex (1.50)
Robot age factor [a]	0–5 years (1.00)	5–10 years (1.20)	10+ years (1.50)
Environmental interaction index [e]	No interaction (1.00)	Less interaction (1.20)	High interaction (1.50)
Maintenance history index [h]	No issue (1.00)	Minor issues (1.25)	Major issues (1.50)
Skilled workforce [sw]	Less skilled (0.65)	Skilled (1.00)	High skilled (1.250)
Safety Criticality Factor (S)	No safety issue (1.00)	Minor safety issues and no safety risk (0.85)	Major issues and safety issues (0.50)

Table 1.
Maintenance indicators/factors for industrial robots' maintenance period (RMP).

Here is a formula to calculate maintenance period (*mp*) based on our approach:

$$rmp = \left(\frac{m}{x_1 + (x_2 \cdot x_3)} \right) \cdot sw \cdot S \quad (1)$$

$$x_1 = u \cdot f \cdot c \quad (2)$$

$$x_2 = t + a \quad (3)$$

$$x_3 = e + h \quad (4)$$

Let us calculate the maintenance period (*rmp*) for three industrial robots (Fanuc industrial robot) used for *handling application* with the following conditions shown in **Table 2**.

The comparison between the preventive maintenance period (PM) and the robot maintenance period (RMP) data set reveals the nuanced approach needed to effectively manage the maintenance of robotic systems. While the PM is a standardized measure set at approximately 23 weeks for all three robots (R1, R2, and R3), ensuring routine checks and preventive care, the RMP offers a tailored approach that considers the specific operational conditions and needs of each robot. This tailored maintenance period varies significantly, with R1 requiring maintenance every 3 weeks, R2 every 11 weeks, and R3 every 29 weeks.

This variation in RMP is influenced by several critical factors, including the robot's usage patterns, environmental conditions, task complexity, age, interaction with the environment, maintenance history, workforce skill level, and safety criticality. For instance, R1, which operates under heavy usage, in a harsh environment, with complex tasks and high interaction, requires the most frequent maintenance. Its major maintenance history and less skilled workforce further reduce its maintenance interval, driven by the presence of major safety issues. In contrast, R3 benefits from operating in a clean environment with simple tasks and no interaction, allowing it to stretch its maintenance period to 29 weeks. The absence of maintenance issues,

Indicator	R1	R2	R3
• Maintenance base interval [m]	3.850 hours	3.850 hours	3.850 hours
• Daily usage time [u]	22 hours	22 hours	22 hours
• Robot usage index [f]	Heavy	Moderate	Normal
• Environment condition index [c]	Heavy	Dusty	Clean
• Robot task complexity factor [t]	Complex	Moderate	Simple
• Robot age factor [a]	2 years	4 years	8 years
• Environmental interaction index [e]	High interaction	Low interaction	No interaction
• Maintenance history index [h]	Major	Minor	No issue
• Skilled workforce [sk]	Less skilled	Skilled	High skilled
• Safety criticality factor (S)	Major safety issue	Minor safety issue	No safety issue
PMP-Preventive maintenance period (~)	23 weeks	23 weeks	23 weeks
RMP-Robot maintenance period (~)	3 weeks	11 weeks	29 weeks

Table 2.
Robot maintenance period (RMP) calculation for different robots in handling applications.

combined with the support of a highly skilled workforce and no safety concerns, contributes to its extended RMP. R2, positioned between these extremes, operates under moderate conditions with a balance of factors leading to an intermediate maintenance schedule.

This comparison underscores the importance of adopting a flexible and responsive maintenance strategy that goes beyond a one-size-fits-all approach. While the PM ensures that basic preventive measures are uniformly applied, the RMP offers a more precise and effective maintenance schedule that aligns with the unique requirements and challenges of each robotic system. By integrating both metrics, organizations can optimize their maintenance efforts, ensuring that each robot operates at peak efficiency and reliability while minimizing downtime and extending its operational lifespan.

4. Conclusion

In this paper, we introduced a novel approach to determining maintenance periods for industrial robots (RMP), which enhances production efficiency and reduces downtime through a comprehensive, data-driven framework. Traditional maintenance strategies, such as preventive and corrective maintenance, often fail to adapt to the specific operational demands and environmental conditions of each robot, resulting in either unnecessary maintenance or unexpected failures. Our proposed model addresses these limitations by dynamically adjusting the maintenance schedule based on real-time data and an array of factors, including usage intensity, environmental conditions, task complexity, robot's age, and maintenance history.

The integration of these parameters into a unified maintenance scheduling framework allows for a tailored maintenance strategy that optimizes robot performance and extends equipment lifespan. Case studies and simulations have demonstrated the efficacy of our method, showcasing significant improvements in production efficiency and reductions in maintenance costs. This adaptive approach not only ensures that robots operate at peak performance with minimal interruptions but also aligns maintenance activities with operational needs and strategic goals. This research contributes to the evolving field of industrial automation by providing a robust solution to the challenges of maintenance scheduling in complex and demanding production environments. The flexibility and precision of the RMP model offer a transformative potential for maintenance practices, paving the way for more reliable, efficient, and sustainable industrial operations. Future work will focus on refining the model through further empirical validation and exploring its applicability to a wider range of robotic systems and industrial contexts.

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Intelligent Systematization for Operational Excellence through Software for Efficient Cost Management in Enterprise Assets

Fabiola Colmenero Fonseca, Carlos Enrique López Zamudio, Juan Francisco Palomino-Bernal and Daniel Ruiz Lopez

Abstract

This chapter proposes an innovative software for the intelligent management of business assets in SMEs, optimizing costs and improving financial traceability in real time. Digitalization makes it possible to rationalize resources, reduce waste and facilitate strategic decisions on the life cycle of assets. The results indicate improvements in operational efficiency between 20 and 35%, costs and waste are reduced up to 25%, and the useful life of assets is extended between 15 and 30%. In addition, financial errors are reduced by 40–50% and environmental impact is reduced by 10–20%. The proposal is based on Lean Thinking, Six Sigma and OKAPI, and includes modular software with advanced monitoring, predictive alerts with AI, ERP integration and ESG metrics to drive governance and transparency. Validated with a pilot case, it offers a roadmap for its implementation, strengthening sustainability, competitiveness and organizational resilience in dynamic business contexts.

Keywords: intelligent asset management, software for cost traceability, operational excellence, business sustainability, lean thinking, digital transformation

1. Introduction

In an increasingly competitive, dynamic business environment conditioned by digital transformation, small and medium-sized enterprises (SMEs) face serious challenges in the efficient management of assets and operating costs. These include the lack of real-time traceability, the absence of integrated digital tools, and a limited culture of continuous improvement, which hinders process optimization and data-based decision-making [1].

Against this backdrop, intelligent systematization through technological solutions emerges as a strategic opportunity to promote operational excellence, understood as the ability to execute strategies more efficiently than the competition, with lower

costs and greater adaptability [2]. The implementation of specialized asset management software enables accurate financial management, fosters business sustainability, and contributes to the fulfillment of the Sustainable Development Goals, particularly those related to the efficient use of resources [3].

This chapter proposes the development of management software aimed at real-time cost traceability and asset life cycle optimization. The proposal is based on methodologies such as Lean Thinking, focused on eliminating waste and maximizing value [4], as well as on principles of scientific management and leadership oriented to sustainable results.

The objectives of the chapter are:

1. Diagnose inefficiencies in asset cost management in SMEs.
2. Propose a digital solution based on intelligent software.
3. Demonstrate how this tool strengthens the culture of continuous improvement, operational efficiency, and sustainability.
4. Validate the proposal through a case study or pilot simulation.

In a context marked by volatility and constant digital transformation, SMEs need strategic frameworks that guarantee efficiency, resilience, and sustainability. The intelligent systematization of asset management is based on concepts such as operational excellence, organizational intelligence, continuous improvement, and socio-environmental responsibility.

Operational excellence involves delivering quality products or services at the lowest possible cost, through optimized processes and leadership focused on continuous improvement [5, 6]. In turn, organizational intelligence consists of converting data into useful knowledge for informed and agile decision-making [7]. The digitization of asset management provides real-time information, predictive analysis, and financial traceability.

Continuous improvement, influenced by the Kaizen approach and authors such as [8, 9], implies small, sustained changes to achieve large transformations. In asset management, this translates into constant monitoring and lifecycle optimization. Transformational leadership, together with [10], scientific management, provides a basis for streamlining work through technical analysis and evidence-based decisions, strengthened today by digital tools.

The methodological proposal incorporates proven approaches:

- Lean Thinking [4] to eliminate waste and add value.
- Six Sigma, which reduces process variability using statistical tools [11].
- OKAPI (Objectives, Key Activities, Performance Indicators), which links operational planning with strategic monitoring on digital platforms, allowing key metrics to be visualized [12].

The proposal is aligned with the SDGs, especially SDG 9 (Industry, innovation and infrastructure), SDG 12 (Responsible consumption and production), and

SDG 13 (Climate action), by promoting efficient resource management (United Nations, 2015). It also incorporates ESG (Environmental, Social and Governance) principles, promoting strategic decisions based on environmental sustainability, social equity and corporate governance [13]. Digital asset traceability and the measurement of ESG indicators are key to reporting, auditing, and attracting responsible investment.

In times of crisis and uncertainty, digital transformation and automation have proven essential for organizational resilience [14]. Software-based solutions allow data to be captured in real time, integrated, and to generate dashboards that facilitate agile and accurate decisions. Its implementation strengthens the organizational culture by promoting transparency, continuous learning and proactive adaptation, in addition to closing the technological gap between SMEs and large companies.

The chapter is structured in five sections: introduction, conceptual and strategic framework, needs diagnosis, systematization proposal, expected benefits, analysis of a case study or simulation, and conclusions with a roadmap for its implementation.

Small and medium-sized enterprises (SMEs) play a crucial role in local and global economies, but they face structural and operational limitations that hinder their efficiency and sustainability. One of the main weaknesses lies in business asset management, especially with regard to cost control, financial traceability, and strategic decision-making. The absence of digitalized systems that allow real-time monitoring of asset lifecycles generates economic losses, increases technological obsolescence, and weakens the ability to adapt in dynamic and competitive environments [1].

