MANUFACTURING AND PROCESSING OF ADVANCED MATERIALS

Editors:
Amar Patnaik
Albano Cavaleiro
Malay Kumar Banerjee
Ernst Kozeschnik
Vikas Kukshal

Bentham Books

Manufacturing and Processing of Advanced Materials

Edited By

Amar Patnaik
Mechanical Engineering Department
Malaviya National Institute of Technology Jaipur,
Rajasthan,
India

Albano Cavaleiro
Mechanical Engineering Department
University of Coimbra,
Coimbra, Portugal

Malay Kumar Banerjee
Research Chair, SGVU Suresh Gyan Vihar University,
Jaipur, Rajasthan, India

Ernst Kozeschnik
Head of the Institute
Materials Science and Technology, TU Wien,
Austria

&

Vikas Kukshal
Mechanical Engineering Department
National Institute of Technology,
Uttarakhand,
India

Manufacturing and Processing of Advanced Materials

Editors: Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik and Vikas Kukshal

ISBN (Online): 978-981-5136-71-5

ISBN (Print): 978-981-5136-72-2

ISBN (Paperback): 978-981-5136-73-9

First published in 2023.

need for a court order if at any point you breach any terms of this License Agreement. In no event will any delay or failure by Bentham Science Publishers in enforcing your compliance with this License Agreement constitute a waiver of any of its rights.

3. You acknowledge that you have read this License Agreement, and agree to be bound by its terms and conditions. To the extent that any other terms and conditions presented on any website of Bentham Science Publishers conflict with, or are inconsistent with, the terms and conditions set out in this License Agreement, you acknowledge that the terms and conditions set out in this License Agreement shall prevail.

Bentham Science Publishers Pte. Ltd.
80 Robinson Road #02-00
Singapore 068898
Singapore
Email: subscriptions@benthamscience.net

BENTHAM SCIENCE

CONTENTS

FOREWORD

I am greatly honoured to write this foreword for the edited book titled "**Manufacturing and Processing of Advanced Materials**" in the field of Mechanical and Materials Engineering published by Bentham Science. The advanced materials and manufacturing processes are revolutionizing all the specialized areas in different fields such as electrical, electronics, mechanical and civil. A high degree of novelty is needed in both structural and functional materials to achieve the goal of sustainability.

This book will provide scientists, researchers, and academicians working in the field of advanced materials and manufacturing to gain a better understanding of information and the necessary components of material science and mechanical engineering. The book chapters published cover recent innovations and emerging methods, materials, and optimization techniques, such as those related to advanced materials, composite materials, manufacturing technologies, industrial tribology, material characterization, *etc*.

I appreciate the authors for their technical input to complete the book. I would like to acknowledge the editors of the book and wish the authors good luck in their future endeavors.

Alok Sathpathy
Department of Mechanical Engineering
National Institute of Technology, Rourkela,
India

PREFACE

The application of advanced engineering materials and manufacturing techniques is currently capturing the attention of prominent researchers, scientists, and academicians in a variety of high-tech fields. There are large numbers of challenges that can be solved by improving the compatibility of the materials and by adopting proper manufacturing processes. Hence there is a continuous need for research and development in the field of materials and manufacturing. This book is dedicated to current research activities in the field on advance materials and manufacturing and engineering applications.

The book entitled "**Manufacturing and Processing of Advanced Materials**" embrace innovations in the field of materials, manufacturing processes, and distinguished applications proposed by numerous researchers, highly qualified professionals, and academicians. This book focuses on the properties and end applications of a wide range of engineering materials, including metals, polymers, composites, fiber composites, ceramics, and other similar materials, as well as their characterization and prospective applications. This book is an updated reference of research activities that bring together various theories, methods, and technologies for a wide range of manufacturing processes adopted for industrial application. All the chapters were subjected to a peer-review process by the researchers working in the relevant fields. The chapters were selected based on their quality and their relevance to the title of the book.

Successful completion of this book includes the efforts of many people. It is very imperative to acknowledge their contribution to shaping the structure of the book. Hence, all the editors would like to express special gratitude to all the reviewers for their valuable time spent in reviewing process and completing the review process on time. Their valuable advice and guidance helped in improving the quality of the chapters selected for publication in the book. We would like to thank all the authors of the chapters for the timely submission of the chapter during the rigorous review process. Finally, we would like to thank the publisher for the invaluable input in the organizing and editing of the book.

Amar Patnaik
Mechanical Engineering Department
Malaviya National Institute of Technology, Jaipur
Rajasthan,
India

Albano Cavaleiro
Mechanical Engineering Department
University of Coimbra,
Coimbra, Portugal

Malay Kumar Banerjee
Research Chair, SGVU
Suresh Gyan Vihar University, Jaipur
Rajasthan,
India

Ernst Kozeschnik
Head of the Institute
Materials Science and Technology, TU Wien
Austria

&

Vikas Kukshal
Mechanical Engineering Department
National Institute of Technology,
Uttarakhand,
India

List of Contributors

Aditya Purohit Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India

Aparna Duggirala School of Laser Science and Engineering, Jadavpur University, Kolkata, 700032, India

Akshay Dvivedi Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee, India

Apurbba Kumar Sharma Department of Mechanical & Industrial Engineering, IIT Roorkee, Roorkee-246174, India

Ankit Kumar Maurya Mechanical Engineering Departmen, Madan Mohan Malaviya University of Technology Gorakhpu, Uttar Pradesh, India

Anjani Kumar Singh Mechanical Engineering Departmen, Madan Mohan Malaviya University of Technology Gorakhpu, Uttar Pradesh, India

Abhishek Pothina Department of Mechanical Engineering, National Institute of Technology Patna, India

Amit Kumar CSIR-Central Mechanical Engineering Research Institute, Durgapur-713209, India

Bappa Acherjee Department of Production and Industrial Engineering, Birla Institute of Technology, Mesra, Ranchi, 835215, India

Botcha Appalanaidu Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee, Uttarakhand, India

Bipul Kumar Singh Mechanical Engineering Departmen, Madan Mohan Malaviya University of Technology Gorakhpu, Uttar Pradesh, India

Chandra Kant Department of Mechanical Engineering, National Institute of Technology Srinagar, Jammu, and Kashmir, India

Dasari Sai Naresh R&D Mechatronics, Design and Engineering, VEM Technologies PVT Ltd, Hyderabad, Telangana, 502321, India

Dileep Chekkaramkodi Department of Mechanical Engineering, National Institute of Technology Calicut, Calicut- 673601, India

Gaurav Kumar Department of Mechanical Engineering, NIT Uttarakhand, Srinagar-246174, India

Ganesh S. Kadam Babasaheb Ambedkar Technological University, Lonere, Maharashtra, India
SIES Graduate School of Technology, Navi Mumbai, Maharashtra, India

Ghulam Ashraf Harmain Department of Mechanical Engineering, National Institute of Technology Srinagar, Jammu, and Kashmir, India

Jinu Paul Department of Mechanical Engineerin, National Institute of Technology Calicut, Calicut- 673601, India

Jyoti Behera Department of Physics GIET University, Gunupur, Rayagada, Odisha, India

Kriti Srivastava	Department of Mechanical Engineering, National Institute of Technology, Patna-800005, Bihar, India
K. Ravi Prakash Babu	Department of Mechanical Engineering, Prasad V Potluri Siddhartha Institute of Technology, Kanuru, Andhra Pradesh, India
Mahaveer Prasad Sharma	Malaviya National Institute of Technology Jaipur, Rajasthan, India
Mukund Kumar	Department of Mechanical Engineering, BIT Mesra, Ranchi - 835215, India
Mudit K. Bhatnagar	Department of Mechanical Engineering, JSS Academy of Technical Education Noida, Uttar Pradesh, India
Mamatha Theetha Gangadhar	Department of Mechanical Engineering, JSS Academy of Technical Education Noida, Uttar Pradesh, India
Mohit Vishnoi	Department of Mechanical Engineering, JSS Academy of Technical Education Noida, Uttar Pradesh, India
Murahari Kolli	Lakireddy Bali Reddy College of Engineering, Mylavaram, Krishna District, Andhra Pradesh, India
Mohammed Yusuf A. Yadwad	Department of Mechanical Engineering, PES University, Bangalore-560085, India
Muhammed Hunize Chuttam Veettil	Department of Mechanical Engineering, National Institute of Technology Calicut, Calicut- 673601, India
Murali Kodakkattu Purushothaman	Department of Mechanical Engineering, National Institute of Technology Calicut, Calicut- 673601, India
N. Rajesh Mathivanan	Department of Mechanical Engineering, PES University, Bangalore-560085, India
Pankaj Kumar Gupta	Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India
Rajendra Kumar Arya	Department of Mechanical Engineering, Indian Institute of Technology, Mumbai, Maharastra, India
Raju Shrihari Pawade	SIES Graduate School of Technology, Navi Mumbai, Maharashtra, India
Rohit Kumar Babberwal	Department of Mechanical Engineering, Army Institute of Technology, Pune-411015, Maharashtra, India
Raosaheb Bhausaheb Patil	Department of Mechanical Engineering, Army Institute of Technology, Pune-411015, Maharashtra, India
Spruha Aniket Dhavale	School of Mechanical Engineering, Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India
Shivprakash Bhagwatrao Barve	School of Mechanical Engineering, Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India
Souradip Paul	School of Laser Science and Engineering, Jadavpur University, Kolkata, 700032, India
Souren Mitra	Department of Production Engineering, Jadavpur University, Kolkata, 700032, India
Shivnandan Bind	Mechanical Engineering Department, National Institute of Technology Patna, India

Sanjay Mishra	Mechanical Engineering Departmen, Madan Mohan Malaviya University of Technology Gorakhpu, Uttar Pradesh, India
Siddharth Srivastava	Department of Mechanical Engineering, JSS Academy of Technical Education Noida, Uttar Pradesh, India
Satendra Singh	Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India
Saroj Kumar Sarangi	Department of Mechanical Engineering, National Institute of Technology Patna, India
Saurabh Mishra	CSIR-Central Mechanical Engineering Research Institute, Durgapur-713209, India
Surendra Kumar	CSIR-Central Mechanical Engineering Research Institute, Durgapur-713209, India
Simadri Priyanka Achary	Department of Physics GIET University, Gunupur, Rayagada, Odisha, India
Sanjukta Mishra	Department of Physics GIET University, Gunupur, Rayagada, Odisha, India
Tapas Bajpai	Microfluidics & MEMS Centre, CSIR-Advanced Materials and Processes Research Institute (AMPRI), Hoshangabad Road, Bhopal 462026, India
Tapan Kumar Patnaik	Department of Physics GIET University, Gunupur, Rayagada, Odisha, India
Upama Dey	School of Laser Science and Engineering, Jadavpur University, Kolkata, 700032, India
Velavali Sudharshan	Department of Mechanical Engineerin, National Institute of Technology Calicut, Calicut- 673601, India
Vansh Malik	Department of Mechanical Engineering, JSS Academy of Technical Education Noida, Uttar Pradesh, India
Vishwas G.	Department of Mechanical Engineering, PES University, Bangalore-560085, India
Yogesh Kumar	Department of Mechanical Engineering, National Institute of Technology, Patna-800005, Bihar, India

CHAPTER 1

A Review on the Joining of Dissimilar Materials with Special Context to Laser Welding

Aditya Purohit[1], **Tapas Bajpai**[1,*], **Pankaj Kumar Gupta**[1] and **Arpana Parihar**[2]

[1] *Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India*

[2] *Microfluidics & MEMS Centre, CSIR-Advanced Materials and Processes Research Institute (AMPRI), Hoshangabad Road, Bhopal 462026, India*

Abstract: In recent times, there has been an increasing demand for dissimilar metal fabrication, as this weldment utilizes the specific benefits of different metals for a particular application. In this paper, the recent trends evolving in the field of dissimilar material joining, which introduces residual stresses, distortions and formation of brittle intermetallics within the structure is discussed. As these are highly undesirable, therefore various techniques were studied by the researchers, which reduce the distortions and formation of brittle intermetallics. The use of numerical techniques in this field was also studied as they provided the researchers with an insight into the process. Mostly, the joining of dissimilar material is done using friction stir welding and laser welding, but the use of friction stir welding has constraints in terms of material temperature thus, the joining of dissimilar weldment is discussed by giving a special context to laser welding technology.

Keywords: Dissimilar material joining, Laser welding, Optimization techniques.

INTRODUCTION

Laser welding is a state of art technique which is normally performed in keyhole mode. Unlike conventional welding techniques, this welding technique enables deeper penetration in the material combined with lower heat-affected zone (HAZ) since the focal diameter of the laser beam can be adjusted according to need. Application of laser welding varies from structural applications, automotive sector to sophisticated applications such as dentures, implants and complex electrical circuits. Dissimilar material welding is one of the fields to be explored. It's a phenomenon concerning the current industrial trend because dissimilar material welding uses the specific properties of different materials for an application that

[*] **Corresponding author Tapas Bajpai:** Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India; E-mail: tapas.mech@mnit.ac.in

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

ranges from dissimilar metal electronic connection of Al-Cu in an electronic vehicle to large structures where dissimilar joints are required [1]. The problem in dissimilar welding is that because of dissimilar materials, the materials have different thermal expansion coefficients, which leads to stress application on the material due to fluctuation in temperatures, and if that stress is higher than the yield stress of the material, then the material might fail [2]. Apart from this, the other reason is the formation of intermetallic phases in the fusion zone because of less solubility between different metals. These phases have hardness variation in the weldment zone, and this variation of hardness might lead to the failure of the joint [3].

It's a well-known fact that in order to get a mechanically sound joint, it is required for the joint to be stress-free to avoid distortions and crack initiation. The major contributor to it is the different expansion coefficients of the material and phase transformation of the material. There are three components of stresses, mainly quenching, phase transformation and shrinkage. Shrinkage leads to tensile stresses, *i.e.,* the region which is last to cool, faces tensile stresses and vice versa. Another factor is phase transformation, so the region that faces phase transformation first is subjected to tensile stresses. Whichever factor dominates the most, its effect is shown on the weldment [4]. Due to high-temperature exposure on the weldment, the temperature rises, and subsequently, a thermal gradient is set up between the weldment zone and the base metals. Due to the gradient and the difference in various material properties, residual stresses are set up in the material, and subsequently, distortions are introduced. The tensile residual stresses in the welding zone lead to a compromise in the structural integrity of the joint. If stresses are above the material's permissible limit, it might lead to the failure of the material. The subsequent distortions introduced within the assemblies are also highly undesirable since they compromise on the tolerance front, which is not desirable in the manufacturing unit. Deformation introduced in the assembly can vary from longitudinal and transversal shrinkage to angular deformation. Therefore to address the above issues and mitigate these phenomena, the researchers are working in this direction. Different aspects of dissimilar material welding were examined by analysis of various fronts of this particular field. The effects of different phenomena which lead to the deterioration of the joint were analyzed, and different researchers tried to mitigate the problem in their own way. Classification on the basis of various paths adopted by the researchers [5].

OPTIMIZATION

Optimization techniques serve as an integral part of research because various optimization techniques give the researchers an idea about the variable parameters, which should be set in such a way that the optimum results are achieved. Various techniques for researchers are available to optimize the variables such as RSM (Response surface methodology), which plots a 3D curve of output variable with respect to input variables.

Researchers as presented in Table **1** used the following optimization techniques:

1. Design of experiments (DOE) or Taguchi optimization

2. ANOVA or Analysis of Variance

3. RSM or response surface methodology

4. Combination of the above techniques

Getting an idea of how various variables in a welding process interacted with each other and the final results, helps in giving a clear outlook of the process and also helps in predicting outcomes. Bhattacharya. *et al.* [6] tried to study the effect of various parameters such as power, frequency, and scanning speed on the weld width and HAZ of the weldments. Centrally composite design technique was used to design the set of experiments for the experiment, and RSM was used to develop a mathematical model, keeping weld width and HAZ as the output. Specimens of polycarbonate and acrylic were taken and welded using Nd-YAG. RSM results showed that with the increase of power, HAZ and weld width increased. After attaining good weld width and strong weld, it starts to decrease with the rise in power. Results also showed that weld width and HAZ do not depend on frequency. The results of ANOVA also validated the same. One way of predicting the quality of the weld is by analyzing the bead geometry, *i.e.,* the dimension of the bead should be kept minimum, with the weldment also serving its purpose. Juang and Tarng [7] analyzed and optimized the weld bead geometry of weldment of stainless steel prepared by gas tungsten arc welding (GTAW). Researchers narrowed down the large number of experiments down to a fixed number using Taguchi DOE technique. Since the bead geometry consists of different variables such as front height, back height and back width therefore instead of optimizing a single variable using a loss function, all the variables are optimized at the same time by assigning weighted residuals to each function according to the literature. The optimization criteria taken by the authors for that particular loss function was "Lower the Better."