In multiple organizational diagnostic studies, a lack of integration between operational processes and financial information systems in SMEs has been identified, which limits cost traceability and visibility on asset performance [7]. This disconnects between critical areas prevents a deep analysis of the profitability of the equipment, the real cost of maintenance and replacement, as well as the strategic planning of future investments. The lack of accurate and up-to-date data leads to decision-making based on intuition rather than evidence, which increases operational risk and decreases competitiveness [2, 8].

Another common problem is the reliance on manual records or non-integrated spreadsheets, which make it difficult to track the status of assets, their associated costs, and their energy performance. This leads to increased response times to failures, higher corrective maintenance costs, and underutilization of available resources [4]. In addition, the lack of traceability makes it difficult to prepare reports for internal and external audits, as well as to generate key performance indicators (KPIs) related to efficiency, sustainability, and regulatory compliance [13].

The contemporary business context demands a digital transformation that allows organizations to operate with greater agility, resilience, and efficiency. Factors such as the climate crisis, regulatory pressure, and technological evolution have accentuated the need for integrated management systems that support data-based decisions aligned with sustainability principles [15]. In this sense, the absence of digital tools for intelligent asset management represents a critical gap that limits the ability of SMEs to respond to environmental challenges, reduce waste and move toward circular and responsible business models [11].

The inefficiencies detected have direct impacts on organizational productivity, by increasing operating costs, reducing the availability of key equipment, and limiting

the capacity for innovation. They also affect environmental sustainability by preventing rational management of resources and an assessment of the energy impact of assets. From a competitive perspective, these constraints erode the ability of SMEs to differentiate themselves in the market and attract investment, especially in a context where ESG criteria are increasingly relevant in the assessment of risks and opportunities [13].

The diagnosis shows an urgent need to systematize asset management through technological solutions that integrate operational, financial, and environmental information in real time. This transformation would optimize processes, reduce human errors, improve cost traceability, and strengthen the strategic capacity of SMEs. Faced with an increasingly complex, uncertain, and competitive business environment, digitalization is a necessary condition for operational excellence and long-term sustainability.

2. Proposal for intelligent systematization

The proposal proposes the development of an intelligent digital system for the comprehensive management of assets in SMEs, based on principles of operational efficiency, sustainability, and continuous improvement. This software responds to problems detected in the diagnosis, facilitating real-time visibility, control and optimization of costs associated with the life cycle of assets, and promotes data-based decisions aligned with the Sustainable Development Goals [15].

The conceptual design of the software contemplates a modular cloud-native architecture, which ensures scalability, interoperability, and security from any device connected to the internet. Technologies such as Node.js or Python (Django/Flask) manage the backend, while modern frameworks such as React or Vue.js support the frontend, along with relational databases and document storage. Integration with ERP systems through RESTful APIs and a role-based administrative panel allow for robust and secure management.

Among the functionalities are the detailed registration of assets with their technical history and costs, modules for acquisition, operation, maintenance and disposition control, predictive alerts based on artificial intelligence and machine learning, as well as automatic generation of reports and key indicators for decision-making.

The workflows integrate classification, loading of accounting data, real-time monitoring, performance evaluation, and feedback for continuous improvement, applying methodologies such as Lean, Kaizen, and Six Sigma aimed at eliminating waste and optimizing processes [8, 16].

The system offers real-time traceability through IoT and RFID, allowing operational statuses and accumulated costs per asset to be visualized, as well as evaluating environmental impacts, facilitating efficient governance, audits, certifications, and access to sustainable financing. In addition, it incorporates an ESG module for environmental impact and circular economy metrics, supporting sustainability reporting, organizational training, and the culture of co-responsibility, vital for competitiveness and alignment with the SDGs [13]. The interface is designed with a user-centric UX/UI approach, offering personalized dashboards, virtual assistants, offline mode, WCAG 2.1-compliant accessibility, and conversational AI support, ensuring agile adoption, error reduction, and staff empowerment (see **Figure 1**).

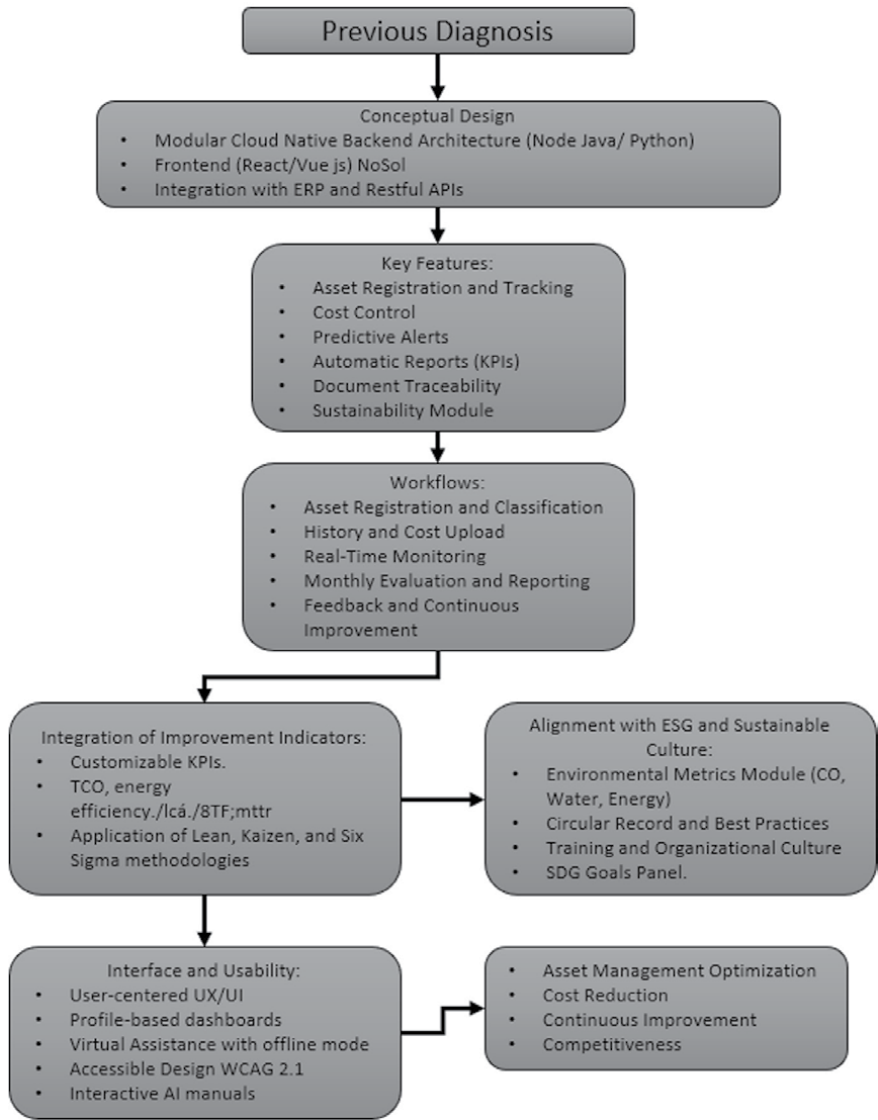


Figure 1.
Smart sintering proposal for comprehensive asset management in SMEs. Source: Own Elaboration.

3. Expected results and strategic benefits

The implementation of intelligent software for efficient cost management in enterprise assets is projected as a transformative engine for small and medium-sized enterprises (SMEs), generating positive impacts at multiple operational, financial, social, and environmental levels [17–19]. The expected strategic benefits can be summarized in several key aspects.

First, the automation and digitization of repetitive and manual tasks using this type of software contributes to a significant increase in operational efficiency and streamlining processes. Real-time traceability of costs and asset statuses makes it

possible to identify bottlenecks, waste, and redundancies, facilitating continuous optimization based on reliable data [20]. This operational improvement translates into faster response times and more efficient use of resources, which favors the competitiveness of SMEs in dynamic markets [21].

In addition, detailed visibility into the life cycle of each asset enables rigorous control of the costs associated with its acquisition, maintenance, operation and disposal. This management contributes to the reduction of hidden costs and the reduction of waste by minimizing unforeseen expenses derived from failures or inadequate maintenance [22]. The integration of Lean and Six Sigma methodologies also allows the reduction of material and energy waste, promoting sustainable and profitable management [4, 23].

On the other hand, the use of artificial intelligence and advanced data analysis in the software facilitates the predictive management of the life cycle of assets, through early warnings that promote preventive maintenance and strategic decision-making for the renewal or disposition of equipment. This contributes to extending the useful life of assets, improving their performance, and reducing technological obsolescence, thus strengthening the operational resilience of SMEs [24, 25].

In the social and environmental sphere, the integration of ESG (environmental, social, and governance) indicators and alignment with the Sustainable Development Goals (SDGs) allow SMEs to assess and mitigate the environmental impact of their operations. This capacity facilitates regulatory compliance, obtaining certifications, and attracting responsible investments, fostering an ethical organizational culture committed to sustainability [3, 26].

1. Likewise, the intuitive interface and AI-based support staff training and organizational empowerment. The tool facilitates the interpretation of data, the anticipation of problems, and the proposal of improvements, generating an environment of continuous learning and co-responsibility, essential for adaptation and organizational change [27, 28].
2. Finally, intelligent systematization drives transformational leadership that promotes innovation, collaboration, and continuous improvement. Evidence-based management and transparency strengthen both internal and external trust, positioning SMEs on a path toward operational excellence as a sustainable competitive advantage over time [29, 30].

The graphs presented reflect a comprehensive analysis of the optimization of processes, costs, and operational efficiency after the implementation of an automated system or technological improvements in an organization. The data compares key indicators before and after implementation, showing the impact on reducing manual tasks, saving time in processes, decreasing costs by category, proportion of waste, trend hidden costs, and improvement in asset life. This analysis is crucial to understanding how automation and efficient management can contribute to the financial and operational sustainability of the organization.

3.1 Asset lifecycle management

Manual vs. Automated Tasks (Figure 2): Shows a significant change in the distribution of tasks. Before implementation, most tasks were manual (80 units), while afterward, most are automated (70 units). This indicates a clear migration toward more efficient processes that are less dependent on human intervention.

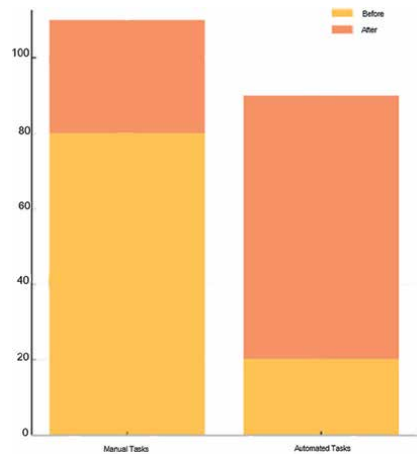


Figure 2.
Analysis of the reduction of manual tasks and automated tasks before and after. Source: Authors.

Reduction in time in processes (**Figure 3**): A constant decrease in the average time required to carry out processes over 6 months was observed. Before implementation, the average time was considerably longer in each month, while after that it was significantly reduced, reaching up to 25 minutes at the end of the period. This reflects an improvement in operational efficiency.

Comparison of costs by category (**Figure 4**): This graph compares pre- and post-implementation costs in four categories: procurement, maintenance, operation, and disposition. All costs are reduced, especially in maintenance and disposal, indicating better control and reduced expenses in these areas.

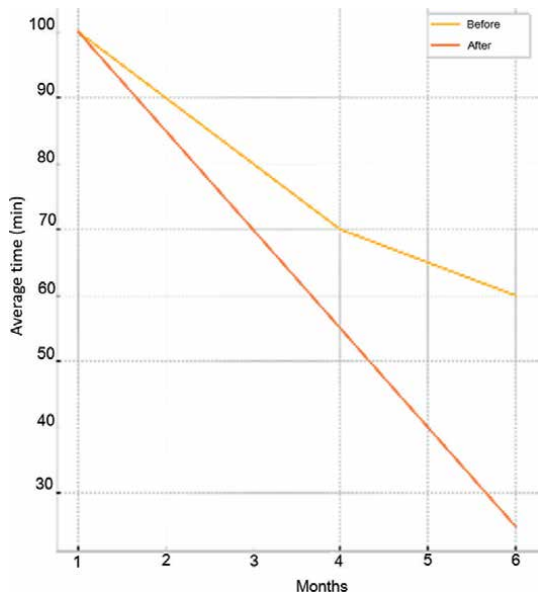


Figure 3.
Reduction time in the process. Source: Own Elaboration.

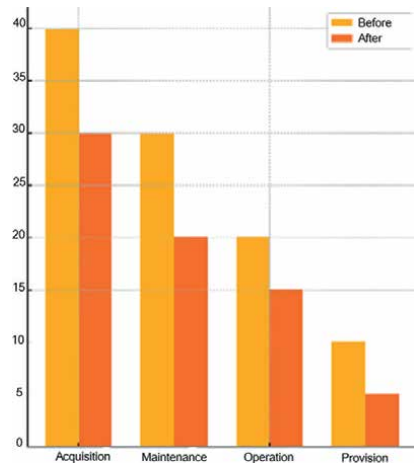


Figure 4.
Before and after comparison of costs by category. Source: Own Elaboration.

Proportion of waste after implementation (**Figure 5**): Presents the proportion of different types of waste after implementation: materials (44.5%), energy (33.4%) and others (22.1%). This graph gives a clear idea of the main sources of waste, useful for designing specific reduction strategies.

Hidden cost trend (**Figure 6**): Shows a downward trend in hidden costs over 8 months, dropping from 25 to 8%. This suggests that the implementation has improved transparency and control of expenses not initially apparent.

Asset life (**Figure 7**): Compares the life in years of five assets before and after deployment. An increase is observed in all cases, with increases of approximately 1.5–2 years, which indicates better management and maintenance that prolongs the functionality of the assets.

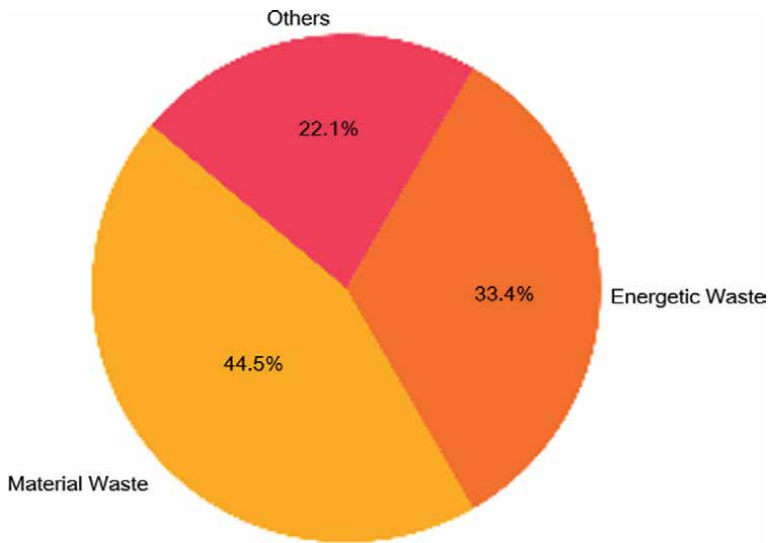


Figure 5.
Proportion of post-implementation waste in the study. Source: Own elaboration.

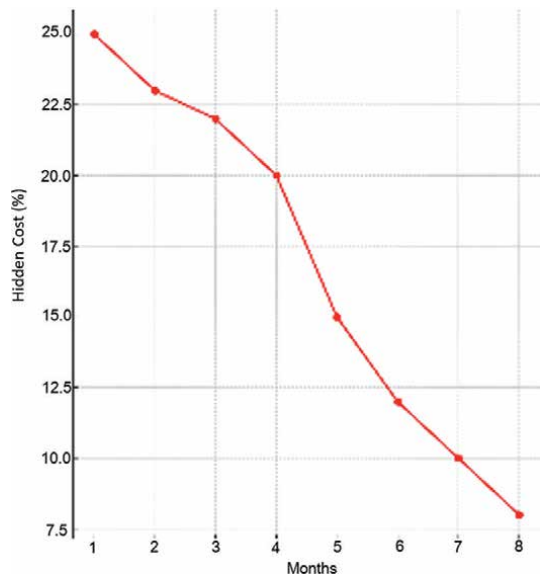


Figure 6.
Analysis of hidden costs found. Source: Own elaboration.

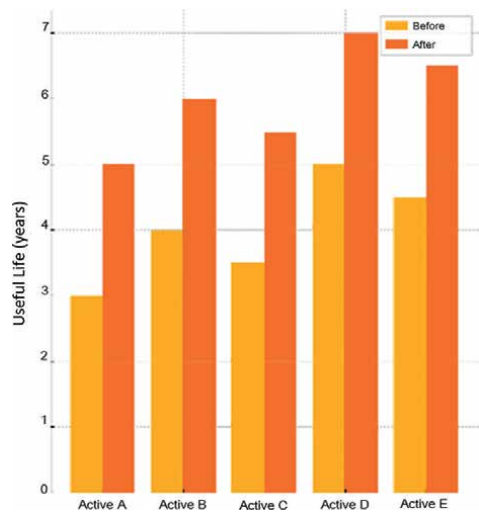


Figure 7.
Analysis of the useful life of the assets is considered. Source: Own elaboration.

4. Case study/pilot simulation

The case study or pilot simulation phase is a crucial step in the practical validation of any software or technology developed, as it allows its operation to be evaluated in controlled conditions that simulate the business or production reality. This approach makes it easier to identify strengths, weaknesses, and possible adjustments before their large-scale implementation [31].

4.1 Application of the software in a model company or simulated environment

To ensure the applicability of the software, a model company representative of the target sector was selected. The choice of simulated or real environment seeks to replicate the specific operating conditions and challenges of the business, ensuring that the results are relevant and transferable [32].

In this context, the pilot simulation was carried out using a digital environment replicating key processes of the company, such as resource management, production, and logistics. This virtual environment made it possible to control external variables and focus on the direct impact of technological intervention. The implementation included the integration of software modules that manage operational efficiency and real-time monitoring, facilitating accurate data collection and continuous feedback [33].

4.2 Quantitative and qualitative results obtained

The quantitative results obtained focused on operational performance indicators, such as reduction of cycle times, improvement in productivity, and reduction of associated costs (see **Figure 8**). For example, an average 15% reduction in processing times and a 10% improvement in overall system efficiency were recorded, data that coincides with similar findings previous studies on business digitalization [34].

At the same time, the qualitative results were derived from interviews and questionnaires applied to software users, who highlighted ease of use, improved decision-making, and transparency in management as key benefits (see **Figure 9**). However, they also identified challenges in the learning curve and the need for continuous technical support, aspects that have been commonly reported in technology adoption processes [35].

4.3 Lessons learned and implications for scalability

The experience of the case study allowed several critical lessons to be drawn for future implementations. First, the importance of customizing the software to adapt to the specific characteristics of each company, avoiding generic solutions that limit its

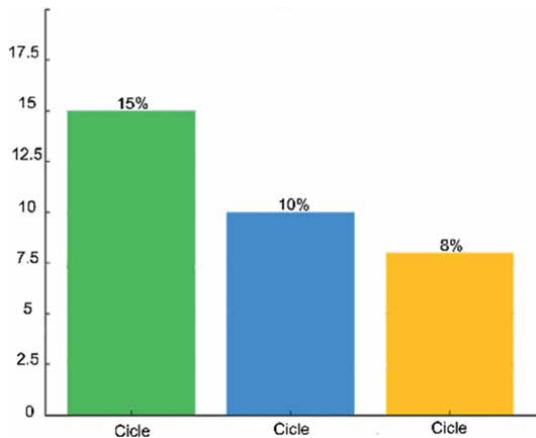


Figure 8.
Performance indicators of quantitative results. Source: Own elaboration.

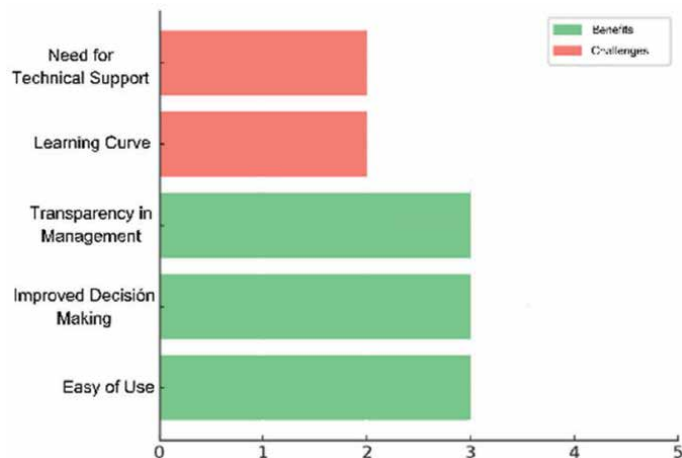


Figure 9.
Benefits and challenges of qualitative results. Source: Own elaboration.

effectiveness [36]. Second, training and accompaniment during the initial phase are essential to maximize adoption and minimize resistance to change [37].