Toughness in weldments is an essential property as far as bridge construction and shipbuilding are concerned. Anawa and Olabi [8], fabricated sheets of 316 SS and low-carbon steel. These dissimilar metals were joined using a continuous CO_2 laser. Firstly using design expert, Taguchi set of experiments was designed, keeping laser power, focus diameter, and speed as variables and impact strength or toughness as the response output. The analysis of the S/N ratio with “larger the

CHAPTER 2

A Study on Friction Stir Welding of Composite Materials for Aerospace Applications

Spruha Aniket Dhavale[1,*] and **Shivprakash Bhagwatrao Barve**[1]

[1] *School of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India*

Abstract: Composite materials define the new age for the development of technologies. In a recent study of aerospace structure, conventional materials are replaced by almost 75% by modern composites. The strength-to-weight ratio of aluminum alloys makes it an attractive choice among other materials for industries. Carbon fiber-reinforced composite materials are better alternatives to conventional materials to prepare lighter panels. In many applications, the joining of these composites becomes troublesome. The promising technique to join the advanced composites is still unrevealed. The proper joining method is an essential need for composites. With this aim, we carry out the study to check the feasibilities of Friction Stir Welding for light panels used in aerospace industries. Friction Stir Welding is a solid-state welding method. The external tool solidifies and mixes the metal at the edge line. We reviewed several research articles to understand the difficulties associated with the friction stir welding method.

Keywords: Aluminum metal composite, Friction stir welding, Light weight structures.

INTRODUCTION

The eco-system balance and sustainability concerns increase the demand for lightweight structures in aerospace. The reduction in fuel consumption is possible only through the overall weight reduction of an aircraft [1].

Aluminium alloys are the most suitable choice for structural parts as they are less costly and provide a good weight-to-strength ratio [2]. Scientists have achieved advances in aluminium alloys for these explicit requirements, such as high-temperature resistance, corrosion resistance, and high load-bearing capacities [3].

* **Corresponding author Spruha Aniket Dhavale:** School of Mechanical Engineering, Dr.Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India; E-mail: spruha.dhavale@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

Fig. (**1**) shows the particular requirements and stresses encountered by a specific part of an aeroplane.

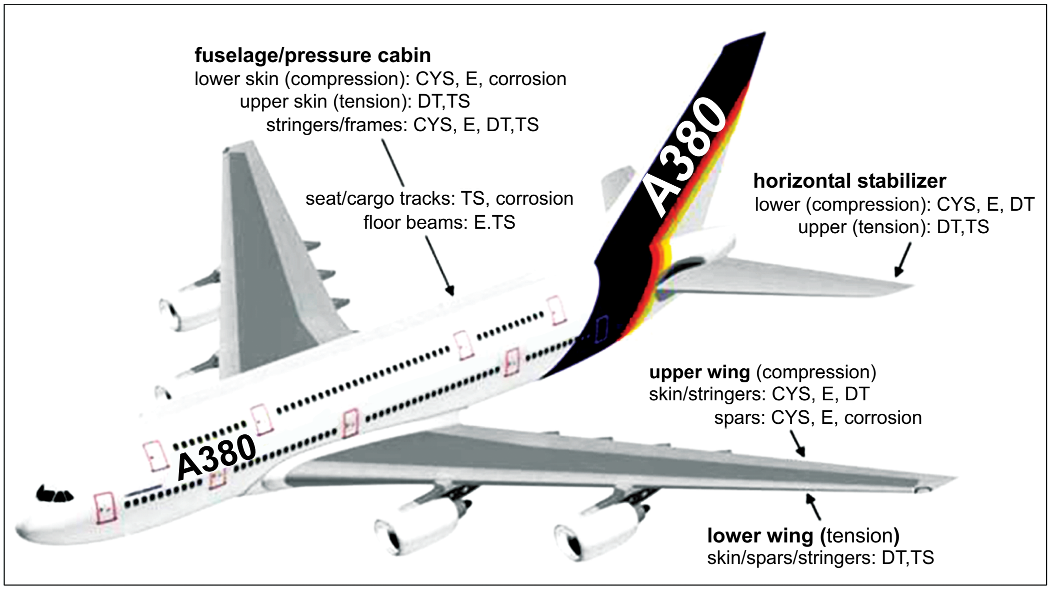

Fig. (1). Property requirements of the specific section concerning stresses encountered [2].

The composite materials are made out of these necessities [4]. Now, these materials define the new age for the development of spacecraft technologies. Several studies have been carried out on aluminum-based composites to get enhanced properties and energy-efficient materials [5, 6]. Wide varieties of aluminum-based composites are available which are used in the aerospace field. Conventional welding showed some limits to forming the solid joint in between the composites. Numerous problems are stated with the fusion welding of these materials, including thermal expansion, gas solubility and oxide formations [7] In many applications, the joining of these composites becomes troublesome. The promising technique to join the advanced composites is still unrevealed [8]. It's essential to get proper joining techniques to prepare firm joints between composites.

The FSW found an appropriate method to join aluminium-based composites. This opens new opportunities for preparing high-quality welds for composites [9, 10]. The FSW is a process where metals are solidified and mixed with the help of an external tool [11]. Fig. (**2**) shows the process and weld created by FSW. The tool in FSW is capable to generate sufficient frictional heat, which is below the melting point. The metals undergo plastic deformation due to stirring action and mix which result in strong weld formation. This welding process avoids formations for defects such as voids, porosities, shrinkages and segregation of reinforcements. The defect rate is reduced up to zero percent through extensive control of the process parameters.

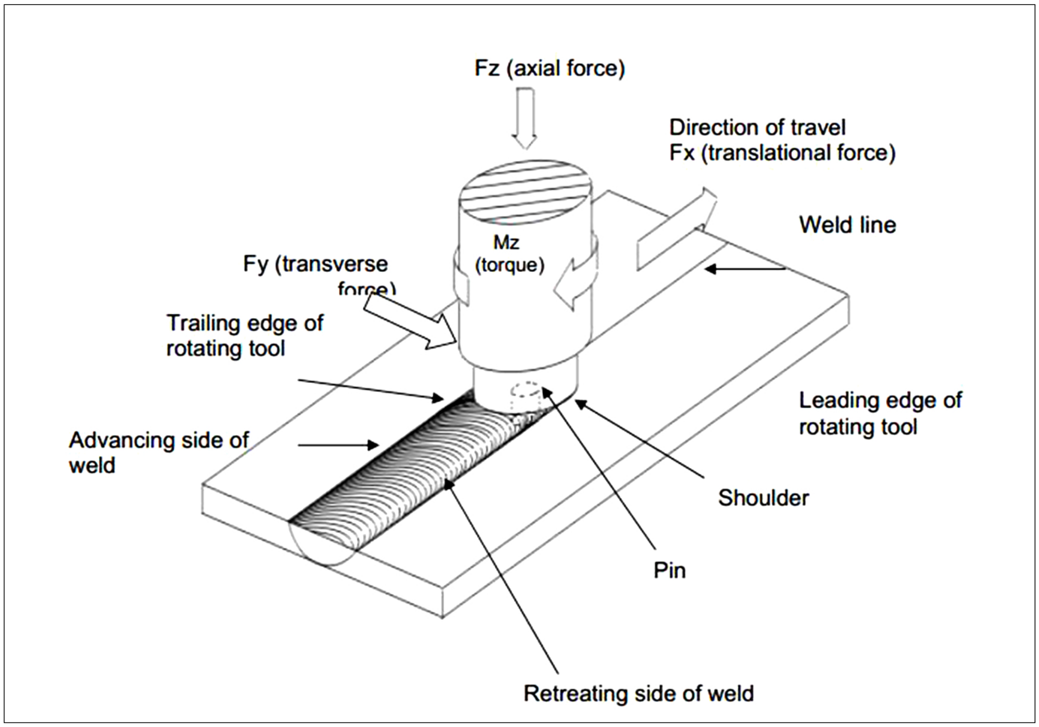

Fig. (2). Friction Stir Welding Process [11].

The aluminium alloys in aerospace industries have been explored by Rajan *et al.* The authors carried out the comparative analysis and discussed enhancement in the mechanical properties of aluminium's 2000 series, 7000 series and aluminium lithium alloys through FSW welding. In addition, a review of developments in aluminium alloy joining methods has been carried out. Their study indicated that FSW was the best choice for aerospace joining applications. FSW was proven to be a game-changer since the joints were seamless, had fewer defects, allowed low welding loads, and improved weld quality [12].

Aluminium Composite Materials

Aluminium Matrix Composites (AMCs) have properties that can improve a product's performance and efficiency [13]. It has an excellent strength-to-weight property, making it ideal for aerospace applications [14]. Table **1** shows the list of

CHAPTER 3

Binder Jetting: A Review on Process Parameters and Challenges

Kriti Srivastava[1,*] and **Yogesh Kumar**[1]

[1] *Department of Mechanical Engineering, National Institute of Technology, Patna-800005, Bihar, India*

Abstract: Binder jetting (BJ) is a 3D printing technology in which objects are manufactured from ceramics, metals, polymers, and composites. Binder jetting process incorporates various types of technologies, such as printing, deposition of powder, complex combination of the binder with powder, and post-processing of sintered part. BJ has high productivity with the utilization of a wide variety of powders. In BJ, the binder is combined with powder of materials that bond together to create an object in a layer-wise fashion that is generally modeled on CAD. In order to obtain desired product accuracy, the main challenges are balancing proper process parameters with manufacturing time, such as characteristics of powders (distribution of particle size, packing density and flowability of powders, green strength), characteristic of binders, *etc.* This paper gives a brief review of technologies, materials, defects and challenges of the binder jetting additive manufacturing process and their future trends.

Keywords: Additive manufacturing, Binder jetting, 3D printing.

INTRODUCTION

AM is a uniquely designed production technology that involves layering materials to make 3-D components right from CAD designs. The most noteworthy profit of AM over other manufacturing is the capability to cope with complex shapes and material complications those subtractive manufacturing technologies cannot create [1].

It enables the development of printed components along with the models. One of the primary advantages of this approach to product production is the capacity to make nearly any profile that would not be possible to the machine. Other profits comprise reduced time and cost, amplified human engagement, and, as an outcome, a rapid product development cycle [2]. Each design and development

* **Corresponding author Kriti Srivastava:** Mechanical Engineering Department, National Institute of Technology, Patna, Bihar, India; E-mail: kritis.phd20.me@nitp.ac.in

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

procedure utilizing a 3D printing machine necessitates the operator performing a specific set of tasks. The accessibility of such a task sequence is emphasized by convenient 3D printing devices. These desk machines are distinguished by their low price, ease of usage, and capability to be used in an industrial and academic environment. Each stage in this system is expected to have a restricted number of alternatives and require the least effort. Nevertheless, this implies that there are restricted options, like restricted selection of materials and many other parameters with which to do experimentation. Bigger, further flexible machines are extra competent at being tailored to encounter a variety of user needs, but they are also more complex to handle.

The additive manufacturing technology has the following process chain, as shown in Fig. (**1**) [3].

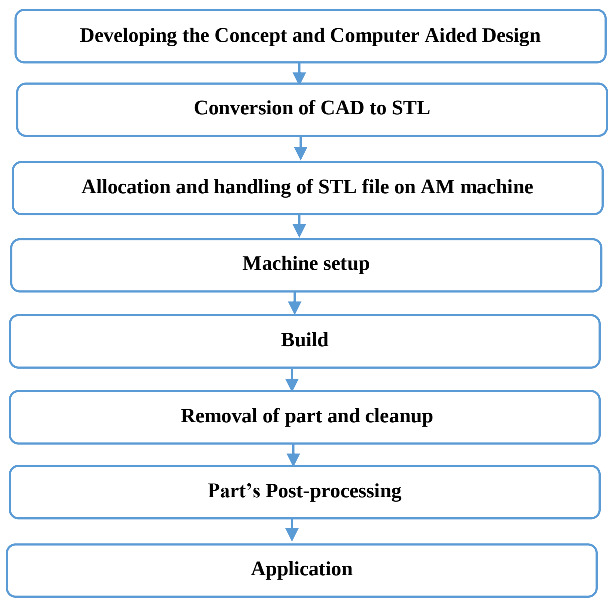

Fig. (1). Process chain of AM [3].

Classification of AM

According to the American Society for Testing and Materials (ASTM)/ International Organization for Standardization (ISO), AM is classified into seven categories, as shown in Fig. (**2**) [4]. All the major types of AM processes are as follows:

1. Powder Bed Fusion

2. Binder Jetting

3. Material Extrusion

4. Metal Jetting

5. Vat Polymerization

6. Sheet Lamination

7. Director Energy Deposition

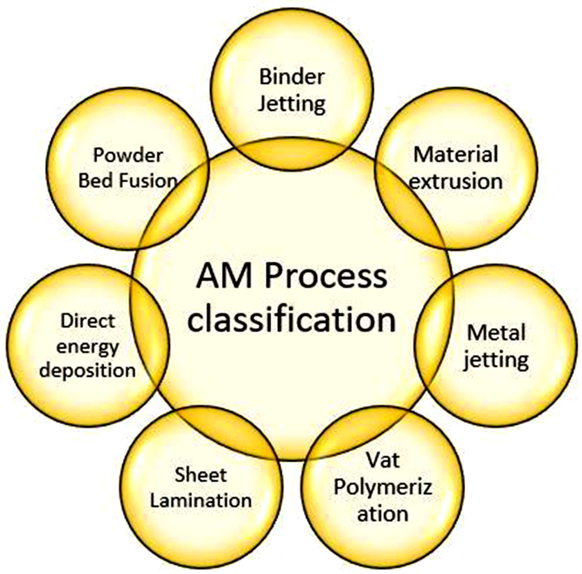

Fig. (2). Classification of AM technology [4].

Table **1** shows a comparison between different AM processes, and Table **2** shows a comparison of binder jetting with Selective Laser Sintering (SLS), Stereolithography (SLA), and Laminated Object Manufacturing (LOM).

Table 1. Comparison between the various AM processes on the basis of some features [5 - 12]

Process	Technologies	Form of feed material
Binder Jetting	Binder and powder 3D Printer	Powders and binder
Powder Bed Fusion	Electron Beam Melting, Selective laser sintering,	Powders
Metal Extrusion	FFF	Rods or wire
Sheet Lamination	Sheet forming	Sheet
Direct Energy De position	Laser Cladding	Wire

CHAPTER 4

Spot Welding of Dissimilar Materials Al6061/ Ss304 with an Interfacial Coating of Graphene Nano Platelets

Velavali Sudharshan[1,*] and **Jinu Paul**[1]

[1] *Department of Mechanical Engineering, National Institute of Technology Calicut, Calicut-673601, India*

Abstract: Spot welding of dissimilar materials Al6061 and SS304 with an interfacial coating of Graphene Nano platelets (GNPs) by using the Resistance spot welding (RSW) technique is described in this chapter. A thin layer of GNPs (a few micrometers thick) is incorporated as an interlayer between Al6061/SS304 sheets (thickness 1 mm) and spot welded in lap configuration. RSW parameters play a vital role in this joining process. It was observed the strength of the lap joint increases with welding time and current. The method of welding held up the metal ejection, which occurs at high welding conditions. The influence of process parameters (welding current, time) on the mechanical and microstructural properties of the spot-welded joint was evaluated in detail. A tensile test was carried out in lap-shear mode to evaluate the strength of the joint and to determine the peak load. The fusion zone and the weld nugget were characterized by Scanning Electron microscopy and hardness analysis. SEM analysis observes that Fe and Al matrix well looped around the Graphene particles leads to the formation of inter-metallic compounds of Fe-GNP, Al- GNP, and Fe-Al-GNP at the joint interface. The results are compared with the properties of joints without and with GNP interlayer. It was found that the GNP interlayer enhances the properties of the spot-welded joint and increases joint strength. Possible strengthening mechanisms include enhanced grain refinement and dislocation pile-ups in the presence of the GNPs.