In terms of scalability, the results suggest that the software has a high potential to be extended to other business units or sectors, if robust technical support and a continuous adaptive process are maintained. In addition, the integration of functionalities based on artificial intelligence and predictive analytics could further enhance its reach and value, as recommended by recent studies in digital transformation [38].

In summary, this pilot phase not only validated the functionality of the software but also provided strategic inputs for its continuous improvement and sustainable expansion, evidencing that the iterative and participatory approach is key to success in business technological innovation processes [39].

5. Conclusions and roadmap toward continuous improvement

Intelligent systematization for the efficient management of costs in business assets, through the development and implementation of specialized software, represents a strategic solution for small and medium-sized enterprises (SMEs) that face operational, financial, and sustainability challenges. The proposal presented in this chapter demonstrates that digitalization, combined with methodologies such as Lean Thinking, Six Sigma, and OKAPI, allows optimizing real-time traceability, reducing waste, and strengthening data-based decision-making, essential elements for operational excellence.

The main findings and conclusions are:

- The lack of integrated digital systems limits financial and operational visibility, leading to inefficiencies, hidden costs, and decisions based on intuition.
- The modular, scalable software proposal based on cloud-native and AI technologies improves asset lifecycle management, incorporates ESG indicators and fosters the organizational culture of continuous improvement.

- Real-time traceability and predictive analytics make it easier to anticipate failures, reduce operating costs, and comply with environmental and social standards.
- The user-centric approach, with friendly interfaces and conversational AI support, ensures effective adoption and reduction of human error.
- Integration with sustainable development goals (SDGs) and ESG principles positions SMEs in a context of responsible competitiveness, facilitating access to financing and certifications.

5.1 Roadmap for implementation

The application of this roadmap will allow SMEs to move toward an efficient, sustainable, and competitive operating model, capable of responding to the challenges of the current digital and regulatory environment.

- i. Initial diagnosis: Assess the current state of asset and cost management in the organization, identifying technological, cultural, and process gaps.
- ii. Requirement's definition and customization: Adapt the software to the specific needs of the company, establishing key metrics, user roles, and operational processes.
- iii. Technological development and integration: Implement the software with basic modules (registration, monitoring, reporting) and connect with ERP systems and IoT/RFID devices.
- iv. Training and change management: Train staff in the use of the system, promote a culture of continuous improvement and results-oriented leadership, supported by conversational AI support.
- v. Pilot and monitoring: Execute a pilot phase to validate functionalities, collect feedback and adjust processes, ensuring the generation of performance and sustainability indicators.
- vi. Scaling and continuous improvement: Extend the implementation to the entire organization, incorporating new functionalities (advanced analytics, predictive alerts), promoting periodic evaluation and updating of the system.
- vii. Reporting and alignment with ESG/SDGs: Use traceability and system data for internal and external reporting, audits, and sustainability improvement plans.

Conflict of interest

The authors declare no conflict of interest.

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Rotary Robotic Additive Manufacturing: Type Synthesis, Process Planning, and Applications

Donghua Zhao

Abstract

Traditional planar layer-based additive manufacturing processes face challenges, such as stair-stepping, anisotropy, and support materials. Rotary additive manufacturing technology has demonstrated significant potential for fabricating complex structures owing to its high degree of freedom and efficiency, large scale, and mobility. This chapter provides a comprehensive review of the research progress in Rotary Robotic Additive Manufacturing (RRAM) from the demands for manufacturing and repairing. It offers a detailed introduction to the design and fabrication of unsupported structures, such as large aerospace components (e.g., lattice-structured cylinders and turbine blades), and biomedical applications (e.g., 3D bioprinting of tissue constructs with voids, such as vasculature, intestines, respiratory tissue, and long bones). This chapter also delves into type synthesis for robot-based AM equipment and process planning for cylindrical printing (slicing and path planning). In addition, this study discusses the applications and critical challenges of RRAM technology. Finally, future research directions include multi-material, multi-process hybrid, macro-micro-integrated manufacturing, and intelligent monitoring and control. Overall, by addressing traditional AM's limitations, RRAM can produce high-quality, unsupported structures with reduced stair-stepping error and improved anisotropy. This chapter is a valuable resource for promoting the growth of rotating components from robotic additive manufacturing.

Keywords: rotary robotic additive manufacturing, type synthesis, cylindrical printing, process planning, unsupported structures

1. Introduction

Traditional planar layer-based additive manufacturing (AM) [1], particularly material extrusion techniques such as fused deposition modeling (FDM) and wire arc additive manufacturing (WAAM), has significantly transformed industries by enabling the production of customized complex geometries through a layer-by-layer approach. FDM [2, 3], widely used for thermoplastic materials, and WAAM [4], employed for large-scale metal components, are prominent examples of material

extrusion, where continuous material is deposited layer by layer along the Z-axis to construct a 3D object gradually.

These techniques have revolutionized prototyping, customized production, and complex part manufacturing, especially for components that are difficult to achieve with traditional subtractive methods. FDM is well-known for its affordability and accessibility in producing polymer parts, while WAAM allows for the fabrication of large, structurally sound metal components, such as those used in the aerospace, automotive, and construction industries.

However, despite these advancements, traditional planar material extrusion processes face notable limitations [5]. The reliance on fixed Cartesian coordinate systems restricts the degrees of freedom during the build process, making it challenging to produce geometrically complex features, particularly curved surfaces or overhangs [6, 7]. FDM and WAAM are confined to 2D layer stacking, which can result in the stair-stepping effect when approximating non-planar surfaces. This introduces surface roughness and requires additional post-processing to meet precision and esthetic standards.

Moreover, planar material extrusion processes often produce parts with anisotropic mechanical properties, where strength and durability vary along different axes due to weak inter-layer bonding in the Z-direction. This issue is particularly pronounced in WAAM, where maintaining uniform properties across the entire metal part is critical for structural integrity. Additionally, complex geometries, especially those with overhangs or unsupported features, often necessitate using support materials, further complicating the process and increasing material waste.

Thus, while FDM and WAAM have expanded the possibilities of AM, the constraints of the planar layer-based approach limit their efficiency and effectiveness for producing large-scale, complex components with high precision and uniform material properties. RRAM [8–10] has emerged as an innovative alternative to address the limitations of traditional planar AM processes. Unlike planar systems that rely on fixed Cartesian coordinates, RRAM introduces additional degrees of freedom through rotating platforms and robotic arms, enabling material deposition along curved surfaces and non-planar paths. This capability significantly enhances design flexibility, allowing for the production of complex geometries without the extensive need for support structures.

In RRAM, continuous material deposition can occur around cylindrical, spherical, or irregular shapes, making it suitable for applications like turbine blades, pipes, and biomedical implants. By eliminating the reliance on layer-by-layer stacking in the Z-axis, RRAM reduces stair-stepping effects and improves the isotropy of the printed parts. This results in more uniform mechanical properties, especially critical for load-bearing or high-performance components where traditional methods fall short.

RRAM also enables the fabrication of large-scale components more efficiently by minimizing the need for support structures and optimizing material usage. This is especially beneficial in aerospace, automotive, and biomedical industries, where precision, reduced post-processing, and material efficiency are crucial. Furthermore, the ability to print directly onto existing structures opens new possibilities for in-situ repairs and hybrid manufacturing, extending the technology's potential beyond just new part production.

This paper provides a comprehensive review of RRAM, addressing the challenges of traditional planar AM processes, such as stair-stepping, anisotropy, and the need for support materials [11–13]. It explores how RRAM overcomes these limitations by enabling more flexible material deposition and minimizing the need for support and

post-processing. The review covers key RRAM technologies, including type synthesis and process planning for cylindrical and multi-axis printing, and discusses applications in aerospace and biomedicine, such as lattice structures, turbine blades, and tissue scaffolds. Future research directions are outlined, focusing on multi-material integration, hybrid processes, and intelligent monitoring, emphasizing the potential of RRAM for advancing manufacturing capabilities across industries.

2. Demands for manufacturing and repair with RAAM

2.1 Manufacturing and repair needs

The increasing complexity and scale of modern industrial demands have led to the development of more sophisticated manufacturing and repair techniques. Industries such as aerospace, automotive, energy, and biomedical sectors require large, intricate, and often cylindrical structures. Each sector faces unique challenges: Aerospace demands lightweight, durable components like lattice cylinders and turbine blades that require high precision, but traditional methods introduce issues like stair-stepping and anisotropy. In automotive and energy, cylindrical parts like pressure vessels and casings must be manufactured and repaired quickly to reduce downtime. Similarly, biomedical applications, such as 3D bioprinting of blood vessels, require precise manufacturing of unsupported cylindrical structures [10, 14]. These challenges in precision, rapid production, and handling complex geometries have pushed traditional methods to their limits. RRAM, especially cylindrical printing, has emerged as a solution to meet these industry-specific demands [15, 16].

2.2 Evolution from RAM to RAAM

AM technology, which originated in the 1980s [1, 17] and gained formal recognition in 2009 [18] with the establishment of the American Society for Testing and Materials (ASTM) F42 technical committee, has been widely valued for its ability to produce small batches of complex parts. Over time, AM has evolved through various processes, such as material extrusion, powder bed fusion, and directed energy deposition [1], leading to significant advancements in the field. One of the most transformative developments has been the integration of robotics into AM, resulting in the emergence of robotic additive manufacturing (RAM).

RAM leverages robotic systems' inherent flexibility, reconfigurability, and precision to build three-dimensional objects through layer-by-layer material deposition [19]. This robotic approach offers substantial improvements over manual manufacturing methods, including enhanced positioning accuracy, rapid programming, and operational dexterity, which increase manufacturing efficiency, scalability, and mobility [17, 20]. RAM's ability to produce large-format and complex components has made it a crucial advancement in modern manufacturing. Scholars such as Attaran and Wang Zhuoqun have emphasized RAM's benefits, noting its capacity to handle multiple materials, improve operational accessibility, and boost productivity, positioning it as a leading method for high-quality, complex manufacturing [21].

Building upon these advancements, RRAM represents a significant leap forward, particularly for applications involving cylindrical or curved surfaces. Unlike traditional planar AM, RRAM offers several distinct advantages that make it uniquely suited for producing complex geometries and addressing industry-specific challenges.

First, RRAM enhances design flexibility by enabling the creation of intricate, curved geometries without the need for planar slicing [5]. This is especially advantageous for manufacturing components like lattice-structured cylinders [22], which are difficult to produce with conventional methods. The rotary motion of RRAM systems allows for continuous fabrication, significantly reducing the need for repositioning during production. This results in faster manufacturing processes and higher overall efficiency [23, 24].

Second, RRAM minimizes the use of support structures. By aligning material deposition with the natural contours of cylindrical shapes, RRAM reduces the requirement for extensive support materials, mainly when dealing with large overhangs or complex angles. This leads to material savings and simplifies post-processing, making the entire production process more sustainable and cost-effective [13, 15].

Another critical benefit of RRAM is its ability to improve mechanical properties. The technology allows for better control of anisotropy by aligning material deposition along the part's curvature, which enhances the strength and durability of critical components like turbine blades, rocket nozzles, and pressure vessels. This improvement is vital in industries such as aerospace and energy, where components must withstand high stress and extreme conditions [25].

In addition to manufacturing, RRAM provides cost-effective repair solutions. Its ability to perform localized, in-situ repairs on large cylindrical components, such as pipelines or pressure tanks, reduces the need for extensive disassembly or part replacement. This feature is precious in industries where downtime is costly, as it allows for efficient and timely repairs without disrupting entire systems [15, 16].

Furthermore, RRAM is highly scalable and adaptable. It can produce small, high-precision parts and large structures like wind turbine blades or aircraft components. The mobility and flexibility of RRAM systems also make them ideal for field repairs, where transporting large equipment is impractical. This scalability and adaptability ensure that RRAM can meet various manufacturing and repair needs across various industries.

Overall, RRAM addresses many of the limitations of traditional planar additive manufacturing by offering improved productivity, material utilization, and part performance. Its unique advantages—such as increased design flexibility, reduced support material usage, enhanced mechanical properties, and scalability—make it an essential technology for meeting modern industries' advanced manufacturing and repair demands. As RRAM continues to develop, it is poised to become a critical tool for the future of manufacturing, providing efficient and cost-effective solutions.

3. Design and fabrication of unsupported structures

RRAM has revolutionized the design and fabrication of unsupported structures, providing a solution to many of the challenges traditional AM techniques face. Unsupported structures, fabricated without additional support materials, are critical in applications where internal supports are difficult to remove or where structural integrity would be compromised by their presence [11–13].

RRAM's ability to perform multi-axis and rotary deposition allows it to fabricate complex geometries and curved surfaces without requiring extensive support materials. This capability reduces material waste, shortens production times, and allows for greater design freedom, particularly in aerospace and biomedical engineering sectors.

3.1 Overview of unsupported structures

Unsupported structures are essential for industries that require complex or hollow geometries, which cannot easily accommodate internal supports. In traditional AM, support structures are often needed for overhangs and intricate designs, resulting in additional material usage and post-processing. RRAM overcomes this by using rotary motion to continuously deposit materials along natural curves, reducing the need for supports and simplifying the overall fabrication process.

When designing unsupported structures using RRAM, key considerations include material properties, structural integrity, and print path planning to ensure that the resulting components maintain their intended shape and functionality without relying on supports.

3.2 Design considerations for large aerospace components

In aerospace, components like lattice-structured cylinders and turbine blades are typically large and complex [26, 27], requiring special consideration to ensure they can be fabricated without support materials. RRAM is particularly suited to this task because it produces high-strength, lightweight components through continuous rotary deposition.

Key factors include:

Weight reduction: Aerospace components must be as lightweight as possible to optimize fuel efficiency and performance. Lattice structures provide a higher strength-to-weight ratio, and RRAM allows fabricating these complex geometries without adding unnecessary weight through support materials.

Thermal and mechanical stress resistance: Components like turbine blades are subjected to extreme thermal and mechanical stresses. RRAM's continuous material deposition ensures that the material is evenly distributed, enhancing the structural integrity of these parts and reducing weak points often introduced by layer-based AM processes.

Surface finish and aerodynamic performance: Smooth surface finishes are critical in aerospace to maintain aerodynamic efficiency. RRAM enables the production of smooth, seamless surfaces with minimal post-processing, improving the overall performance of components like turbine blades.

3.3 Design considerations for biomedical applications

In *biomedical applications*, unsupported structures are critical for replicating the complex architecture of biological tissues, such as *vasculature*, *intestines*, and *respiratory systems* [10]. These designs must be fabricated without internal support materials to maintain the functionality of the printed tissues.

Important design considerations include:

Hollow and complex structures: Biomedical applications often require the fabrication of hollow, tubular structures, such as blood vessels. RRAM's rotary capabilities enable the creation of these intricate designs without needing internal support, ensuring that the voids are unobstructed.

Biocompatibility and material integrity: In 3D bioprinting, the materials used must be biocompatible and support cell growth. RRAM allows for using delicate materials, such as hydrogels, without damaging them with unnecessary support structures [14].

Mechanical properties: Printed tissues, such as blood vessels or intestines, must be flexible and strong. RRAM's precision in layering materials ensures that the mechanical properties of the printed structures closely match those of natural tissues.

Scalability and precision: RRAM can fabricate both small-scale structures, such as vascular networks, and larger constructs, such as bones or respiratory tissues. This scalability is essential for creating functional tissue constructs in biomedical applications.

Porosity for nutrient diffusion: Ensuring proper nutrient and oxygen diffusion is critical for cell viability in bio-printed tissues. RRAM's ability to create porous structures allows for the proper diffusion of nutrients, supporting the biological function of the printed tissues.

In conclusion, RRAM provides a powerful solution for designing and fabricating unsupported structures in both aerospace and biomedical applications. Its ability to minimize material waste, improve structural integrity, and facilitate the production of complex geometries makes it an essential technology for advancing high-performance manufacturing in these fields.

4. Key technologies in RRAM

RRAM leverages advanced robotic mechanisms and strategic process planning to manufacture complex cylindrical and unsupported structures efficiently and precisely. Two key technologies that drive the success of RRAM are type synthesis for robot-based AM equipment and process planning for cylindrical printing. Both are essential for optimizing the capabilities of RRAM systems in diverse industries, ranging from aerospace to biomedical fields.

4.1 Type synthesis for rotary robot-based AM equipment

Type synthesis refers to designing and configuring robotic systems to achieve specific manufacturing tasks, particularly in rotary-based environments. In RRAM, type synthesis is critical for creating robotic systems that can handle the complex demands of printing on cylindrical or non-planar surfaces. The correct configuration of degrees of freedom (DOF), movement coordination, and actuation is vital to achieving precise control over the print head and the rotating platform.

Several methods are used in the synthesis of robotic mechanisms for RRAM. These include motion-based approaches like Lie group theory [28] and finite screw theory [29], which provide precise mathematical models for movement. Constraint-based methods, such as screw theory [30] and virtual chain [31] methods, offer alternative approaches, focusing on the constraints imposed on the movement of the robotic system. However, these methodologies can involve complex analysis, requiring thorough understanding and application in manufacturing.

A practical type synthesis results in the optimal coordination of robotic motion to ensure continuous and stable material deposition, especially for curved and cylindrical structures. For example, in RRAM systems designed for cylindrical printing, configurations such as 2T1R, 2T2R, or 2T3R (where T represents translation, and R represents rotation) provide the necessary freedom of movement for precise and adaptable printing [32]. These systems are especially beneficial for complex tasks such as helical [33] or ray-based printing [34], enabling the efficient creation of

cylindrical components with minimal reliance on support materials. These advancements highlight the growing capability of RRAM in addressing challenges associated with unsupported, complex geometries in additive manufacturing.

4.2 Process planning for cylindrical printing

Process planning in RRAM involves optimizing two key aspects: slicing methods and path-planning techniques [5, 35, 36]. These aspects directly influence the printed parts' accuracy, surface finish, and structural integrity, particularly when working with cylindrical or non-planar geometries.

Slicing methods in traditional additive manufacturing typically use planar slicing, where each layer is deposited horizontally. However, this method is inadequate for cylindrical printing due to stair-stepping effects and surface inaccuracies. In RRAM, curved layer slicing is used to follow the natural curvature of the cylindrical part. This method allows for smoother surface finishes and better material distribution, significantly reducing the errors associated with traditional slicing. Adaptive slicing—where layer thickness is varied based on the geometry—optimizes build time and surface quality. For example, thicker layers are used in areas with low curvature, while thinner layers are applied in regions with high curvature, ensuring both efficiency and precision.

Path planning techniques are equally essential for ensuring the successful execution of the manufacturing process. Path planning in RRAM requires generating optimal tool paths that can accurately follow the cylindrical contours of the part. Three common approaches are used: direct cylindrical slicing, cylindrical mapping, and parametric path planning. In direct cylindrical slicing, tool paths are generated directly on the curved surface of the object, allowing for precise material deposition. Cylindrical mapping, on the other hand, transforms the cylindrical surface into a planar representation, making it easier to generate tool paths that can then be mapped back onto the cylindrical geometry. Finally, parametric path planning bypasses traditional slicing altogether, directly generating paths based on predefined geometric parameters, which is particularly effective for periodic structures like helices.

The integration of slicing and path planning is crucial for optimizing RRAM processes. In applications such as printing turbine blades or biomedical scaffolds, precisely coordinating these two elements ensures that material is deposited accurately, minimizing the need for support structures and post-processing. Furthermore, these techniques contribute to the overall efficiency of the manufacturing process, reducing build time and material waste while ensuring high-quality output.

In conclusion, type synthesis and process planning form the technological backbone of RRAM, allowing for the fabrication of complex, unsupported, and cylindrical structures with enhanced precision and efficiency. These technologies enable RRAM to meet the demands of advanced industries by optimizing robotic configurations and process strategies for superior manufacturing outcomes.