Keywords: Dissimilar welding, Graphene nanoplatelets, Interfacial coating, Lap joints, Resistance spot welding.

INTRODUCTION

Resistance Spot Welding (RSW) is one of the most commonly used welding methods. It is used in a broad range of industries, prominently for joining thin

* **Corresponding author Velavali Sudharshan:** Department of Mechanical Engineering, National Institute of Technology Calicut, Calicut- 673601, India; Email: sudharshan_m190618me@nitc.ac.in

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

sheets for light vehicle parts. The RSW is normally performed by overlapping sheet metals in a lap configuration. RSW is essentially used to join pieces, usually up to 4 mm in thickness. The intensity of the RSW joint depends on the nugget size of the weld zone. RSW nugget zone or weld zone diameter ranges from 2 mm to 13 mm depending on the electrode's tip [1 - 8].

In Fig. (**1**), the principle of resistance spot welding is illustrated. In stage-1, metal sheets with a good surface finish are placed on the bottom fixed electrode in overlapping positions. In stage-2, pressure is applied by the movable upper electrode, and now both electrodes hold overlapped workpieces and high current supplied through the electrodes. In stage-3, the resistance at the interface generates heat at the interface, causing the melting of material up to the plastic melting stage. In stage-4, after the formation of the molten metal nugget between overlapped workpieces, the current supply is stopped, but electrodes are not free, and it still holds the overlapped workpieces. In stage-5, a squeezing force is applied to electrodes leading to the joining of the plastic molten metal at the interface. The excess heat from the joint is removed by the water cooling facility provided on the electrode. In stage 6, the electrode is made free by removing the forces, and the finished welded lap joint is taken out.

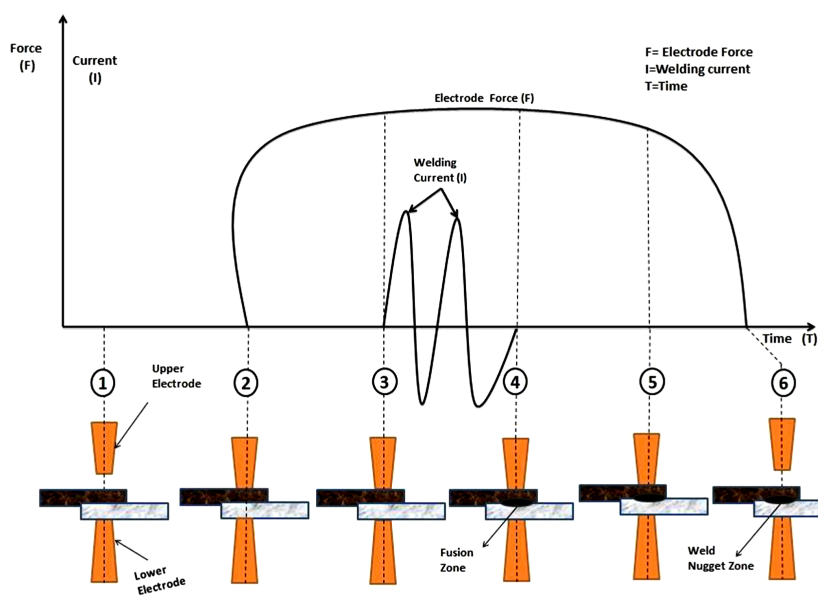

Fig. (1). Lap joint spot-welding processes.

In Resistance spot welding, the joining at the interface is attained by simultaneously applying current and force. The overlapped workpieces are in between the electrodes. The overlapped work pieces compressed together between the electrodes leads to melting at the interface of the contact surface. Thus, while the current stopped, the molten nugget region of workpieces solidified to form a joint. RSW has also been demonstrated for the joining of dissimilar materials like magnesium/aluminium [2, 4, 9], low carbide steel /aluminium [3], etc.

One of the major problems associated with the resistance spot welding process is the weldability of highly conductive materials like Aluminium. Since Aluminium is highly conductive, the resistance at the interface may not be sufficient to generate the required amount of heat. Further, the high thermal conductivity of Aluminium easily transfers the heat from the nugget zone, which prevents its melting.

In order to address this issue, a commonly used method is the usage of interlayers. It was reported that interfacing a layer of suitable material at the interface of the joint leads to increase the strength of the joint [2 - 7, 9, 10]. The interfacial element or the interlayer could be Ni [2], Tin [9], CNT [5, 7], Lead, Zinc [4], etc. Graphene, a single-layer honeycomb lattice [6, 10 - 13] possessing a lighter weight, high conductivity, strength, and flexibility, has also been reported as an interlayer. Baidehish Sahoo [6] modified Aluminium surface with graphene using a resistance heat pressing technique shown in Fig. (**2**). This study describes that introducing graphene leads to surface modification on the topography of Al6063 and forms an internal nanometallic compound on the top surface resulting in ~5 times enhancement in surface hardness in optimum conditions. Also, approximately 200% improvement in young's modulus and 60% improvement in the tensile strength as compared to the bare sample was reported. This result in significant improvement in the surface mechanical properties of Al6063.

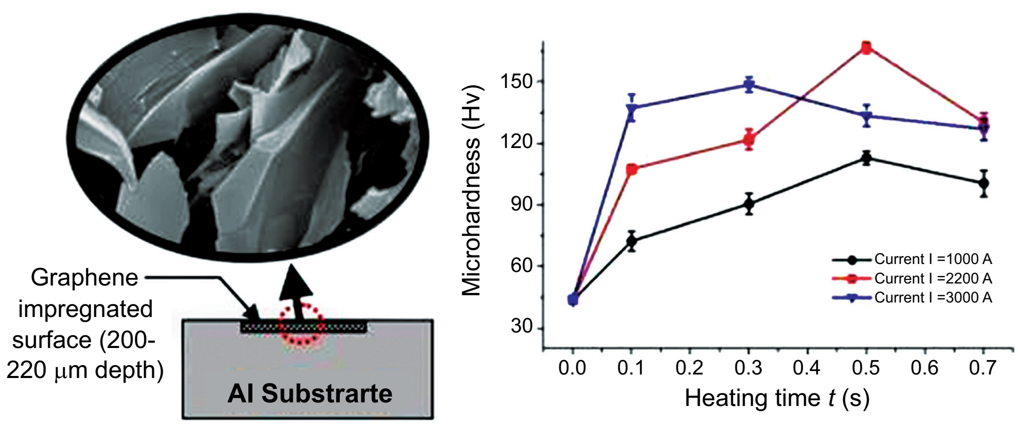

Fig. (2). Graphene impregnated (left), Hardness vs. heating time(right) [6].

CHAPTER 5

Optimization of Laser Welding Parameters of Aluminium Alloy 2024 using Particle Swarm Optimization Technique

Aparna Duggirala[1,*], Upama Dey[1], Souradip Paul[1], Bappa Acherjee[2] and **Souren Mitra[3]**

[1] *School of Laser Science and Engineering, Jadavpur University, Kolkata, 700032, India*

[2] *Department of Production and Industrial Engineering, Birla Institute of Technology: Mesra, Ranchi, 835215, India*

[3] *Department of Production Engineering, Jadavpur University, Kolkata, 700032, India*

Abstract: Laser welding is a viable method of joining aluminium alloys. The input parameters employed in the welding process have a significant impact on the weld quality. There are several parameters that influence weld quality, however, describing their relationship with weld seam characteristics is challenging. This study uses the Taguchi approach and particle swarm optimization (PSO) techniques for improving the weld quality in an Al 2024 lap joint to achieve a consistent and reliable joint. The experiments are performed on a laser welding machine following an L9 orthogonal array experimental design with peak power, scanning speed, and frequency as input parameters. Here, breaking load, bond width and throat length are considered as the responses. Experimentally a maximum breaking load of 1233 N and a minimum bond width of 398.81 µm is achieved. The throat length ranged from 340.72 µm to 983.94 µm. Regression analysis is used to establish the relationship between the input and the responses. The regression equations are utilized as the objective function in an optimization problem. The crowding distance PSO is used to acquire the global optima. Finally, the optimal process parameters for achieving the desired goals are presented.

Keywords: Aluminium alloy 2024, Design of Experiments, Laser welding, Particle Swarm Optimization, Taguchi method.

INTRODUCTION

There is an increase in demand for fuel-efficient automobiles, low-cost flights, and low-cost goods. As a result, there is an ongoing need for research into novel

* **Corresponding author Aparna Duggirala:** School of Laser Science and Engineering, Jadavpur University, Kolkata, 700032, India; E-mail: aparna.sudhakiran@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

materials that have a higher strength-to-density ratio while staying economically viable. Aluminium alloys continue to be critical for structural components due to their availability, simplicity of fabrication, and low cost. 2xxx (Al-Cu) series alloys with a high damage tolerance are frequently employed in fatigue-critical applications [1]. Due to their corrosion resistance, ease of manufacture, and high specific strength, alloys of the 5xxx (Al-Mg) and 6xxx (Al-Mg-Si) series are in great demand. The 7xxx (Al-Zn) series alloys are the strongest of all aluminium alloys and are utilised in high-stress aerospace equipment [1]. Despite their increased specific strength, the usage of 7xxx series alloys is restricted owing to the reduced dependability of welded components that occur due to flaws such as fusion zone softening, cracking, and porosity [2]. Certain aluminium alloys are difficult to weld using traditional welding procedures. As a result of its heat source, which is very intense, laser welding is favoured for welding alloys of aluminium. Among its benefits are its rapid rate of manufacturing, high energy density, and low deformation [3, 4]. Numerous process factors have an effect on the quality of the welded component. Various combinations of input parameters result in excellent joints, but it is critical to pick the most effective combination [5]. Kovacocy *et al.* [6] investigate the role of beam traverse speed, shielding gas, and laser power in making reliable welds. The authors determine the effectiveness of various laser welding settings on the production of flaws, impaired microstructure, and fusion zone fracture [7 - 9]. To obtain high-quality welds, experimental design optimises and establishes mathematical correlations between the input parameters and their related outputs. Even an emaciated layer may be adequate to supply the joints with the necessary strength [10]. In many cases, a thicker welded layer leads to increased power consumption and also in faults. Additionally, the geometry of the weld pool, which is influenced by heat conditions, affects the development of weld grains significantly. As a result, selecting the appropriate settings is critical to obtaining the greatest outcomes. Additionally, thanks to developments in numerical modelling approaches, the solidification of a weld may be explored more efficiently and precisely [11]. The Taguchi approach is frequently used in offline mode to optimise quality features. Multi-objective particle swarm optimization (MOPSO) is a relatively new and commonly accepted computer technique that employs a nature-inspired approach that is simple to implement and efficient in terms of time. Numerous references [12 - 14] describe a range of statistical strategies for developing and improving welding process parameters. This article discusses numerous optimization strategies and their use in manufacturing processes.

The effect of the laser beam's maximum power, frequency, and scanning speed on the weld width, load-bearing capacity, and throat length is investigated in this study utilising aluminium alloy 2024. Due to the alloy's physical and thermal qualities, conventional welding is challenging. As a result, the input parameters are optimised to produce a narrow weld width while keeping a high load-bearing capacity and nominal throat length. The trials are developed using the Taguchi approach; moreover, MOPSO is used to determine the global optimal process parameters that result in dependable lap joints.

EXPERIMENTAL SETUP

Table **1** contains the chemical composition of aluminium alloy 2024 as acquired from the material source. The specimen is 75 mm long, 20 mm wide and 2 mm thick. The experiment is conducted utilizing a 300W pulsed laser welding system with a maximum obtainable power of 300W and a wavelength of 1.064 m. When focused, the laser beam has a diameter of 0.6 m. Argon is employed as the shielding gas, with its supply concentric with the output of the beam. Fig. (**1**) illustrates the setup used for lap welding the components.

Table 1. Material composition of AA 2024.

Material	Cu	Mg	Mn	Si	Zn	Ti	Cr	Others	Al
Composition	4.9	1.8	0.9	0.5	0.25	0.15	0.10	0.05	Remainder

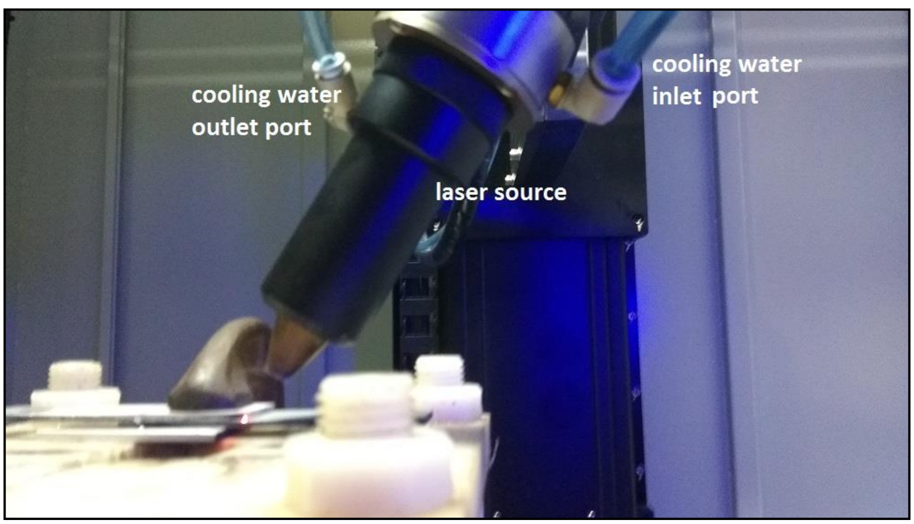

Fig. 1. Laser welding setup.

EXPERIMENTAL DESIGN

To achieve the targeted breaking load capacity, nominal throat length, and reduced weld width, the investigation's parameters include laser peak power, pulse frequency and scanning speed. Table **2** lists the process variables that were

CHAPTER 6

A Review on Theories and Discharge Mechanisms in Electro-Chemical Discharge Machining

Mahaveer Prasad Sharma[1,*], **Pankaj Kumar Gupta**[1] and **Gaurav Kumar**[2]

[1] *Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India*

[2] *Department of Mechanical Engineering, NIT Uttarakhand, Srinagar-246174, India*

Abstract: Electro-chemical discharge machining (ECDM) is a hybrid machining process that can machine conductive and non-conductive materials at the micro level. It caters to the benefits of two well-established constituent processes, namely, electro-chemical machining (ECM) and electric discharge machining (EDM). The technology is quite established. However, the control of discharges in ECDM still needs further research. In this view, the present study reviews the various theories and mechanisms of discharge in ECDM given by researchers. The study also comprises an introduction to the ECDM technique, its various names given by different researchers, applications, and historical developments.

Keywords: Discharge mechanism, Electro-chemical discharge machining, Electro-chemical machining, Electric discharge machining, Hybrid machining.

INTRODUCTION

In today's world of miniaturization, glass and ceramics are extensively being used in micro-systems manufacturing. Machining of such materials by traditional machining methods experiences considerable machinability challenges due to their inherent properties, such as hardness and brittleness. Excessive tool wear, surface cracks, and damages are some of the challenges. Several non-traditional micro-machining technologies like abrasive-based machining, ultrasonic machining, chemical etching and laser-based machining are suitable for machining these materials. However, these technologies have some limitations regarding surface quality, productivity, dimensional accuracy, aspect ratio, and sometimes even hazardous [1, 2].