5. Applications, challenges, and future research directions

RRAM has the potential to transform various industries by enabling the fabrication of complex, unsupported, and cylindrical structures with high precision and efficiency. However, RRAM faces several critical challenges alongside its growing

range of applications. To fully realize its potential, future research must address these challenges and expand its capabilities through technological innovation.

5.1 Applications of rotary robotic AM

Aerospace industry: The aerospace sector is one of the primary beneficiaries of RRAM due to its need for lightweight, strong, and aerodynamically optimized components. RRAM can produce complex parts such as turbine blades, lattice-structured cylinders, and fuselage components, all benefit from its ability to print without supports [37]. The precision of RRAM ensures high structural integrity and smooth surfaces, which are essential for maintaining performance in demanding aerospace applications. Moreover, RRAM's capability to reduce weight while maintaining strength improves fuel efficiency and overall aircraft performance.

Biomedical applications: RRAM fabricates intricate tissue scaffolds and medical devices in biomedical engineering. For example, RRAM's ability to print hollow structures without internal supports greatly enhances 3D bioprinting of cylindrical tissues like blood vessels, intestines, and respiratory structures. This technology also enables the production of patient-specific prosthetics and implants, ensuring a customized fit and biocompatibility. RRAM's precision in printing complex geometries, such as those required for tissue scaffolds, aids in creating environments conducive to cell growth and tissue regeneration [10].

Other industrial applications: Beyond aerospace and biomedical fields, RRAM is used in automotive, energy, and construction [38]. In the automotive and energy sectors, RRAM can produce pipes, pressure vessels, and other components that require high strength and complex geometries. The ability to print without support materials reduces material waste and production time, making RRAM a cost-effective solution. Additionally, RRAM's capability for in-situ repair of large components, such as oil pipelines, reduces downtime, and operational costs. RRAM could produce large-scale architectural elements in construction, especially for complex and customized structures.

5.2 Critical challenges

Technical challenges: One of the primary technical challenges in RRAM lies in integrating robotic systems with additive manufacturing processes. Developing highly precise and coordinated multi-axis robotic movements that allow for accurate rotary printing is complex. Ensuring that the print head and build platform move in sync without errors is critical, particularly when working with large-scale or intricate geometries. Furthermore, developing robust software supporting advanced slicing techniques and path planning for curved and cylindrical structures is still evolving and requires refinement.

Material challenges: RRAM faces significant challenges related to material development. In aerospace, materials must withstand extreme temperatures and mechanical stresses, while in biomedical applications, biocompatible materials are essential for patient safety and effective tissue integration. Developing a wider variety of materials that can be reliably used in RRAM, especially for multi-material printing, is critical. In addition, ensuring that material properties are consistently maintained throughout the printing process—especially for unsupported structures—remains a complex task.

Process optimization challenges: In RRAM, particularly with cylindrical and non-planar geometries, process optimization is more complex than in traditional additive manufacturing. Achieving a balance between build speed and surface quality, while minimizing defects like stair-stepping or misalignment, requires ongoing development of advanced slicing methods and path-planning algorithms. Furthermore, optimizing the interaction between material extrusion rates, layer height, and movement speed is necessary to ensure high-quality prints with minimal material waste.

5.3 Future research directions

Multi-material manufacturing: One promising direction for future research is the integration of multi-material printing capabilities into RRAM. This would allow for creating parts that combine materials with different properties, such as flexibility and strength, within a single print. For aerospace, this could enable the production of lightweight, graded materials that improve performance. In biomedical fields, multi-material printing could facilitate the creation of complex tissue structures with varied biological properties.

Multi-process hybrid manufacturing: Combining additive and subtractive processes in a hybrid RRAM system could significantly improve surface finish and dimensional accuracy while reducing post-processing time. For example, integrating CNC machining into RRAM could allow for producing high-precision components directly after printing, which is particularly important in industries like aerospace and automotive, where tight tolerances are critical.

Macro-micro integrated manufacturing: RRAM's ability to simultaneously handle both large-scale and micro-scale features presents a key area for future development. By improving its capacity for macro-micro integration, RRAM could produce components that combine large structural elements with fine details, essential for aerospace components or biomedical devices. This could eliminate the need for separate fabrication processes and improve production efficiency.

Intelligent monitoring and control: Developing intelligent control systems for RRAM ensures consistent print quality and process reliability. Future research could integrate machine learning algorithms and sensor data to monitor the printing process in real time, automatically adjusting parameters such as temperature, speed, and extrusion rates. Such intelligent systems could also predict and prevent potential defects before they occur, reducing waste and increasing the reliability of RRAM systems.

Potential future applications and developments: Looking to the future, RRAM could have far-reaching applications in fields like construction, where its ability to print large, complex structures could revolutionize building processes. Additionally, space exploration could benefit from RRAM's ability to produce lightweight, high-strength components in environments where traditional manufacturing is impossible. Autonomous RRAM systems, capable of operating in remote or extreme environments such as deep sea or space, represent another exciting frontier for research and development.

In conclusion, while RRAM has already demonstrated its potential across multiple industries, addressing its current technical, material, and process-related challenges is essential for its continued advancement. By exploring innovative research directions such as multi-material manufacturing, hybrid processes, macro-micro integration, and intelligent control, RRAM can unlock new possibilities for high-precision manufacturing, leading to its broader adoption and application across various cutting-edge industries.

6. Conclusion

RRAM represents a significant advancement over traditional planar additive manufacturing methods by addressing key limitations such as stair-stepping, anisotropic material properties, and the excessive use of support materials. RRAM offers enhanced design flexibility and enables the efficient fabrication of complex, unsupported structures through its ability to perform multi-axis material deposition, particularly on cylindrical and curved surfaces.

This paper has reviewed the critical technologies behind RRAM, including type synthesis for robot-based AM equipment and process planning techniques such as advanced slicing and path planning for cylindrical printing. These technological advancements have proven essential for aerospace and biomedical engineering industries, where RRAM's precision and material efficiency meet critical demands. In aerospace, RRAM has enabled the creation of lightweight, high-strength components such as turbine blades and lattice-structured cylinders, while in biomedical applications, it has facilitated the fabrication of intricate tissue scaffolds and custom prosthetics.

Despite its potential, RRAM faces challenges in material development, process optimization, and technical integration. Addressing these issues, particularly in multi-material capabilities, hybrid manufacturing, and intelligent process control, is essential for the broader adoption and further enhancement of RRAM. Future research directions will focus on these areas, alongside exploring new applications such as space exploration and construction, which stand to benefit from RRAM's ability to produce complex, high-performance components.

In conclusion, RRAM offers a powerful solution to many of the challenges facing modern manufacturing, and with continued innovation, it will play an increasingly critical role in shaping the future of advanced manufacturing technologies.

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Appendices and nomenclature

AM	additive manufacturing
ASTM	American society for testing and materials
DOF	degrees of freedom
FDM	fused deposition modeling
MEX	material extrusion
R	rotation
RAM	robotic additive manufacturing
RRAM	rotary robotic additive manufacturing
T	translation
WAAM	wire arc additive manufacturing

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Advancements in Enhancing Structural Reliability and Functional Properties in 3D Printed Materials

Abdul Jabbar Khan, Yi Zhang, Ling Gao and Guowei Zhao

Abstract

3D-printed functional materials have emerged as ideal candidates for energy storage devices owing to their advanced structural integrity, miniaturization and enhanced functional properties. This chapter presents a thorough examination of recent advancements in enhancing the structural integrity and functional properties of 3D printed materials, emphasizing novel methods that improve mechanical strength and durability, focusing on the use of advanced composite materials and state-of-the-art printing techniques. This discussion includes significant breakthroughs in additive manufacturing, enabling the integration of multifunctional characteristics into printed objects. This chapter highlights the key applications in energy storage devices and demonstrates the benefits and transformative potential of these systems. Furthermore, it addresses current challenges in the field and suggests future research directions to further optimize the performance and reliability of 3D printed materials, thereby paving the way for more robust and adaptable 3D printing materials in energy storage systems.

Keywords: 3D printing, structural integrity, functional materials, additive manufacturing, energy storage applications

1. Introduction

The emergence of highly efficient energy storage systems has garnered significant attention owing to the increasing demand for rapid advancements in the global electronics industry [1–3]. In recent years, additive manufacturing (AM) techniques, also known as three-dimensional (3D) printing techniques, have emerged as promising methods for addressing the limitations of traditional fabrication processes [4–6]. The utilization of 3D-printed functional materials has had a profound impact on diverse industries, particularly on energy storage. The integration of complex geometry, customization, and material efficiency, which are inherent advantages of 3D printing,

has led to its emergence as a leading technology for the fabrication of advanced materials [7–10]. Supercapacitors are energy storage devices known for their high-power density, rapid charge/discharge capabilities, and long cycle life. They play a crucial role in applications requiring quick bursts of energy, such as electric vehicles and backup power systems. Introducing 3D printing in supercapacitor fabrication enhances precision, scalability, and design flexibility, offering new possibilities for improving performance and reducing manufacturing costs [7].

Improving the structural integrity of 3D-printed materials is a crucial area of research for energy storage. Ensuring the mechanical strength and durability of these materials is essential to their dependability and long-term performance in practical applications. Advancements in composites, such as the addition of carbon fibers, graphene, and nanomaterials, have shown great potential for boosting these properties [11–14]. Wu *et al.* illustrated that incorporating graphene into polymer matrices [15] enhanced the mechanical properties and thermal stability of 3D-printed structures. Orangi *et al.*'s study on the synthesis of MXene functional materials demonstrated how 3D printing with additive-free 2D $\text{Ti}_3\text{C}_2\text{T}_x$ (MXene) ink enhances structural stability for fabrication of micro-supercapacitors [16].

The utilization of cutting-edge printing techniques, such as selective laser sintering (SLS) and digital light processing (DLP), has significantly contributed to the exceptional structural characteristics of 3D-printed materials. By offering precise control of the printing process, techniques such as SLS and DLP address the challenge of creating denser and more robust structures, a key obstacle in the field of 3D-printed energy storage devices. Additionally, the employment of multi-material printing, which entails the simultaneous use of various materials during the printing process, has been proven to improve the overall performance of printed objects. This technique enables the combination of materials with complementary properties to create multifunctional structures with enhanced mechanical and functional attributes [17–19].