[*] **Corresponding author Mahaveer Prasad Sharma:** Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India; E-mail: mahaveer.gpc@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

Electric discharge machining (EDM) and electro-chemical machining (ECM) are the two non-conventional machining processes assisted by electrical energy. Though these two processes are well-established, these two processes are suitable for electrically conductive materials only. The absence of electrical conductivity in the workpiece limits the use of these two processes [3]. Electro-chemical discharge machining (ECDM) has emerged as a hybrid machining process to overcome these limitations, which exploits the benefits of ECM and EDM processes [2, 4]. ECDM is an economical and promising technique for non-conductive materials which cannot be easily machined by other techniques. However, ECDM is not restricted to electrically non-conductive material. Researchers have used ECDM for various materials such as glass (*i.e.*, soda-lime glass and borosilicate glass), ceramics (*i.e.*, alumina and silicon nitride), quartz, copper, and some composites (*i.e.*, Carbon fiber and Kevlar epoxy composites). Electro-chemical arc machining (ECAM) was capable of giving higher machining rates than ECM and EDM alone [5]. Researchers studied and found ECDM performs better regarding material removal, dimensional integrity and surface quality during ECDM than ECM and EDM alone [6].

On being an economical and potential micro-machining process, the commercial use of this technology is still limited because of challenges in the control of discharges. The current limitations in the universal commercial acceptance of this technology open up opportunities for further research in this field. In view of attracting researchers to explore the process capabilities, this article presents a comprehensive review of theories and discharge mechanisms reported by researchers. A brief introduction of the ECDM process, its historical development in chronological order, and process names are given by various researchers, which also make up part of this article.

HISTORICAL DEVELOPMENTS IN ECDM

The first development of spark-assisted chemical engraving (SACE) occurred in Japan in the late 1950s for application in diamond die workshops. Further developments in this field are tabulated below Table (**1**) [7].

Table 1. Historical developments in ECDM [7].

Year	Chronological Development in ECDM	Researcher
1968	First reported	Kurafuji and Suda
1973	First characterization	Cook *et al.*
1985	First variant “wire electro-chemical discharge machining”	Tsuchiya *et al.*
1990	First application in the field of MEMS published	Esashi *et al.*

(Table 1) cont.....

Year	Chronological Development in ECDM	Researcher
1996	First theoretical model of spark generation	Ghosh *et al*.
1999	First model of discharge phenomenon	Jain *et al*.
2002-04	Study in light of electrochemistry	Fascio *et al*.
2006	Use of pulsed power	Kim *et al*.
2009	Machining structures (<100μm)	Cao *et al*.
2014	First commercial machine	By Posalux SA, the Swiss company

Different researchers have given different names to the ECDM process, such as "Electro Chemical Arc Machining" ECAM [5, 8], "Electro Erosion Dissolution Machining" EEDM [6], "Electro Chemical Discharge Machining" ECDM [9], "Electro Chemical Spark Machining" ECSM [10], "Spark Assisted Chemical Engraving" SACE [11, 12] and "Spark Assisted Etching" SAE [13].

ELECTRO-CHEMICAL DISCHARGE MACHINING (ECDM) SYSTEM

An electro-chemical cell forms the primary basis of an ECDM system, as shown in Fig. (**1**). An electro-chemical cell consists of two electrodes with grossly different sizes (about a factor of 100). An electric spark is generated at the electrode (tool)-workpiece interface above a critical value of voltage. This phenomenon is called the electro-chemical spark/discharge. The workpiece material gets removed in the close vicinity of the discharge zone primarily by the thermal effect of discharge energy.

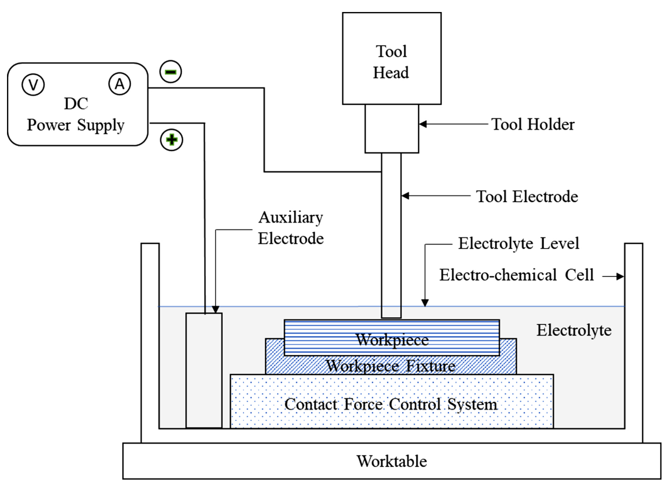

Fig. (1). Schematic of electro-chemical discharge machining (ECDM) system.

CHAPTER 7

Investigations on Magnetic Field Assisted Electrochemical Discharge Machining Process

Botcha Appalanaidu[1,*], **Rajendra Kumar Arya**[2] and **Akshay Dvivedi**[1]

[1] *Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee, Uttarakhand, India*

[2] *Department of Mechanical Engineering, Indian Institute of Technology, Mumbai, Maharastra, India*

Abstract: Electrochemical discharge machining (ECDM) process is an arising unconventional machining process for the micromachining of non-conducting materials. During the ECDM process, surface damages, machining continuity at higher depths and hole over cut (HOC) are the main issues during drilling. Previous researchers reported that gas film thickness, debris evacuation and electrolyte replenishment are the prime reasons for the lack of surface quality and lower hole depth. The present investigation has employed a magnetic field during the machining process, and they found a positive effect on the above-mentioned issues. Lorentz force was produced during the machining process, and created a circular motion of the electrolyte around the tool electrode. This phenomenon helped to control the gas film thickness, debris flushing, and electrolyte replenishment at the tool end. In the present work, the authors used a 1300 Gauss Fe-based ceramic permeant ring magnet. Magnetic field strength for both south and north poles was measured using a digital Gauss meter. A high-speed image-capturing camera was used to understand the bubble generation, gas film formation, and debris evacuation during the machining process. The authors applied both north and south-pole magnetic fields for the investigation of the machining process and compared the results with the conventional ECDM process. Better results in surface quality, hole depth, and HOC were achieved with the south pole magnetic field compared to the traditional ECDM process.

Keywords: Borosilicate glass, ECDM, Gas film, Lorentz force, Magneto hydrodynamic effect, NaOH.

* **Corresponding author Botcha Appalanaidu:** Department of Mechanical Engineering, GITAM University, Visakhapatnam, India; Email: botchaappalanaidu1@gmail.com.

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

INTRODUCTION

The electrochemical discharge machining (ECDM) process is a hybrid micromachining process and gained researcher's attention in recent times [1]. The eminent feature of the ECDM process is that all kinds of work materials can be machined [1, 2].

However, in recent times, the ECDM process gained popularity for machining hard-to-machine materials such as borosilicate, soda lime glass, quartz, zirconia, *etc* [1, 3]. The experimental facility of an ECDM process has two electrodes (tool and counter electrode), a power supply unit, an electrolyte medium (in general alkaline solution), and a feeding unit [2]. The tool electrode (highly conducting material) is placed in a tool holder and immersed in the electrolyte bath nearly about 2 mm [3]. The counter electrode (highly conducting material) is fully dipped in an electrolyte medium. A potential difference was created using a DC power supply. Hydrogen bubbles are generated at the cathode, and oxygen bubbles are at the anode. Due to the lower surface area, bubbles are densely concentrated at the tool electrode and coalesce with each other to form a gas layer on the tool. As the potential difference increases beyond the critical voltage, the film gets ionized, and the peak voltage increases. At this condition, the film breaks by producing thermal discharges around the tool. When the work material is in the vicinity of the discharges, the thermal discharges strikes to the work material. As result of this, material gets melted and evaporated in micro level. These thermal discharges also increase the temperature in the machining zone. As a result, high-temperature chemical etching also takes place on the work material. Eventually, along with material melting and vaporization, high-temperature chemical etching also involved in the material removal mechanism [4].

Being thermal energy is the main source in the material removal mechanism during the ECDM process, the scope for thermal damage at the machined surface is high. The same was reported in the past literature with micro-cracks over the hole periphery, hole entrance damages, hole over cut (HOC), and micro-cracks propagation into macro cracks, and sometimes this leads to breakage of work material [2]. There are several reasons to state the above deteriorations. During the machining process, a depth of around 250-µm is considered as the discharge regime. In the discharge regime, the thermal discharges are responsible for the major material removal process. As the machining progress, the tool electrode enters into the hydrodynamic regime. In the hydrodynamic region, evacuation of debris from the machining area (beneath the tool electrode and between tool side walls and the machined hole) is difficult. Therefore, the tool electrode is surrounded by molten material. In addition, due to the lack of fresh electrolyte availability, it is difficult to continue the machining process further. Meanwhile, the electrolyte evaporates in the machining zone and leaves salt. This slat accumulates as sludge at the tool end. Both the phenomenon of lack of availability of the electrolyte and sludge/debris formation around the tool tip hinders further machining. On the other hand, an abundance of electrolytes at the hole entrance continued the machining process and channeled the major energy to the hole entrance region. As a result, hole depth was reduced, and HOC and hole taper increased [5].

In order to minimize the above-mentioned phenomenon, several works have been reported in the past. Sabahi *et al.* added two different surfactants, such as C-TAB and SDS, to minimize the surface tension of the gas bubbles. This phenomenon produced a thin gas layer over the tool. The thin gas layer generated low potential sparks in the machining area. Low-intensity sparks reduced the thermal damage over the hole entrance. However, this technique failed to provide the solution for the evacuation of sludge and debris and the addition of fresh electrolytes into the machining area [6]. Zheng *et al.* applied tool rotation motion during the machining process, as depicted in Fig. (**1a**). Tool rotation produced the centrifugal motion of gas bubbles. As a result, larger bubbles were moved from the machining region, and smaller bubbles participated in the film formation. Electrolyte rotation aided to evacuate sludge from the hole bottom and electrolyte availability in the machining zone [7]. Rathore and Dvivedi provided the ultrasonic motion to the tool, as shown in Fig. (**1b**). The vibration motion of the too electrode separated the larger bubbles from the machining zone. This phenomenon helped to develop a thin film over the tool. Due to rapid up-an--down motion of the tool helped debris to evacuate from the machining zone [8]. Han *et al.* applied the vibration to the electrolyte medium during the machining, as shown in Fig. (**1c**). This phenomenon improved the spark discharge efficiency by modifying the gas film. As a result, hole depth was improved, but HOC and machined geometry as still major issues. Singh *et al.* used a textured tool during machining to increase nucleation sites for better spark discharges by lowering film thickness, as shown in Fig. (**1d**). Though this process enhanced the machined geometry quality, it still had issues with sludge removal [9]. Tool shape modification [10], supplying electrolytes through tool electrodes [5], and application of an external magnetic field in the machining zone [11] also tried to achieve better results. All the above-mentioned processes solved only one of the major issues (flushing, replenishment, increment in hole depth, reduction in HOC and hole damages), and some process variants needed external attachments, which include mechanical forces and alignment issues. Therefore, a novel method is needed in this field to enhance hole quality and hole depth without affecting existing experimental facility.

CHAPTER 8

Microwave Drilling of Polymer Based Composite: Challenges and Opportunities

Gaurav Kumar[1,*], **Apurbba Kumar Sharma**[2] and **Mukund Kumar**[3]

[1] *Department of Mechanical Engineering, NIT Uttarakhand, Srinagar-246174, India*

[2] *Department of Mechanical & Industrial Engineering, IIT Roorkee, Roorkee-246174, India*

[3] *Department of Mechanical Engineering, BIT Mesra, Ranchi - 835215, India*

Abstract: Microwave drilling is an advanced machining process in which electromagnetic energy converted into thermal energy with the help of a metallic concentrator is used to create the desired shape in the work material. High strength electric field developed around the tooltip ionizes the dielectric media around the tooltip and results in plasma formation. High-temperature plasma ablates the material just beneath the tool tip to create the desired hole in the workpiece. In the present research work, micro-hole drilling on thermoset and thermoplastic-based composites using microwave energy in the air and transformer oil has been investigated. The drilling characteristics have been investigated in terms of the heat-affected zone, and overcut; a comparison has been made in air and transformer oil. The study revealed that drilling in the presence of dielectric-like transformer oil reduces the defects like HAZ and overcut significantly. It was also observed that thermal damage was more in thermoset-based composites as compared to thermoplastic-based composites.

Keywords: Composite, Heat affected zone, Microwave drilling, Micro-hole, Overcut.

INTRODUCTION

Difficult-to-machine materials like glass and polymer composite are gaining vast popularity these days due to their wide application in aerospace, naval, automotive, MEMS and other industries. Drilling of micro-hole in polymer composite using conventional drilling methods is a challenging task due to its unique physical and mechanical properties [1 - 4]. Polymer composite often experiences machining damage like fuzzing, matrix cracking, spalling, fiber pull-out, excessive dust, tool wear, thermal degradation, and delamination due to their inherent anisotropy and heterogeneity [4]. Thus, it becomes crucial to minimize

* **Corresponding author Gaurav Kumar** Department of Mechanical Engineering, NIT Uttarakhand, Srinagar-246174, India; Email: grv.kmr@nituk.ac.in

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

machining damage for better surface integrity of the machined product. Above mentioned machining damage associated with conventional machining resulted in the development of advanced machining methods like AWJM, LBM, *etc*. Though the above-mentioned non-conventional methods have made significant strides in the field of micromachining of glass and plastic fiber composites, the use of water with AWJM and USM for machining of composite reduces the strength of composite significantly. Laser machining has shown significant potential in the field of micromachining, but defects like heat-affected zone and taper are a serious concern [5].

Microwave drilling has drawn the wide attention of researchers in recent times due to its Omni-machining characteristics, high machining rate, and eco-friendly characteristics [6 - 16]. It has been successfully used to drill a hole in materials like metals, glass, ceramics, *etc*., irrespective of their electrical conductivity [7 - 16]. Jerby *et al*. reported the successful drilling of the hole on various materials like ceramics, concretes, *etc*., using a coaxial near-field radiator-based microwave drill experimental setup in the year 2002 [7 - 10]. But, the leakage of high-power microwave radiation was a significant concern as the complete machining process was taking place in an open environment. A significant improvement in the microwave drilling experimental setup has occurred since 2002. Later on, Lautre *et al*. used a gravity-fed microwave drilling set-up in which a concentrator made of metal concentrated the electromagnetic energy at its tooltip in a domestic microwave applicator which ensured no leakage of radiation [11, 12]. But, the defect around the drilled micro-hole in the glass was significant. Later on, Gaurav *et al*. changed the media around the tool by immersing the tool and workpiece inside a dielectric media [13 - 16]. The defect around the hole was reduced significantly, but the process still needed improvement to drill a hole with an almost negligible defect. Later on, Gaurav *et al*. used controlled feed to drill a hole in the glass. Subsequently, the effect of feed rate, tool-workpiece gap, immersion depth, and shape of the tool on heat-affected zone, material removal rate, roundness, and overcut was studied. Tool having a conical tip outperformed tool having a cylindrical tip. It was observed that a particular machining gap, i.e., ~ 300 μm, helped in reducing the roundness error and thermal damage in glass drilling, whereas overcut and material removal rate got increased as compared to zero tool work gap due to the removal of glass residue from the material removal zone. Moreover, it was observed that an increase in feed rate (up to 1.2 mm/s) and immersion depth (up to 45 mm) affects the thermal damage and overcut inversely [14]. However, defects were not completely eliminated from the machining zone. In the Year 2021, it was reported that dielectric in dynamic mode minimized the defect to a greater extent as compared to static dielectric and air. Drilling at lower power using dynamic dielectric helped in minimizing defect further, but a decrease in power in the case of stagnant dielectric and air increased the defect significantly. However, the machining time was less in the stagnant dielectric as compared to the dynamic dielectric due to the formation of a concentrated plasma zone in the stagnant dielectric. Cracks around the hole were less in the case of dynamic dielectric as compared to stagnant dielectric due to the low value of thermal stress. Thermal stress was observed to be low in the case of dynamic dielectric due to the flushing out of excess thermal energy from the machining zone as compared to stagnant dielectric [16].

The micro-hole drilling on composite laminates using non-conventional methods like laser machining, Electric discharge drilling, Abrasive Jet Machining, *etc*. has been reported by various researchers [1 - 4, 17 - 22]. Ravinder *et al*. successfully reported the drilling of micro-holes in carbon-fiber reinforced composite using Electric discharge drilling [3]. But, the inherent limitation of the EDD process is that the fibre should be of conductive nature. Feng *et al*. reported the successful drilling of holes in carbon fiber-reinforced epoxy composite without fiber pull-out and taper using rotary ultrasonic machining (RUM). However, chipping was observed around the hole. Further, the deformation of the composite during machining caused fluctuation in thrust forces, increasing the surface roughness [18]. Besides, excessive tool wear and comparatively higher machining time are observed in drilling hole in composite using ultrasonic machining [18, 19]. Non-conventional machining processes like laser machining and AJM can be used to drill holes all types of composite, but thermal damage and taper in the case of laser machining and stray cutting in the case of AJM is a serious concern [20 - 22].

Microwave drilling has shown a significant potential to drill a hole in all types of materials regardless of their conductivity. The present work was focused on drilling a micro hole in glass fiber and natural fiber reinforced polymer composite at a controlled feed rate in air and transformer oil and compares the defect like HAZ and overcut in different dielectric media like air and transformer oil.

MATERIALS AND METHODOLOGY

Glass fiber and natural fiber-reinforced composites (40×30×4 mm) of rectangular shape were used as a test specimen for the present study. Glass fiber reinforced epoxy composite was developed by hand lay-up process using glass fiber and epoxy, whereas natural fiber reinforced polypropylene composite was prepared using an injection molding process. Tungsten carbide (Diameter: 500 μm) has been used as a tool material due to its good thermo-physical properties. The microwave drilling set-up, as evident from Fig. (**1**) comprises a domestic microwave oven that acts as a source for the microwave, a metallic concentrator, which is used to concentrate the microwave energy at its tip, a tool holder which

CHAPTER 9

Parametric Evaluation in Context to the Functional Role of Eco-Friendly Water Vapour Cutting Fluid Through Chip Deformation Analysis in HSM Of Inconel 718

Ganesh S. Kadam[1,2,*] and **Raju Shrihari Pawade**[1]

[1] *Babasaheb Ambedkar Technological University, Lonere, Maharashtra, India*

[2] *SIES Graduate School of Technology, Navi Mumbai, Maharashtra, India*

Abstract: Demand for increased production rates, better quality, and incorporation of green manufacturing practices has been continually challenging the manufacturers. This could be feasible by adopting high-speed machining (HSM) using eco-friendly cutting fluids but with careful process control. On these lines, the current paper explores process characteristics of the exotic superalloy Inconel 718 being turned at high speeds with tooling as coated carbide inserts and eco-friendly cutting fluid as water vapour. The experiments were carried out by varying three process parameters, viz. cutting speed, feedrate as well as water vapour pressure, following central composite design based on response surface methodology. A special tool holder with an in-built fluid supply channel was used to facilitate precise delivery of water vapour cutting fluid onto the machining zone. The process mechanics has been analyzed with the aid of the chip deformation coefficient as the same is a crucial indicator revealing the cutting fluid performance in machining as a result impacting the surface integrity, tool wear, machinability, etc. Analysis revealed that the response surface quadratic model for the chip deformation coefficient was statistically significant. The feedrate, vapour pressure, and the interaction between feedrate and vapour pressure were highly dominating factors influencing the chip deformation coefficient, with contributions of around 23.41%, 25.33% and 21.49%, respectively. An increase in vapour pressure was highly beneficial in lowering the chip deformation coefficient on account of water vapour's better penetrability and performance into the machining zone. Overall usage of cutting fluid as water vapour within feasible HSM parametric ranges can be notably beneficial.

Keywords: Chip deformation coefficient, Eco-friendly, High-speed machining, Inconel 718, Water vapour.

* **Corresponding author Ganesh S. Kadam:** Babasaheb Ambedkar Technological University, Lonere, Raigad, Maharashtra, India; Email: gskadam@ymail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

INTRODUCTION

Manufacturers worldwide have constantly been seeking methods for increasing productivity. In machining, productivity can be appreciably enhanced by incorporating high-speed machining (HSM). HSM basically involves carrying machining at those cutting speeds as well as feed rates that are much higher than that of their conventional counterparts. Superalloy Inconel 718, a nickel nickel-based alloy, possesses excellent properties like good corrosion resistance, strength at high-temperature and lower thermal conductivity. This makes it suitable for critical applications in aerospace, defense, gas turbines, nuclear reactors, chemical plants, marine equipment, etc [1]. However, Inconel 718 is also known as difficult-to-machine material as a result of its properties leading to poor machinabilities, like preserved strength during machining, exorbitant strain rate sensitivity, and poor thermal conductivity [2]. The majority of the problems during machining primarily originate on account of higher cutting temperatures, and the control over it can be exercised by proper selection as well as delivery of cutting fluids. Also, due to stringent environmental laws imposed by governments worldwide for manufacturing industries, there imposes a necessity to use eco-friendly cutting fluids. A variety of researchers have focused their attention on the machining of Inconel 718, wherein different cutting fluids and application methods ranging from conventional to eco-friendly grades like wet [3 - 10], high-pressure jet cooling [7, 8, 10 - 12], minimum quantity lubrication (MQL) [9, 11, 13 - 17], cryogenic cooling [3, 4, 9, 11, 15], *etc*. have been explored, and the benefits noted in the form of better surface finish reduced cutting forces and improved tool life.

During the 1990s, Podgorkov and Godlevski proposed water vapour as a new possible cutting fluid during machining [18]. Water vapour is cheap as it can be made easily available and further absolutely pollution-free too. Till date, very few studies have been reported on using cutting fluid as water vapour specifically for machining steels [18 - 20], Ti6Al4V [21] and Inconel 718 [22]. Water vapour basically serves as a lubricant and thus coolant in machining. Water vapour forms a lubrication film of low shear strength on the underside of chip, thus alleviating friction at the chip-tool interface and hence reducing cutting temperatures also. It can be concluded from past work that water vapour as cutting fluid in machining aids in lowering friction coefficient, cutting forces, and tool wear which, as a result, improves surface integrity in comparison to other machining environments like dry, wet, compressed air and gases. Even though having known the importance of water vapour in contrast to other machining environments, its functional role towards lubrication performance needs to be assessed especially in the case of HSM of Inconel 718. It becomes investigatory to understand how water vapour's functional performance varies under different parametric ranges as a negligible amount of work has been carried out on the same. The present paper discusses the same within the HSM regime for Inconel 718 with a due focus on exploring the effects of process parameters on the resulting chip deformation coefficient as the helpful monitoring element. Initially, a wise selection of cutting tools and process parameters has been done and further followed by vigorous experimentation adopting a design-of-experiments methodology. This is followed by an analysis of the results with due focus on reasoning and explanation of the same. Finally, keeping a broad view, conclusions from the study and the scope for further work have been made.

MATERIALS AND METHODOLOGY

Keeping in view the need for productive and sustainable practices by the manufacturers, it was decided to incorporate HSM of Inconel 718 using eco-friendly cutting fluid as water vapour. The experimental design established on RSM (response surface methodology) was adapted for conducting and analyzing experiments. The work particularly involved experiments at high-speed turning formulated on CCD (central composite design) of RSM. The three process parameters, cutting speed, feed rate and water vapour pressure, were varied. The levels of these process parameters are given in Table **1** [23]. The selection of these machining parameters was through wisdom from literature and past experience. Chip deformation coefficient was selected as the response as it is a crucial indicator for describing the status of lubrication in machining as well as analyzing machining characteristics [24].

Table 1. Process parameters along with their corresponding levels.

Levels	Coded Levels	Cutting Speed V_c (m/min)	Feed f (mm/rev)	Pressure P (bar)
1	-2	72.96	0.05	0.20
2	-1	90	0.07	0.30
3	0	115	0.10	0.45
4	+1	140	0.13	0.60
5	+2	157.04	0.15	0.70

Round bar specimens of Inconel 718 were employed as the work material with 25 mm diameter and 100 mm length. Inconel 718 had a chemical composition comprising of Ni-Cr-Fe-Nb-Ti-Co-Al-Si-C to be 54.95-17.90-16.54-4.85- 0.92-0.92-0.52-0.08-0.03 taken in order. The cutting tool used was carbide inserts with PVD TiAlN coating having specification CNMG120408MS and grade KCU10

CHAPTER 10

Parametric Analysis and Modeling of die-sinking Electric Discharge Machining of Al6061/SiC Metal Matrix Composite Using Copper Electrode

Bipul Kumar Singh[1,*], **Ankit Kumar Maurya**[1], **Sanjay Mishra**[1] and **Anjani Kumar Singh**[1]

[1] *Mechanical Engineering Department, Madan Mohan Malaviya University of Technology Gorakhpur, Uttar Pradesh, India*

Abstract: Aluminum-based metal matrix composites (MMC) are widely used in modern industries due to their lightweight, high strength, and superior hardness. In this study, silicon carbide (SiC) reinforced MMC has been fabricated using the stir casting method. Die-sinking EDM of fabricated MMC was performed using a copper (Cu) electrode. Experiments were carried out using the response surface methodology of box-behnken design (BBD) (RSM). The response surface plot was used to do parametric analysis on the effect of peak current (I_p), gap voltage (V_g), pulse-on-time (T_{on}), and duty factor(τ) on material removal rate (MRR) and surface roughness (Ra) using a second order regression model. The interaction effect of current with a pulse on time and duty factor has a substantial effect on MRR, while the interaction of current and voltage has a major impact on Ra, according to ANOVA. The increase of current increases both MRR and Ra. In the case of pulse-on-time, the value of Ra begins to decrease after 150 µs when the machining is performed at low voltage (40 V).

Keywords: ANOVA, EDM, MMC, MRR, RSM, Stir Casting, Surface Roughness.

INTRODUCTION

Aluminum-based MMCs are widely used in automobiles, aerospace, military, marine, *etc.* It has improved physical properties like high strength with low weight, enhanced stiffness, and hardness with improved tribological properties. Silicon carbide (SiC) is used for reinforcement due to its high hardness. Stirred casting technique is applied for the fabrication of composite material. Matrix and reinforcement were mixed in the ratio of 90wt% and 10 wt%, respectively. The molten mixture aluminum and reinforcement were mixed effectively using four

* **Corresponding author Bipul Kumar Singh:** Mechanical Engineering Department, Madan Mohan Malaviya University of Technology Gorakhpur, Uttar Pradesh, India; Email: bipulkumarsingh742@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

-blade stirrers. The fabricated composite was machined using a die-sinking electric discharge machine (EDM). EDM precisely removes the material from the electrically conductive workpiece through the spark generated between the interelectrode gaps. The sparking in EDM is regulated by DC pulses, and the direct current ionizes dielectric fluid within the interelectrode gap. Due to high heat, the workpiece material melts or even vaporizes. When the electric current is switched off the plasma channel collapses and ejects the re-solidified material in the form of debris through flushing.

Phate *et al.* [1] explored the wire-EDM machining of SiC-reinforced Aluminium MMC with different wt % of reinforcement, *i.e.*, 0%, 15% and 20%. MRR and Ra were studied in relation to feed, speed, and electric-related input parameters. Parametric analysis of Al7075 reinforced with 10% wt Boron Carbide (B_4C) was investigated by Gopalakannan *et al.* [2]. The analysis reveals that pulse on, and current affects the MRR, EWR and Ra. Shandilya *et al.* [3] proposed that the feed rate of wire and pulse-off duration were the highly significant and least significant factors, respectively, during wire EDM of SiC-reinforced Al6061. S Debnath *et al.* [4] developed a hybrid composite by the ex-situ method. Multiple regressions were used for the analysis of parameters for machining like pulse-on-time, current, pulse-off-time and voltage. Rizwee *et al.* [5] explained EDM parameters should be optimized for EDM machining of MMC and compared the prediction accuracy of artificial neural network (ANN) and RSM model. They proposed that ANN has better accuracy than RSM. Arunkumar *et al.* [6] developed Mg/SiC composite by powder metallurgy and discovered that it currently influences the output responses TWR, MRR, and Ra. Hourmond *et al.* [7] investigated the EDM of hybrid composite $AlMg_2Si$ using a copper tool with positive polarity. Using RSM, an experimental model for MRR and EWR was created, and it was discovered that the interaction effect of voltage and current had the greatest impact on these two parameters.

Khajuria *et al.* [8] developed Al2024/Al_2O_3 MMC by stir casting method using 5wt% reinforcement. EDM was performed for input parameter voltage, pulse-o--time, reinforcement wt% and current. Authors found that increasing pulse-o--time increases MRR, and increasing wt% of reinforcement, decreases MRR. Singh *et al.* [9] investigate the EDM of Inconel 601 and characterize the effect of machining settings on MRR and Ra by RSM. They discovered that current has a direct impact on Ra and MRR. Shihab *et al.* [10] performed W-EDM on friction stirred welded 5754 Al alloy. ANOVA indicates that pulse-on-time is the most effective factor for kerf width, Ra and MRR.

This study developed a second order regression model for MRR and Ra for die-sinking EDM of Al6061/SiC MMC using a copper electrode. Experiments were performed using the BBD approach of RSM, and the effect of major interaction factors on output responses was investigated using parametric analysis. The effect of peak current, gap voltage, pulse-on-time, and duty factor, as well as variations in output response about these input parameters, have been explored and analysed using response surface plots.

EXPERIMENTAL PROCEDURE

Material Preparation

In this research work, Aluminum 6061 rods were used as a matrix, and silicon carbide (SiC) powder was used as reinforcement. The weight fraction of silicon carbide reinforcement is 10 wt%. The composite has been formulated by the stir-casting method. Al6061 rods are cut into small pieces and then melted in a graphite crucible up to 800°C. The SiC particles are preheated in a crucible up to 750°C before mixing so that there is no moisture content remains in reinforcement which leads to porosity after mixing. SiC is preheated for 1 hour. After melting aluminum 6061 alloy, SiCp is mixed with the help of a stirrer for 15 minutes. After proper mixing of matrix and reinforcement, the molten mixed material is poured into a mold cavity to get the desired shape.

Tool Selection

A cylindrical shape copper tool of diameter 14 mm was used as an electrode. The negative polarity electrode was mounted vertically with a workpiece. Kerosene oil acts as dielectric fluid due to its greater flash point, better transparency of fluid, good dielectric strength, low specific gravity, and low viscosity.

Equipment Used

Machining of the developed MMC has been performed on ELEKTRA Pulse S-50 ZNC, die sinking EDM produced by Electronica Machine Tools Limited, Pune, as shown in Fig. (**1**). It has a maximum peak current of 50A and pulse duration of 4000µs. In the present research work, four process parameters, *i.e.*, I_p, V_g, T_{on} and τ, are used for the investigation of MRR and Ra. MRR was determined using Eq. (1). Digital weighing equipment with a precision of 0.01g is used to determine the weight of the workpiece. The workpiece is cleaned with a clean cloth and dried so that dielectric fluid and dirt are removed from the surface before weighing. The change in weight of the sample composite before EDM machining and after machining is the total material removed during the machining of workpiece. The MRR in g/min was calculated by dividing the change in material weight by the machining time [11].

CHAPTER 11

A Comprehensive Review on Application of Spark Discharge Method (SDM) for Production of Nanoparticles

Mudit K. Bhatnagar[1], **Siddharth Srivastava**[1], **Vansh Malik**[1], **Mamatha Theetha Gangadhar**[1] and **Mohit Vishnoi**[1,*]

[1] *Department of Mechanical Engineering, JSS Academy of Technical Education Noida, Uttar Pradesh, India*

Abstract: Nanoparticles encompass great potential in the current era due to their small size. They are employed in a myriad of applications, from biotechnology to manufacturing and energy applications. The production of nanoparticles, therefore, has been a focus of interest for researchers since its inception. Amongst non-conventional methods for nanoparticle production, Spark Discharge has emerged as an effective and viable method. This review encapsulates various experiments and works done over the years on the application of the spark discharge method for the production of nanoparticles and postulates the prospects of future work in the field. Different ways to control nanoparticle size by altering different parameters such as dielectric medium spark frequency, the gap between electrodes, and energy per spark and flow rate have been explored. Contrast has been drawn between conventional and non-conventional processes of nanoparticle production. In conclusion, new non-conventional techniques and hybrid techniques for nanoparticle production with spark discharge methods have been discussed, along with the applications of nanoparticles in emission control, cooling and lubrication.

Keywords: Energy Application, Ferro-fluids, Lubrication, Nanoparticles, Spark Discharge method.