The importance of functional properties, such as electrical conductivity, thermal management, and electrochemical performance, in 3D-printed materials for energy storage devices cannot be overstated. These properties are crucial for the efficiency and effectiveness of energy storage systems. Innovative approaches have been developed to embed these properties into 3D-printed materials, including the use of conductive inks and filaments to fabricate batteries and supercapacitors with excellent electrochemical properties. A notable advancement in this field is the development of hybrid inks that combine conductive polymers with metal nanoparticles, resulting in materials with high electrical conductivities and flexibilities. Additionally, the incorporation of active materials, such as lithium-ion and sulfur-based compounds, into 3D-printed electrodes has led to significant improvements in energy storage capacity and cycling stability [20].

The potential for transformative advancements in energy storage devices through the utilization of 3D-printed materials is evident in various key applications. Compared to their traditionally manufactured counterparts, 3D-printed batteries and supercapacitors exhibit remarkable performance improvements. These enhancements not only increase the efficiency and long life of energy storage devices but also enable the miniaturization and integration of these systems into complex structures and devices [21, 22]. For instance, 3D-printed lithium-ion batteries display higher energy densities and faster charging times, making them suitable for a broad range of applications, including portable electronics and electric vehicles. Additionally, 3D-printed

supercapacitors have shown exceptional power densities and long cycle lives, which are essential for applications that require rapid energy delivery and storage [23–26].

Despite significant progress, challenges such as material compatibility, printing resolution, and scalability still need addressing. These issues include material compatibility, printing resolution, and scalability. Future research should focus on developing innovative materials and printing techniques to overcome these limitations. Moreover, there is a need to investigate the long-term stability and environmental impact of 3D-printed materials. The exploration of biocompatible and sustainable materials for 3D printing is a promising direction, as it aligns with the growing emphasis on environmental sustainability, allowing more researchers to access advanced technologies and materials [5, 27].

In this chapter, we summarize and highlight the most recent advancements in 3D printed-based materials for energy storage applications. We briefly discuss the properties and structural reliability of supercapacitors and batterie-based materials. Finally, we discuss the critical scientific challenges and prospects of 3D printed materials for sustainable energy storage applications.

2. Development of 3D printing composite materials for energy storage devices

The use of three-dimensional printing has emerged as a game-changing technology in the production of energy storage devices. This technology enables the manufacturing of complex designs and the optimization of material properties for better performance. Composite materials specifically designed for 3D printing applications in supercapacitors, lithium-ion batteries, and other energy storage technologies have seen major advancements in recent years. These advancements have been made possible by the development of composite materials. In this section, we will discuss important printing processes, composite materials, and the applications of these materials in energy storage containers.

American Society for Testing and Materials (ASTM) International has identified seven distinct specific techniques of 3D printing processes such as (1) (FDM) and material extrusion (including DIW), (2) vat photopolymerization (such as stereolithography (SLA)), (3) selective laser melting (SLM)) and powder bed fusion (including selective laser sintering (SLS), (4) laminated object manufacturing (LOM), (5) binder jetting (BJG), (6) materials jetting (MJ), and (7) direct energy deposition (DED) are all examples of 3D printing [8]. A thorough knowledge of the 3D printing technique and the characteristics of various 3D printing methods is essential for developing new materials and processes. These 3D printing methods allow for the precise and scalable production of complex structures, enhancing the overall performance of devices such as supercapacitors, lithium-ion batteries, and structural batteries. The composite materials used in these processes, such as graphene, MXenes carbon nanotubes, metal oxides, and conductive polymers, which improve conductivity, flexibility, and energy density for energy storage systems. **Figure 1** provides a graphical representation of these seven approaches relative to other materials, ink requirements, design flexibility, resolution, size capabilities, throughput, multi-material capacity, and price. **Table 1** shows representative comparison on various 3D printed techniques based on costing materials, and their application in different types of energy storage materials.

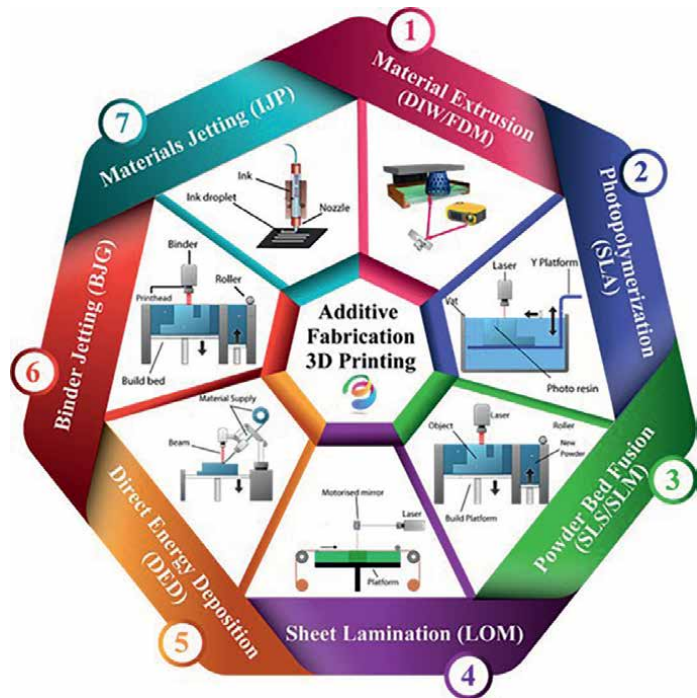


Figure 1.
Schematic diagram of seven specific techniques of a 3D printing process in fabricating the functional materials.

Printing technology	Costing materials	Applications
SLS	Metals, Ceramics	Structural Batteries, Electrodes
SLA	Photopolymer Resins	Thin-film Batteries, Flexible Energy Devices
DIW	Plastics, metals, ceramics, and composites	Zn-Ion battery
IJP	Conductive polymers, and carbon-based materials	Zn-Ag battery
LOM	Paper, Plastic	Micro-supercapacitors (MSCs)
FDM	Polymer and carbon composites	Supercapacitors, Lithium-ion Batteries

Table 1.
Comparison of 3D printing technologies, costing composite materials, and their applications in energy storage devices.

3. Enhancing structural integrity in 3D printed materials

Zhu *et al.* [28] developed a simple melt extrusion technique for constructing MXene-decorated 3D-printed carbon black-based electrodes MXene@PTC to enhance structural strength for charge transport and improve the performance of the 3D-printed electrode **Figure 2a**. The X-ray diffraction (XRD) spectra of the MXene@PM-12 h and MXene@PTC-12 h electrodes exhibited a weak peak at a 2 θ angle of 6.6° (**Figure 2b**), suggesting the presence of the MXene nanosheets. These findings indicated that the mechanical strength of the DMF-activated electrodes

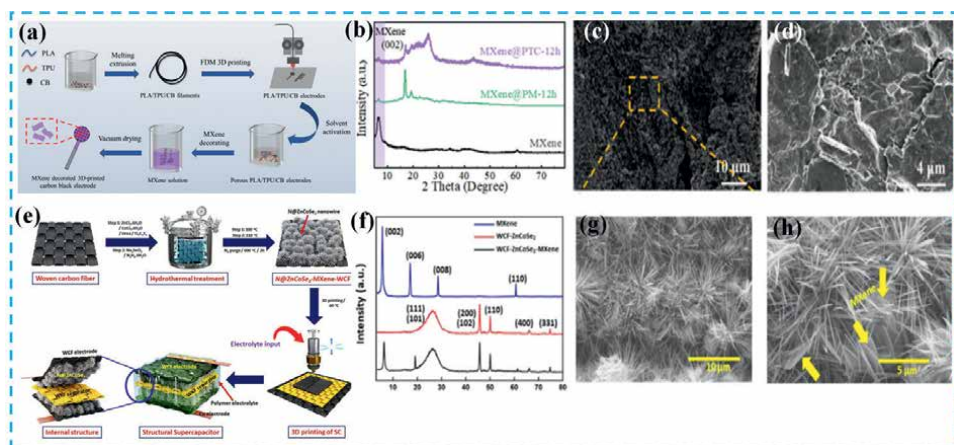


Figure 2.
(a) Schematic of the fabrication method of an MXene-based free-standing electrode through the FDM 3D printing and activation processes. (b) XRD pattern. (c, d) SEM images of DMF-activated PTC-2 h and 12 h electrodes. (a-d) Reproduced with permission, [28]: Copyright 2023, RSC. (e) Schematic diagram of MXene-N@ZnCoSe2 nanowires on WCF and advancement of the SC by the 3D printing method. (f) XRD spectra of MXene and N@ZnCoSe2-WCFs. (g and h) SEM images of MXene nanowire growth on the WCF. (e-g) Reproduced with permission [29]: Copyright 2023, ACS.

was improved by coating them with MXene. The use of higher magnification scanning electron microscopy (SEM) allows the observation of a large number of carbon black (CB) nanoparticles incorporated within the PLA/TPU polymers, as displayed in **Figure 2c, d**. The DMF-activated PTC-12 h electrodes demonstrated greater porosity and a higher concentration of CB nanoparticles, resulting in improved electrochemical sites and increased electron transfer owing to their long activation times [28, 30].

Deka *et al.* [29] designed a novel structural supercapacitor based on a WCF using 3D printing technology and thermosetting polymer electrolytes. The CF electrode was modified with Zn-Co selenide nanowires synthesized in the presence of MXene, as shown in **Figure 2e**. A crystallographic analysis of MXene ($\text{Ti}_3\text{C}_2\text{T}_x$, where $\text{T}_x = \text{O}^-$ or F^-) revealed the presence of characteristic diffraction peaks at 5.5 and all peaks of CoSe, ZnSe, and N@ZnCoSe₂-WCF-MXene composite were observed at their respective positions as displayed in **Figure 2f**. The growth of Zn-Co selenide nanowires on WCF is shown in **Figure 2g, h** through scanning electron microscopy analysis. The micrograph revealed that the nanowire length was approximately 2–3 μm , and its diameter was approximately 50–80 nm.

4. Functional properties of 3D printed materials

3D printed materials provide the ability to customize functional qualities, such as mechanical strength, thermal resistance, and electrical conductivity. Owing to their capacity to generate complicated geometries and achieve optimal performance, they are highly suitable for use in energy storage applications. **Figure 3a** illustrates the fabrication for a 3D-printed graphene structure, involving the preparation of graphene oxide (GO) inks by adding a small amount of metal cations to link the functional groups of GO sheets, thereby improving the functional properties of the prepared material. **Figures 2c** and **3b** show X-ray diffraction (XRD) patterns and

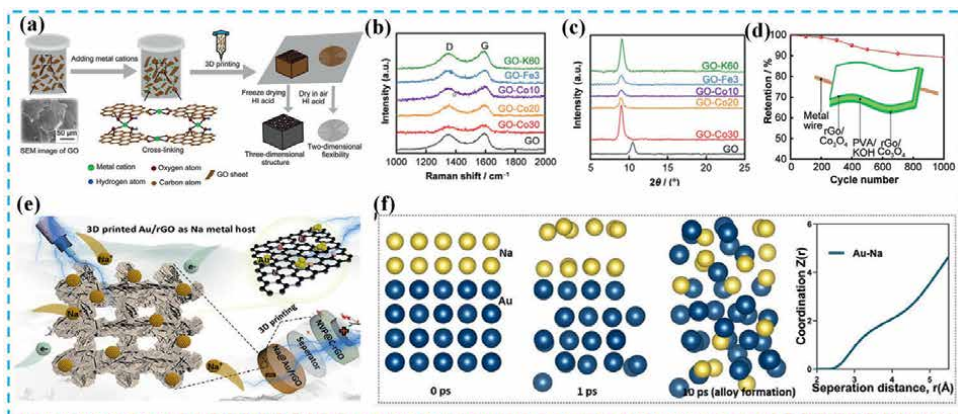


Figure 3.

(a) Schematic of the 3D printing of rGO architecture. (b, c) XRD and Raman spectra of GO, GO-Co10, GO-Co20, GO-Co30, GO-K60, and GO-Fe3. Reproduced with permission [31]: Copyright 2023, Springer. (d) Cycling stability test over 1000 cycles. (e) Schematic illustration of 3D printed Au/rGO substrate for the sodium metal anode. (f) The AIMD simulations of deposition kinetics of Na atoms on Au surface after 0, 1, 5, and 10 ps. Reproduced with permission [32]: Copyright 2024, Elsevier.

Raman spectra for various inks, including pure graphene oxide (GO) and GO mixed with cobalt at 10, 20, and 30%, as well as GO mixed with Fe³⁺ and K60. The peak at 10.5° (2θ) corresponds to the (002) crystalline plane of the pure GO. The other peaks matched those reported in the literature. The increased interlayer spacing results from the interaction between the metal cations and oxygen-containing groups, or the insertion of metal cations between the GO sheets. The peaks at approximately 1354 (D band) and 1591 cm⁻¹ (G band) indicate structural defects and well-ordered scattering, respectively, in graphene. The ID/IG intensity ratio of the cross-linked GO inks showed a slight increase, indicating additional structural defects due to successful cross-linking with the GO sheets, which enhanced the functional properties of the material. Additionally, the SC device exhibited favorable cycling stability, maintaining over 90% of its capacitance over 1000 cycles, as shown in **Figure 3d** [31]. **Figure 3e** shows a schematic illustration of a 3D printed Au/rGO substrate designed for a sodium metal anode. The AIMD simulations depicted the deposition kinetics of Na atoms on the Au surface at different time intervals (0, 1, 5, and 10 ps). **Figure 3f** shows three snapshots of the AIMD simulations of deposition kinetics of Na atoms on Au surface after 0, 1, 5, and 10 ps. Upon annealing at 700 K, the Na atoms progressively permeated into the bulk gold, forming a 3D Na-Au alloy network by 10 ps. This process is expected to significantly enhance the Na-ion redox dynamics and mitigate morphological instability. The coordination number ($\langle Z(r) \rangle$) around Au is obtained by integrating the radial distribution function (RDF), revealing that Au atoms preferentially bond with approximately two Na atoms in the first coordination shell, which is consistent with the experimental XRD results [32].

5. 3D-printed materials for energy storage applications

This section discusses the most recent advances in the development of 3D printed-based materials as electrodes for a wide range of energy storage applications.

5.2 Batteries

2D MXenes are promising candidates for lithium metal batteries (LMBs) owing to their superior ion transport between interlayers (~ 1.3 nm) and large surface areas available for better ion adsorption, quick surface redox reactions, and exceptional electrical conductivity. Using a scalable Direct Ink Writing (DIW) technique, Ma *et al.* [35] synthesized a hierarchically $\text{Ti}_3\text{C}_2\text{T}_x$ MXene porous skeleton, as shown in **Figure 5a**. The LFP||MXene@Li LMB exhibited significantly improved rate capability, achieving 108.6 mAh/g at 3 C and 91.2 mAh/g at 5 C, which is substantially higher than the LFP||Li battery's performance of only 51 mAh/g at 3 C and 18.7 mAh/g at 5C (**Figure 5b**). This demonstrates the favorable charge transport at the interface. Additionally, the cycling performances of LFP||MXene@Li and LFP||Li at 1 C were compared, showing that LFP||MXene@Li LMB provided a higher capacity and superior long-term cycle stability at 1 C for 500 cycles, outperforming LFP||Li with bare Li foils (**Figure 5c**). These results further indicate that the hierarchically porous and conductive lattices of LFP enhance charge and ion transfer kinetics, whereas the MXene scaffolds reduce the formation of dead Li during continuous charge-discharge cycles [37].

Wu *et al.* [36] fabricated 3D Printed Graphene array scaffolds (3DGs) with a tube structure (3DGT) and pillar (3DGP) structure current collectors for AZIBs using digital light processing (DLP) as depicted in **Figure 5d**. In **Figure 5e**, the utilization of zinc and its capacity in terms of the area of the 3DGs@Zn// V_2O_5 pouch cells are compared with those of other aqueous zinc-ion batteries (AZIBs). The utilization rates of Zn in 3DGT@Zn and 3DGP@Zn were 47.12 and 42.94%, respectively. Areal energy densities of 3.27 and 2.72 mWh cm^{-1} are significantly higher than those of AZIBs with low zinc utilization. This suggests that the 3DGs@Zn anode has a great potential for producing ultralight and high-energy-density AZIBs for practical applications. The highly aligned array structures in the 3DGs@Zn anode effectively redistribute the

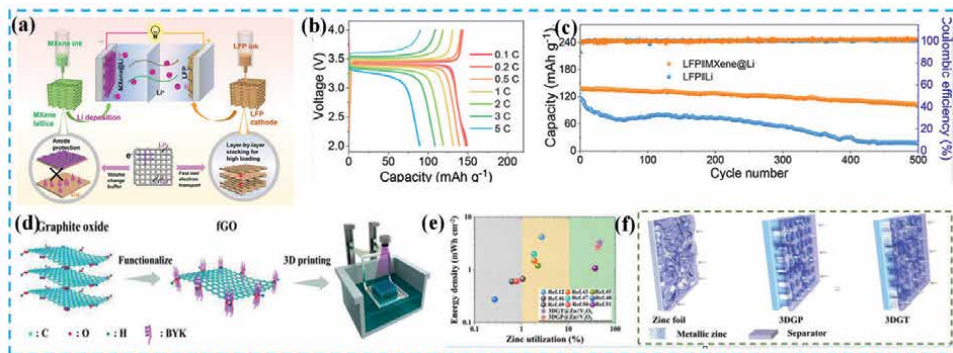


Figure 5.

(a) illustrates the fabrication process for 3D-printed lithium metal batteries (LMBs). The top panel shows the working principle of the LMB using a 3D-printed MXene scaffold and a thick lithium iron phosphate (LFP) lattice. The bottom panel depicts the 3D-printed lattices designed to protect the lithium metal anode and facilitate electron/ion transport in thick electrodes. (b) displaying the galvanostatic charge-discharge (GCD) profiles of the LFP||MXene@Li tested from 0.1 to 5 C. (c) presenting the cycling performance. Reproduced with permission, [35]: Copyright 2023, Elsevier. (d) Fabrication and characterization of 3D printed graphene arrays using digital light processing (DLP) method. (e) illustrates a Ragone plot comparing the performance of 3DGs@Zn// V_2O_5 pouch cells with that of other reported aqueous zinc-ion batteries (AZIBs). (f) Schematic illustration of the zinc deposition and separator protection mechanisms of the 3DGs@Zn anode, reproduced with permission [36]: Copyright 2023 Elsevier.

zinc-ion surface distribution and accommodate volume changes during cycling better than the 2D zinc foil (**Figure 5f**). This leads to improved electrochemical performance and cycle life of AZIBs because the separator is protected from interactions with zinc dendrites.

6. Future directions and challenges

During the last decade, clean and renewable energy development and application have become a global aim and consensus. This chapter presents a detailed overview of the current breakthroughs in using 3D-printed-based materials as electrodes for energy storage applications, including supercapacitors and batteries. Although 3D-printed materials provide excellent prospects for use in applications involving electrochemical technology, several challenges remain.

The development of cutting-edge tools for 3D printing is critical for designing high-performance electrode materials for electrochemical energy storage devices. Software design and simulation are crucial for creating novel, efficient, and advanced electrode structures. However, many electrode geometries have been designed using human intuition rather than theoretical calculations. The advancement of machine learning algorithms will enable the automatic design and optimization of more complex electrode architectures, functionalities, and scalability in manufacturing, saving time and making electrode architecture design more effective [5, 38]. As a transformative tool, 3D printing can be used to address fundamental issues related to energy storage devices, and it can also be used to design and manufacture high-performance electrodes. To improve the precision of printers for use in the design and application of energy storage systems, it is crucial to develop high-resolution printers and formulate functional inks compatible with advanced printing systems. The challenge is to enhance the application of 3D printing in the development of batteries and supercapacitors. By overcoming these challenges, the capabilities and applications of 3D-printed energy storage solutions will be reshaped, thereby paving the way for more sustainable, reliable, and efficient solutions for next-generation 3D printed materials.

The literature also emphasizes that, even though 3D printing provides energy storage devices with design flexibility and precision, they continue to face challenges such as low energy density and limited cycle life. Innovation in printable materials with superior electrochemical properties is necessary to address these obstacles. Research indicates that the efficiency of hybrid composites, conductive polymers, and nanomaterials can be enhanced. However, to completely address these limitations and advance the practical application of energy storage devices such as supercapacitors and batteries, 3D printing must consistently innovate around new materials.

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Conflict of interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this book.

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