INTRODUCTION

Nanoparticles are tiny particles of any metal oxide, alloy, semiconductor, composite, or Multi-Walled Carbon Nanotube of the order of 10-1000nm. They can also be defined as particulate dispersions. In addition, with their small size, they are employed in a wide array of applications due to their unique thermal and mechanical properties [1].

* **Corresponding author Mohit Vishnoi:** Department of Mechanical Engineering, JSS Academy of Technical Education Noida, Uttar Pradesh, India; E-mail: vishnoi.mohit06@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

In biomedical, they are used in the form of nano gel for cancer therapy [2]. In addition, new green methods to synthesize the nanoparticles were explored using living cells which irrefutably proved to be less toxic and hazardous [3, 4]. Metallic nanoparticles' ever-increasing popularity in the field of thermal and energy applications is attributed to their high conductivity and mechanical endurance, which could be explained by their high heat-carrying capacity used in automobiles and supercapacitors [5, 6]. Quantum dots, which are zero-dimensional nanoparticles, are extensively used in optoelectronics, hydrogen evolution, and energy applications [7]. Nanoparticles are also used in nanocomposites to form electrodes and membranes in supercapacitors and hydrogen fuel cells [8]. Pertaining to their vast use, the efficient production of nanoparticles is crucial. This review articulates the production of nanoparticles by Spark Discharge Method (SDM). In addition to the aforementioned applications, the review's focus would be on their efficient use in lubrication, cooling, and emission control.

Phenomena like lubrication, heat transfer, sealing, combustion, catalysis, and mass diffusion are key to a proper functioning mechanical or physical system [9, 10]. These are the properties that govern most of the machining process. The addition of NP is one of the easiest ways to enhance these properties, which would further contribute to a positive and more effective outcome [11, 12]. SDM is a top-down thermal method that breaks down larger clusters of solid particles in the form of smaller nanoparticles by the action of successive spark discharges. As no chemical process is involved, it was observed that SDM produced nanoparticles with enhanced efficiency and rate. It is similar to Laser Ablation, which is entirely environmentally friendly with no chemical precursors required and leaving zero waste products [13, 14].

NANOPARTICLE (NP) PRODUCTION THROUGH SDM

Experimental Apparatus

The Experimental setup varies from one material to another depending upon the properties required in NP and their method of quenching and flow rate of dielectric or inert gas.

The typical setup consists of four major parts (i) A magnetic stirrer along with a stirring bar; (ii) A dielectric medium of water or ethanol to form the gold nanoparticle suspension and to facilitate the dispersion of gold nanoparticles; (iii) A power supply to regulate a stable pulse voltage between electrodes to ionize the medium; (iv) The servo motor system to control the gap between electrodes.

As the name suggests, the energy liberated during Spark discharge is used for the production of NP. This is the same procedure the first time used by Svedberg [15] to produce colloidal suspensions; the electrodes of the required material are placed under a dielectric or inert gas medium with a particular spark gap to maintain a repetitive spark between the electrodes [16]. Plasma consisting of a spark reaches a temperature near 20,000˚K for a few seconds. This temperature is sufficient for the boiling and nucleating of droplets of metal. These tiny droplets further solidify into NP. The properties of metal depend upon the grain sizes that are directly influenced by the Quenching ability of the dielectric used. The dielectric medium/liquid used may be organic, aqueous, or cryogenic, depending upon the property of NP required.

In the working of SDM, various researches were conducted. Hallberg *et al.* used hydrogen assisted spark discharge method to produce metallic nanoparticles. The formed nanoparticles proved to be different from other nanoparticles as the nanoparticles formed through this method had a reduced tendency towards oxidation [17]. Controlling the composition of nanoparticles is still a concern for many researchers. Kohut *et al.*, in their paper, concluded that the tenability of nanoparticles was achievable through the use of SDM [18]. In the experimental papers by Sabzehparvar *et al.* [19], Sahu *et al.* [20], and Tseng *et al.* [21], it was observed that SDM could be used to achieve varied forms of nanoparticles such as super magnetic nickel oxide, aluminum NPs, and Nano-Ag colloid by varying the process conditions. These researches aided in forming a comprehensive path to understanding the effects of various process parameters (input parameters) on the formation of nanoparticles. These are explained in the following section.

Material Selection for NP Production

There is no definite restriction of Material in conducting or semiconducting metals and their alloys [22, 23]. Multiple kinds of research have already been done to produce NP using Spark Discharge Method (SDM); some of their results are given in Table **1**.

Table 1. Synthesis of NP of different Materials.

S. No.	Material Class	System	Notes	Reference
1.	**Metal**	W, Cu, Ag, Nb, Pd, Mg, Sb	Special precautions with regard to O_2 needed in the case of Mg	[24, 25]
		Au	For the 5nm range, go with ethanol	[1]

CHAPTER 12

Natural Fiber-Reinforced Polymer Composite: A Review

Satendra Singh[1,*] and **Pankaj Kumar Gupta**[1]

[1] *Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India*

Abstract: The manufacturing industry uses a variety of materials, including pure metals, alloys and composites. Due to the inability of pure metals to meet the demands of modern products, a transition in materials from pure metals to composites is taking place. Composite materials are invented to attain the desired properties, including lightweight, high strength, creep resistance, high corrosion resistance, fatigue resistance, high-temperature resistance and high wear resistance. Natural plant fibers, such as flax, hemp, kenaf, jute, sisal, coir and cotton, are a reliable source for producing composites because they have various advantages over synthetic fibers, including cheaper cost, low specific gravity, biodegradability, lightweight, fewer health hazards, availability, low-grade greenhouse emissions and high flexibility. Natural fiber-reinforced polymer composites (NF-RPC) are commonly utilized in automotive applications because they are lighter in weight, resulting in lower fuel consumption and greenhouse gas emissions. The mechanical properties of NF-RPC, such as tensile strength, Young's modulus, flexural strength, hardness and many others, are affected by several factors, for example, fiber aspect ratio, the weight percentage of fiber, different orientations of fiber, usage of the fabrication process, chemical compositions of fiber and different pre-treatments of fiber. Therefore, in this article, some specific applications, mechanical properties, fabrication techniques of NF-RPC, and methods to enhance the properties of natural fibers, have been discussed.

Keywords: Polymer matrix composites, Natural plant fibers classifications, Natural fiber reinforced composites.

INTRODUCTION

The term "composite material" refers to a substance that is made up of two or more chemically different constituents that result in unique properties of both individual constituents. The matrix and reinforcement are the two major constituents of composite materials. The matrix categories composite materials

* **Corresponding author Satendra Singh:** Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India; Email: singhid750@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

into three groupings, for example metal-matrix composites, ceramic-matrix composites and polymer-matrix composites.

Based on reinforcement, composite materials are also classified into three groupings, such as particulate-reinforced composite, structural-reinforced composite and fiber-reinforced composite [1 - 4]. A pure polymer frequently lacks the mechanical strength needed for use in a variety of applications. The load-carrying component of these materials is fibers, which offer rigidity and strength, whereas polymer matrices keep the fibers aligned (position and orientation). They also shield them from the environment and other potential harm. There are numerous types of natural fibers and synthetic fibers as per their source of origin, as shown in Fig (**1**) [5 - 7]. Natural fibers were first used 3000 years ago in antique Egypt in composite approaches, wherein clay and straw were mixed to make walls. Polymer matrix materials reinforced through natural plant fibers have acquired a lot of curiosity in the past decade, from many companies and universities [8]. Moreover, natural plant fibers are used because of several desirable factors, such as low cost, biodegradability, lightweight, fewer health risks, availability, low-grade carbon emissions and great adaptability. As a result, when compared to synthetic fiber-reinforced polymer composites and metal alloys, NF-RPC is in high demand [9, 10]. NF-RPC is thus used in a variety of engineering fields, for example, aerospace, marine construction, vehicles, sports, transportation, biomedical, packaging and structural applications [11 - 13]. Natural plant fibers, on the other hand, have several disadvantages, such as low thermal stability, non-water resistance, seasonal quality changes, aggregate formation tendency during processing, and many more. Therefore, an appropriate extraction technique, physical pre-treatment, alkaline pre-treatment and chemical pre-treatment are necessary to improve fiber quality and compatibility with the matrix, which further enhances the mechanical, physical and thermal properties of NF-RPC [14 - 17]. NF-RPC is typically made *via* hand lay-up techniques, resin transfer molding (RTM), injection molding, extrusion and compression molding [18].

There are some natural plant fibers, for example, flax, pineapple, jute, hemp, coir (coconut) and kenaf, that can be obtained from their source of origin, as shown in Fig (**2**).

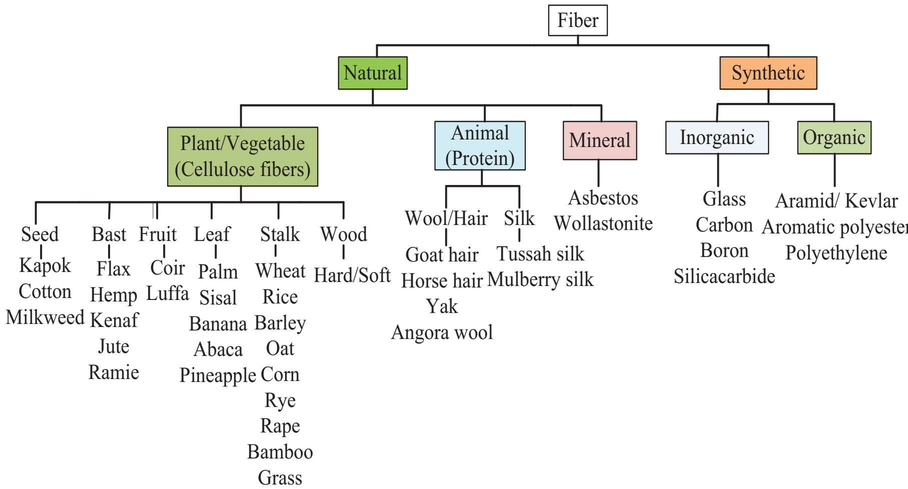

Fig. (1). Classification of fiber [5, 7].

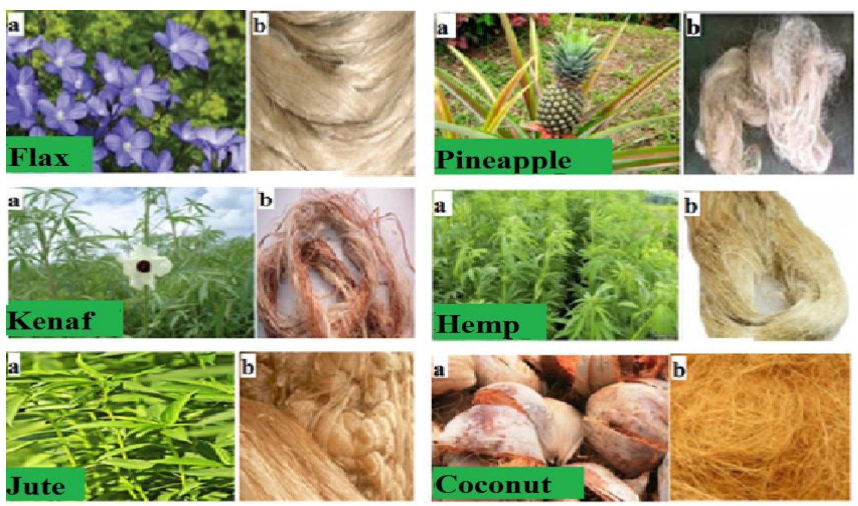

Fig. (2). Some natural plant fibers with their source of origin **(a)** Plant **(b)** Fiber [9 - 11, 16].

NATURAL FIBER-REINFORCED POLYMER COMPOSITE

In modern times, all research focuses on sustainability. As to environmental concerns and the limited amount of conventional resources of energy, there is a need to use non-conventional resources of energy for sustainable development. So, there is a replacement of synthetic fibers, for example, carbon, glass and kevlar, with natural fibers, for example, hemp, flax, jute, sisal, kenaf, wheat and rice, as reinforcement in composites [19 - 21]. The different types of polymer matrix materials are used with natural plant fibers to fabricate the NF-RPC, as shown in Fig (**3**).

CHAPTER 13

Analysis of Pineapple Leaf Fiber Reinforced Composite Vehicle Bumper with Varying Fiber Volume Fraction

Abhishek Pothina[1] and **Saroj Kumar Sarangi**[1,*]

[1] *Department of Mechanical Engineering, National Institute of Technology Patna, India*

Abstract: This paper presents the analysis of the Pineapple Leaf Fiber (PALF) reinforced composite used as a material for car bumpers. Impact analysis is performed on the modeled front car bumper at different fiber content, *i.e.,* at the difference in the value of the fiber volume fraction, and the results are discussed. The objective is to model a car's rear bumper with considered dimensions, and analyze it by simulating in the circumstances of a crash, *i.e.,* the impact is simulated against a rigid body at speed as per the standards of the vehicle. The natural fiber reinforced composite, which has good specific weight compared to synthetic fiber, results in a reduction in the weight of the whole body, resulting in less weight-to-volume ratio, when compared to the use of synthetic fibers and, therefore, can be considered as a material for car front bumper. There may certainly be a difference in performance, but depending on the required applications, the fiber-matrix bonding, and the aspect ratio can be varied. For PALF, the compensation for the low value of modulus can be done by having a very high aspect ratio, as the composite modulus is influenced by both young's modulus and aspect ratio. In PALF reinforced Composites, the variation of fiber content affects the performance of the composites with less increase in overall weight compared to that of synthetic fibers.

Keywords: Fiber reinforced composite, Natural fiber, Pineapple leaf fiber.

INTRODUCTION

In recent times, fiber-reinforced composites have been used for car bumpers, as they have lightweight, and the conventional aluminum and steel prices are increasing. As the bumper was meant to be lightweight, and should be able to reduce the damage caused to car parts, natural fiber reinforced composites are also being considered as having a few advantages over synthetic fiber like high aspect

* **Corresponding author Saroj Kumar Sarangi:** Department of Mechanical Engineering, National Institute of Technology Patna, India; E-mail: sarojksarangi@yahoo.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

ratio, environmental friendly, and easier attainability. In this simulation, we consider pineapple leaf natural fiber, as it possesses a better aspect ratio than other natural fibers. The matrix considered are polymer matrices, as we will perform the analysis using the same fiber, but with different matrix materials and fiber content to get an optimal result for the specific function of the car bumper.

Car bumper

In an Automotive Vehicle, the bumper is not employed for crashworthiness or occupant protection in a period or cumulative of collisions, but are primarily concentrated on the energy absorption, providing comfort to both passengers and also for the vehicle. For this provision, certain standards are to be followed by the bumper and its arrangements, such as range of clearance and load withstanding competency with regard to speed.

The clearance between the surfaces of the road to that of the bumper normally ranges between 16 inches to 20 inches, and also, the bumper has to, under duress, endure the vehicle speeds of 2mph, 1 mph and 5mph from corner to corner, full width and parked environment crashes correspondingly. In accidents at low speeds, the bumper is one of the methods of protection, which is a place in the rear, *i.e.*, backside and also the front of the automobile body. As these bumpers are designed so as to, in the case of impact of a car, absorb the energy of the said impact.It has been designed with considered materials and shape, such that the above can be achieved with minimum cost. It is to be noted that the bumpers generally are not designed to avoid fracture at high speeds, but at minimum or standard speed, which ranges from 30 kmps to 50 kmps. So, at low speeds, it can prevent injury to passengers and protect other components of the automobile, such as the trunk, exhaust, fuel tank, hood, cooling systems, grille, *etc.* When the vehicle is struck from the front end, most of the energy is absorbed by the front bumper, at low speeds, which leads to the deformation of the bumper, but no energy will be shifted to the passengers of the vehicle, as the impact speed of the vehicle is very low. The same cannot be said in the case of high speeds, as the impact due to the collision of the vehicle may or will cause injury to the occupants and also impose damage to the vehicle. The widest part of the vehicle, which is 100% of the width, is considered to overlap the front impact of the vehicle. The standards of the bumper are given by the National highway traffic safety administration (NHTSA) for the light passenger vehicle. These standards are applicable to the performance requirements for passenger vehicles at low speeds for front and rear accidents.

In recent days, there has been numerous attempt to alter the design and material of the bumper for the improvement in safety, performance of car and expand the aerodynamics of the vehicle. Hence the research for this enhancement is still on going by groups of scientists and researchers.

Manufacturing Method

The process of integration of fibers into the matrix for the fiber-reinforced polymer matrix composite or polymer matrix composite (PMC) is done mainly of two methods; first one being that the fibers and matrix are treated directly into the finished product and the second method makes use of prepeg, which are made in form of sheets by incorporating fibers into the matrix and then stored to be used later to form a laminate structure by methods such as autoclave moulding, compression moulding *etc.*

The thermosetting matrix composite, as being used in this analysis, which is epoxy matrix composite, can be made by different methods such as filament winding, pultrusion, hand layup, spray layup, resin transfer moulding and autoclave moulding. The method that is generally recommended and practiced widely for the fabrication of the required PALF-reinforced PMC for this analysis is the hand layup (HLU) technique.

In the HLU (Fig. **1**) a gel coat is applied on the open mold, followed by application of fiber reinforcement, upon which base resin, which is mixed with catalyst, is applied by pouring and brushing. The layup is built by applying layer upon layer until the desired thickness is obtained.

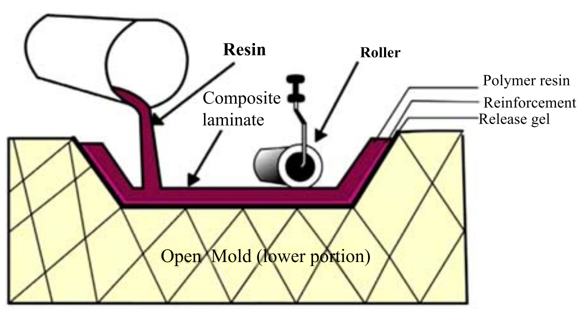

Fig. (1). Hand layup process.

Literature Review

In this section, various research papers related to the characteristics of natural fiber and their composites, along with the design and analysis of car bumpers, are discussed. These are considered the basis for developing the present work.

CHAPTER 14

Experimental studies on Mechanical characteristics of Bamboo Leaf Ash reinforcement with Aluminum 7075 alloy using Rotary Stir Casting Technique

Murahari Kolli[1,*], **Dasari Sai Naresh**[2] and **K. Ravi Prakash Babu**[3]

[1] *Lakireddy Bali Reddy College of Engineering, Mylavaram, Krishna District, Andhra Pradesh, India*

[2] *R&D Mechatronics, Design and Engineering, VEM Technologies PVT Ltd, Hyderabad, Telangana, 502321, India*

[3] *Department of Mechanical Engineering, Prasad V Potluri Siddhartha Institute of Technology, Kanuru, Andhra Pradesh, India*

Abstract: Aluminium metal matrix composites are an exclusive class of materials that have improved performance parameters than their pure metal-based counterparts. These composites are widely used in structural, marine, aviation, defense and mining industries. Numerous synthetically derived hard ceramic reinforcements were widely researched for property enhancement of Aluminum Metal Matrix Composites, but, the exclusivity and the economic concerns of the synthetic reinforcements paved the way for widespread studies of agro-waste-based and industrial waste based Aluminum Metal Matrix Composites. In the current study, Bamboo Leaf Ash, an agro waste derived ceramic reinforcement based Aluminum Metal Matrix Composite; Al 7075/Bamboo Leaf Ash is fabricated using the Liquid Metallurgy Stir Casting technique with varying volume percentages from 2% to 8% of reinforcements in the matrix by weight. Mechanical and Microstructural characterization of the metal matrix composite is performed to ascertain the degree of improvement in properties of the composite compared to the base metal. The results from the study confirmed that a sound composite with higher hardness and strength was obtained. The microstructural characterization also confirmed that the grain structure is significantly refined, leading to property enhancement.

Keywords: Al 7075, Aluminium Metal Matrix Composites, Agro waste, Bamboo Leaf Ash, Rotary Stir Casting.

* **Corresponding author Murahari Kolli:** Lakireddy Bali Reddy College of Engineering, Mylavaram, Krishna District, Andhra Pradesh, India; E-mail: kmhari.nitw@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

INTRODUCTION

Nowadays, the manufacturing scenario is changing in the usage of conventional materials as they have been replaced by advanced materials. Metal Matrix Composites (MMCs) are one such advanced materials that are playing a prominent role in the manufacturing sector due to their properties like high specific strength, lightweight, specific stiffness, wear resistance, corrosion resistance and elastic modulus, mostly applicable for aerospace, automobile, marine, mining and mechanical structures [1]. Metal matrix composites (MMC's) are metals and alloys combined with other materials that ultimately result in performance enhancement of the metal/alloy. Ever since their inception, copper, aluminium and magnesium-based MMC's were significantly researched [2]. In particular, Al-based MMC's can be broadly categorized as synthetic ceramic derivatives, agro-waste derivatives and industrial waste derivatives [3]. Aluminium based MMC's were manufactured with many synthetic ceramic reinforcements due to their strength and desirable properties, such as Silicon Nitride (Si_3N_4), Alumina (Al_2O_3), AluminiumTitanate (Al_2TiO_5), Zirconia (ZrO_2), Aluminium Nitride (AlN), Boron Carbide (B_4C), Silicon Dioxide (SiO_2), etc. due to their strength and desirable properties [4]. Expensiveness and inadequate availability of conventional ceramic reinforcements in many developing countries prompted a compulsory paradigm shift in the choice of selection for reinforcement particles [5]. Hence, the usage of agro-waste and industrial waste-derived MMC's has gained prominence in the recent past because such reinforcements mitigated the expensiveness of the reinforcements and were able to achieve properties on par with ceramic composites [6]. There have been numerous reports on Aluminium Industrial waste agro waste derived MMC's.

Balasubramani *et al.* investigated the mechanical properties of Al 7075/B4C/coconut shell fly ash composites fabricated through the friction stir processing technique. It was observed from the results maximum tensile strength was indicated for 9% B4C and 3% CSFA in the matrix material. The hardness values are also enhanced with the reinforcement particles being added to the matrix [7]. Bhasha and Balamurugan examined the Al 6061 hybrid composites reinforced by nanoTiC/Rise husk ash using an *ex-situ* process *via* ultrasonic probe sonicator stir casting. Microhardness, tensile, and flexural strength were considered as testing results of the composite. When 3-6% of TiC was added with 3% of RHA, a better result of the composite was found; further, increasing the addition of 6-9% TIC with 3% of RHA gave results with lower values because of the agglomerations and clusters formed on the composite [8]. Gireesh *et al.*, attempted to use aloe vera particles as reinforcement into the aluminum matrix to examine the mechanical properties of the composites. They concluded that the addition of aloe vera particles in the Al matrix significantly improved the tensile strength, impact strength, and hardness compared with the base and Al/FA composites [9]. Joseph and Babaremu studied different kinds of literature and identified the various agricultural wastes being added as reinforcement particles addition into aluminum matrix materials to enhance the mechanical properties of the composites. Some of the wastes include reinforcement materials like groundnut shells, coconut shells, rice husk, breadfruit seed ash, aloe vera, bean pod ash, cow horn, and so on [10].

Jose *et al.*, investigated the mechanical characterization of Al 6061 alloy by adding lemon grass ash as reinforcing particles in the MMC by compocasting. The results showed that tensile strength and microhardness values increase linearly because the adequate diffusion of LGA reinforcement particles hindered the movement of dislocations in the MMC [11]. Manikandan and Arjunan fabricated Al 7075 hybrid metal matrix composites with agro-waste, cow dung ash, and boron carbide particles as reinforcement in the matrix, and a two-stage stir casting method was also adopted in their study. The influence of reinforcement particles of the composites was examined for mechanical, microstructural and tribological properties. It was concluded that adding two or more reinforcements in the aluminum matrix enhanced the properties compared to single-reinforcement composite materials [12].

Kumar and Birru investigated the effect of BLA reinforcement on Al material by fabricating the composite using the stir casting method. Hardness and tensile strength properties were considered as measuring characteristics of the composite when the addition of BLA reinforcement's particles from 2% to 8% to the matrix material. They concluded that 2% to 4% of reinforcement added to material increase the hardness and tensile properties [13, 14]. Alanemeand andAdewuyi studied the mechanical properties of Aluminium magnesium silicon alloy composites filled with Al2O3 as well as BLA reinforcements. Particulates of Al_2O_3 compounded by 0%, 2%, 3%, and 4% wt BLA were added to fabricate 10 wt.% of reinforcement in the matrix material and adapted the dual stir casting technique. Tensile strength, yield strength, and elongation, hardness tests were examined in their study [15]. Singh *et al.* examined the mechanical properties of Al 6063 composites filled with groundnut shell ash using the liquid metallurgy technique. The result indicated increases in the tensile strength and compressive strength with groundnut shell ash added to Al 6063 material [16].

Many such instances are available in the literature. It was also notified in the literature that although numerous techniques are available for manufacturing MMC's and HMMC's, stir casting has always been a vastly economical and well-established process. Also, the structural properties of the composites prepared through the stir casting route were superior to composites prepared through other

CHAPTER 15

Experimental Investigation on the Joint Efficiency of Grit Blasted and Silica Particle Coated Adhesively Bonded Carbon and Glass Fibre Reinforced Polymer Composite Laminates

Mohammed Yusuf A. Yadwad[1,*], **Vishwas G.**[1] and **N. Rajesh Mathivanan**[1]

[1] *Department of Mechanical Engineering, PES University Bangalore-560085, India*

Abstract: Composite material is formed when one or more material is distributed or reinforced in a continuous second phase called a matrix. Composites have many superior properties, including low density, high strength-to-weight ratio, and good durability, which make them attractive in many industries. Composite materials have been used extensively in various applications. In any application where the strength-t--weight ratio plays a vital and important role, Fibre Re-inforced Polymer's (FRP) is the best material and offers the most efficient solution. Adhesive bonding is one of the most powerful joining techniques for FRP's because of its high mechanical properties. It has applications in all the fields like aerospace, marine technology, defence systems, and automotive industries, as well as structural applications and sports. However, the mechanical performance is biased undesirably by contaminants, like release agents, and also an excess of matrix in the top layer. In order to generate the most appropriate surface pre-treatment, their effect on adhesively bonded joints of carbon and glass fibre re-inforced polymer composite laminates have been investigated. The adhesively bonded surfaces are treated with grit blasting and silica particle coating and later tested in order to determine the failure modes. It was found that the mechanical properties of adhesively bonded joints depend on the surface characteristics of the substrate. The results indicate that it is possible to increase the bond strength of the joints to maximum by various surface treatments.

Keywords: Adhesive bonding, Carbon fibre re-inforced polymer, Grit blasting, Glass fibre re-inforced polymer, Surface treatment, Silica particle coating.

INTRODUCTION

Fibre re-inforced polymer composite laminates can be used to get net-shaped manufactured parts. However, there is a challenge in getting parts produced by

* **Corresponding author Mohammed Yusuf A. Yadwad:** Department of Mechanical Engineering PES University Bangalore-560085, INDIA; E-mail: mdyusufyadwad@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

net-shape manufacturing, thereby it leads to products produced near net-shape manufacturing. Secondary manufacturing processes are inevitable to parts produced using FRP composite laminates. Machining and joining are some of the commonly performed secondary operations on composite laminates [1].

The annual demand for Carbon and Glass Fibre Reinforced Polymer (CFRP/GFRP) composite laminates has been steadily increasing, essentially in aircraft, defence, marine technology, sports goods, *etc*. and many other engineering applications. The automotive sector has made the proper utilization of composite laminate adhesive bonding hence the demand for the light weight. It has the application in automobiles like interior panels made up of aluminium frame; another example is they are used in the oil and gas industry where every single weight adds up to the platform, resulting in the outcome of the fuel and cost of the oil that has pumped and stored. The adhesive bonding is feasible for both the movement of the platform and the actual of the crude oil and hydrocarbon at very high temperatures. Hence, the adhesive joining of composite materials is very widely searching its place into many new things which exits the old methods by conventional fastening. Composites are retained to reduce the weight of the products and improve the aesthetic and environmental resistance, which permits the improved structure and strong design to weight criteria [2 - 4].

Adhesive bonding plays a vital role in joining composite laminates. Adhesive bonding is a material joining process in which an adhesive is placed between the adherend and surfaces, and solidifies to produce an adhesive bond. Recently, adhesively bonded joints have overtaken mechanical joints, such as mechanical fasteners, the conventional fasteners often result in the cutting of fibres which will give rise to stress concentration by reducing the structural integrity [5, 6]. Particularly with regard to composite in fields of engineering application by considering the advantages like higher strength-to-weight ratio, low cost of fabrication and higher damage tolerance. Four step bonding procedure proposed by Kyungtae Kim *et al.* enhanced greater damage protection as well as the accessibility of application to the conventional method [7].

Adhesives are used for bonding a wide variety of comparable and different metallic and non- metallic materials, composites, and apparatuses with various shape, size, and thickness. The merits of bonding with adhesive over conventional joining or bonding like mechanical closure, which is fastening, is now acknowledged. Specific adhesives deliver greater design flexibility, allocate load over a larger area hence decreasing the stress concentration as well as improving the fatigue and corrosion resistance of the bonded joints. The adhesive selection is preferred bond material for the given application. There is a need to choose the proper adhesive because various adhesives are available, and all the properties of adhesives match themselves. So, the selection requires knowledge properties of selected adhesives and where the adhesive is being utilised. The assortment of adhesive process is very problematic because no adhesives are used as a universal adhesive for all the methods and the selection of the adhesives are very complex manner because there are a number of adhesives available in the market. However, the selection of an adhesive is the main factor, such as the nature and type of the adherend surface to be joined and curing the adhesive for the application of expected manner and adhesive related to the environment. Hence the price of adhesive is a very important criterion for the selection in the situation of production [8].

The joining surface plays a dominant role in the process of adhesive bonding, which influences the quality of an adhesive joint. The pertinent surface pre-treatment can often confer additional properties to the surface of the bond. Davis et at. [9, 10] strongly insists to have surface pre-treatment prior to the application of adhesives is recommended to achieve maximum mechanical strength. The appropriate surface pre-treatment has a direct influence on the strength of the bond. Composite laminates usually suffer a cohesive kind of failure, perhaps the failure is largely associated with the surface preparation of bonded joints. The challenge in using adhesive for carbon fibre reinforced polymer bonded joints is because of the presence of a thick polymer layer of 2-10μm on the top of the surface of the laminates [11].

Based on the loading conditions such as shear and peel strength, the toughness of the material, ductile and fragile behaviour as well as high fatigue cycles, creep, strength-to-weight ratio and stiffness to weight ratio and wetting properties of the surface of the bond and environmental degradation and resistance, the strength of the adhesive bond strongly depends upon the type of the adhesive. The increased utilization of the resin matrix reinforcement for the composite material is very necessary to develop a feasible system of adhesive. The epoxy adhesive that is usually used for the composite matrix is applied for the bonding of composites based on the adhesives and due to the mixing of resin and adhesive [12].

Surface pre-treatment is followed by the important and crucial step in the adhesive joining process; proper adhesive bond testing is performed to improvise the surface pre-treatment. Choosing surfaces to be pre-treated mainly depends on the desired durability and strength of the bond, even if taking economy like time as well as the cost involved in the preparation, which plays an important role selection. Perfect pre-treatment is very necessary for better strength of the joint and maintaining the ever-lasting integrity of the structural joints bonded. Poor pre-treated surface results in the adhesive joint failure of the bond, which will occur in the adhesive and substrate interface. Surface pre-treatment is followed to

CHAPTER 16

Colossal Dielectric Properties Of $(Ta_{0.1}Sm_{0.9})_{0.04}Ti_{0.96}O_2$/PVDF Composites For Energy Storage Applications

Dileep Chekkaramkodi[1,*], **Muhammed Hunize Chuttam Veettil**[1] and **Murali Kodakkattu Purushothaman**[1]

[1] *Department of Mechanical Engineering, National Institute of Technology Calicut, Calicut-673601, India*

Abstract: In this study, $(Ta_{0.1}Sm_{0.9})_{0.04}Ti_{0.96}O_2$/Polyvinylidene fluoride composites were synthesized and analyzed for colossal dielectric properties. The ceramic powder was prepared by solid-state ceramic route, confirmed its phase purity through an X-ray diffractometer, and composites with different volume fractions were synthesized by finely dispersing the filler in the Polyvinylidene fluoride (PVDF) matrix followed by compression molding. Dielectric properties (dielectric constant and loss) up to 1 MHz were studied using an impedance analyzer. A high dielectric constant of 45 along with an acceptable loss of 0.089 was obtained for an optimum filler volume of 50% at 1 kHz. Hence the composites can be effectively used for energy storage applications.

Keywords: Ceramics, Colossal permittivity, Dielectrics, PVDF, Impedance analyzer.

INTRODUCTION

Polymers having excellent dielectric performance are used in various fields such as electrical engineering, microelectronics, high energy density storage, etc [1]. In electronic circuits, polymer dielectric materials are suitable owing to their mechanical flexibility, easiness of processing and low cost. However, for applications requiring good dielectric permittivity (ε') and low loss ($\tan\delta$), polymer materials are not desired, as it has a very low dielectric constant compared to ceramic materials. However, ceramic materials have drawbacks of difficulty in fabrication into larger size and brittle nature. Ceramic/polymer composites can surmount these disadvantages and are generally used for these purposes.

* **Corresponding author Dileep Chekkaramkodi:** Department of Mechanical Engineering PES University Bangalore-560085, India; E-mail: mdyusufyadwad@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

$CaCu_3Ti_3O_{12}$(CCTO) and its derivatives are non-ferroelectric oxide ceramics exhibiting good dielectric permittivity in the range of 10^4-10^6 [2]. Hence, they are widely used to enhance the dielectric performance of various polymer materials. However, they possess comparatively a high dielectric loss (> 0.1). Co-doped TiO_2 ceramics are other groups of dielectric materials that show good dielectric permittivity and low loss [3 - 6]. Compared to the CCTO family, the high activation energy of the co-doped TiO_2 is responsible for this low dielectric loss [7].

Recently, various elements have been co-doped in TiO_2 for tuning its dielectric properties. Among these, Ta and Sm co-doped TiO_2 show good dielectric properties [8]. TiO_2 shows a dielectric constant of 140 at 1 kHz. Co-doping of Ta would increase the dielectric constant and loss, whereas the presence of Sm reduces the dielectric loss. In this family, ($(Ta_{0.1}Sm_{0.9})_{0.04}Ti_{0.96}O_2$) is a promising ceramic material, which is having ε′ of 703.71 and tanδ of 0.08 at 1 kHz at room temperature. In this study, to exploit the advantages of a heterogeneous system, a ceramic/polymer composite of Ta and Sm co-doped TiO_2 (TSTO)/PVDF has been developed. TSTO powders prepared in two different particle sizes have been used as filler material to study the effect on packing density, water absorption, and dielectric properties of the composite material.

Experimental Part

Preparation of TSTO

TSTO ceramic powder was prepared via conventional solid-state reaction using TiO_2 (99.9% purity, Merk), Ta2O5 (99.98% purity, Sigma Aldrich) and Sm2O3 (99.9% purity, Sigma Aldrich). The raw materials were weighed according to stoichiometric ratio and mixed for an hour using agate mortar in de-ionized water medium to ensure uniform mixing. It was oven dried to remove water content. The powder thus obtained was calcined at 1100ºC for 2 hours. Then the obtained powder was checked for its phase purity and carefully ground. Half of the powder thus prepared was ball-milled using 3mm diameter zirconia balls for 12h at 250 rpm to reduce particle size. Ball: powder ratio was 8:1.

Preparation of Polymer/Matrix Composites (PMCs)

TSTO powders with two different particle sizes were used as the filler materials. PVDF polymer (Alfa Aesar) was chosen as a polymer matrix. Finely dispersed TSTO in the PVDF matrix was prepared at various filler fraction (fTSTO = 0.1 to 0.5) by ball milling in an ethanol medium for 2h. Then the mixture was heated to evaporate ethanol to form a composite powder. Polymer composite samples were prepared by hot pressing the composite powder at 220 °C for 20 min, at a pressure of 10 MPa, in a cylindrical mould of 10 mm size.

Characterization

An X-ray diffractometer (Panalytical, Aeris) was employed to analyse the crystal structure and phase purity of the TSTO powder. A particle size analyser (Malvern Panalytical's master sizer 3000) was used to analyse the size and distribution of the fillers. Scanning electron microscopy (SEM) (Jeol 6390LA/OXFORD XMXN) was used to examine microstructure of the composite. Moisture absorption characteristics were studied as per the standard IPC-TM-650 2.6.2.1 method.

Dielectric Measurement

The composite samples were polished and silver coated for dielectric measurements. Impedance analyser (Agilent 4294A) was used to measure the capacitance and dissipation factor of the filler and composite using a parallel capacitance technique in the frequency range of 40 Hz to 1MHz at a 500mv oscillation voltage.

RESULTS AND DISCUSSIONS

Particle size analysis curves of the powders before (PA) and after (PB) ball milling are shown in Fig. (**1**). Before ball milling, the average particle size and specific surface area of the powder have been found at 5.15µm and1759 m^2/kg respectively, whereas after ball milling specific surface area has been increased to 10280 m^2/kg and average particle size reduced to 1.06µm.

The XRD pattern of PA and PB powders is illustrated in Fig. (**2**), which matches standard JCPDS pattern 21-1276 and clearly indicates the phase purity of the synthesized TSTO ceramic fillers. Compared to PA powder, the peak intensity of PB powder is found to be less. It is attributed to internal stress resulting from the lattice defects due to the ball milling. During the milling time, this lattice stress decreases the crystallinity of the material and the intensity of peaks gets reduced. The morphologies of PA and PB filler materials observed using SEM images are depicted in the inset (1) and (2), respectively.

CHAPTER 17

Modelling the Effects of Carbon Nanotube (CNT) and Interphase Parameters on Mechanical Properties of CNT-Reinforced Nanocomposites

Saurabh Mishra[1], **Surendra Kumar**[1,*] and **Amit Kumar**[1]

[1] *CSIR-Central Mechanical Engineering Research Institute, Durgapur-713209, India*

Abstract: CNT-reinforced polymer nanocomposites are emerging as a pioneer material for structural applications because of their enhanced mechanical properties as compared with neat polymers. The load transfer mechanisms and effective mechanical properties of these nanocomposites are strongly influenced by CNT parameters (volume fraction, length, aspect ratio, etc.), and thickness and mechanical properties of the interfacial region between the embedded CNT and the matrix. In this paper, modelling studies have been carried out to analyze the effects of these parameters on the effective elastic properties of a polymethyl methacrylate matrix embedded with single-walled CNTs. A three-phase continuum mechanics-based 3-D model of the nanocomposite is analyzed using the finite element method to predict the effect of an interphase on the elastic properties (elastic modulus and Poisson's ratio) of the nanocomposite in longitudinal and transverse directions. The effect of the interphase having a varied modulus (ranging from that of CNT to that of matrix) through its thickness is also investigated. The Mori-Tanaka homogenization method is also applied to the three-phase and multi-phase micromechanical models to determine its feasibility in estimating the influence of the interphase on the elastic properties of the nanocomposite.

Keywords: Carbon nanotube (CNT), Finite element analysis, Interphase, Mori-Tanaka method, Nanocomposite.

INTRODUCTION

Nanostructured composites have garnered major research interest for structural applications in recent years because of their unprecedented mechanical properties. Carbon nanotubes (CNTs) are perhaps the most favourable and extensively used nanofillers possessing high elastic modulus, multi-functionality, physical characteristics, and other mechanical properties [1]. In general, different theor-

* **Corresponding author Surendra Kumar:** CSIR-Central Mechanical Engineering Research Institute, Durgapur-713209, India; E-mail: surend_kr@yahoo.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

etical and experimental studies have indicated that the insertion of CNTs into the polymers has effectively improved the elastic properties of nanocomposites [2 - 4]. However, theoretical predictions have some discrepancies with experimental results. These discrepancies are attributed to the following reasons: (1) Poor dispersion and aggregation of CNTs into bundles, (2) Misaligned and entangled CNTs, and (3) Insufficient knowledge of interfacial characteristics. Out of these concerns, the properties of interphase are an influential issue and need to be addressed properly in order to obtain optimistic effective properties of polymers embedded with CNTs [5]. The effect of surface to volume ratio of nanotubes in poly(vinyl alcohol) was experimentally studied by Cadek *et al*. [6]. Their findings revealed maximized surface area for small diameter multi-walled nanotubes compared to single walled nanotubes, resulting in more crystallinity of polymer on the nanotube surface. Namilae and Chandra [7] investigated the role of interface on the elastic properties of nanocomposites using a hierarchical multi-scale model comprising molecular dynamics (MD) simulation and finite element simulation. It was reported that chemical functionalization has effects on the interfacial strength, and the higher the attachments more will be the interfacial strength. Montazeri and Naghdabadi [8] used a multi-scale model comprising molecular mechanics and finite element method (FEM) to investigate the effect of interphase on (10,10) SWCNTs reinforced polymethyl methacrylate (PMMA) polymer composite. A comparative study revealed a 1.8% reduction in effective young's modulus obtained from the three phases representative volume element (RVE) model as compared to MD simulations and found it a more reliable model. Arash *et al*. [9] estimated the elastic properties of interphase by examining the fracture behaviour of CNT/PMMA composites. The study revealed that interfacial bonding relies on the aspect ratio of CNTs, and that by increasing the aspect ratio, the properties of the interface were significantly improved. Amraei *et al*. [10] developed a closed-form model to compute transverse isotropic elastic properties and thickness of interfacial region between polymer matrix and CNTs. MD simulations performed on cylindrical RVE for different SWCNTs revealed the dependency of the thickness of interphase on the diameter of CNTs. Malekimoghadam and Icardi [11] examined a multi-scale hybrid model comprising CNTs, carbon fiber, interphase and matrix. They discovered that adding a small amount of CNTs into the matrix (about 2 wt%) reduced the interfacial radial stress, which is responsible for debonding. It was also reported that non-bonded interphase merely affected the interfacial properties of hybrid composites, but no impact was observed on Young's moduli. Studies using continuum mechanics have obtained some observations in the context of the interface in the CNT-reinforced composites but are sporadic in nature. In order to bridge the gap between the analytical model and atomic level analysis, Guru *et al*. [12] parametrically studied the effect of the interphase with MD simulation in conjunction with FEM and reported variation in longitudinal elastic modulus of a composite at different thicknesses and stiffnesses of the interphase. However, the stiffness of the interphase was kept constant through its thickness.

In order to further reduce ambiguity in terms of different CNT and interphase parameters, this paper presents a detailed study of SWCNT-reinforced PMMA polymer composite with and without interphase. Continuum -based finite element (FE) models of two-phase and three-phase RVEs are developed, and parametric analyses are done to investigate the influence of CNT at different volume fractions and aspect ratio. Also, the effects of interfacial properties, such as thickness and stiffness, on the elastic properties of the nanocomposite have been studied comprehensively. The novelty of this paper is reflected in the study of the effect of interphase having a varied modulus (ranging from that of CNT to that of the polymer) through its thickness. This study is also aimed at providing a comparative analytical model to validate the results obtained from the FE analysis. Accordingly, the Mori-Tanaka homogenization method is applied to three-phase and multi-phase micromechanics models for estimating the effects of interphase parameters on the properties of the nanocomposite, and the predicted results are verified with those obtained by FE modelling.

MODELLING AND COMPUTATIONAL METHODOLOGY

Finite Element Modelling of RVE

3-D FE modelling is undertaken for the RVE of a nanocomposite of CNTs embedded in a homogeneous isotropic polymer matrix. The modelling is performed for the two-phase as well as the three-phase composites. The RVE of square cross-section has been chosen in such a way that the assumed CNT and interphase are densely packed inside the surrounding matrix, and computational efforts are minimized. The analyses of RVEs give the same elastic properties as those of the composites while also reducing the efforts required in the time-consuming analyses of complex nanostructures. The material system taken is (10,10) SWCNT embedded in a poly methyl methacrylate (PMMA) polymer matrix. Since, end caps of CNT do not contribute to the effective elastic properties of RVE, and they are discarded from the FE models. The diametral dimension of CNT is calculated from its chiral vectors. In order to obtain dimensions of the square RVE, a basic approach of volume fractions is applied. Both long and short CNTs are considered. The type of reinforcement in which a CNT spans the full length of the RVE is termed a long CNT, while if the CNT lies inside the RVE, it is denoted as a short CNT. Fig. (**1**) illustrates the RVEs having fully-embedded long and short CNTs inside the polymer matrix.

CHAPTER 18

Vibration and Deflection Analysis of Quadrilateral Sandwich Plate with Functionally Graded Core

Shivnandan Bind[1], **Manish Kumar**[1] and **Saroj Kumar Sarangi**[1,*]

[1] *Mechanical Engineering Department, National Institute of Technology Patna, India*

Abstract: This chapter presents the analysis of the vibration and deflection of a quadrilateral sandwich plate with a functionally graded core for different temperature conditions. The plate is made of functionally graded carbon nanotube-reinforced composite (FG-CNTRC), and results are obtained with the help of ANSYS software. The uniform distribution (UD), functionally grading V type distribution (FG-V), functionally grading X type distribution, and functionally grading O type distribution are the four different distributions of the reinforcements grading that are taken into consideration as a core in the direction of thickness (FG-O). The uniformly distributed grading is applied to the face plate for all the cases. Young's modulus, mass density, and Poisson's ratio are all important material properties calculated by the extended rule of mixture with the CNT efficiency parameter, accounting for size dependence. Detailed analysis is done in this paper to reveal the effect of volume fraction and temperature on the natural frequency and central deflection of the quadrilateral sandwich plate, and compared it with the results of a normal quadrilateral plate. Numerical results are obtained and presented using Ansys R17.2 and MATLAB. The results suggested that UD-type grading has the highest natural frequency and lowest central deflection compared to other types of functionally grading material.

Keywords: CNT reinforcement, Functionally graded core, Sandwich plate, Volume fraction.

INTRODUCTION

Carbon nanotubes (CNTs) were discovered by Iijima in 1991 [1]; from then to now, much research have been conducted on carbon nanotubes. The carbon nanotubes possess superior characteristics like high mechanical strength as compared to regular steel and elastic modulus as well as excellent thermal and electrical conductivities [2]. In a recent development, researchers are combining

* **Corresponding author Saroj Kumar Sarangi:** Department of Mechanical Engineering, National Institute of Technology Patna, India; E-mail: sarojksarangi@yahoo.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

their research of carbon nanotubes by grading them functionally to form multiphase composites with smooth property variations along the thickness [3]. In functionally grading, there are mainly three types of distribution *i.e.* functionally grading V type distribution (FG-V), functionally grading X (FG-X) type distribution, and functionally grading O (FG-O) type distribution [4]. These functionally grading properties vary linearly in the thickness direction as per the distribution of CNTs volume fraction. These are superior to conventional laminated composite structures. The laminated composite structures have delamination-related problems. High temperatures are frequently encountered during the entire life cycle of composite structures when employed in industrial or automotive applications. These temperatures impact the stiffness and strength of the material and can cause dynamic instability in these structures [5]. Plate structure of irregular shape plays a noteworthy role in engineering applications like aircraft wings, naval structures, and a bridge, so when these structures undergo with due to thermal and mechanical load, stress concentration or in-plane compressible forces occur. The structure failure can be accountable by buckling, which reduces the load-carrying capacity of the structure [6]. These days, sandwich composite is a very good option all over the world because the sandwich structure has a good strength-to-weight ratio of material and high bending stiffness as compared to traditional composite structures. Therefore, the sandwich structure is an excellent solution in a number of applications.

Zhu *et al.* used the theory of shear deformation by infinite element analysis to analyse the static deflection as well as free vibration of a composite plate reinforced by carbon nanotubes. They also examined the impact of various boundary conditions and found that the results obtained using this method agreed with those obtained using the ANSYS [2]. It was found that the plate width-t--thickness ratio and its boundary conditions have an impact on the bending deflection, whereas the central axis stress and the CNT volume fraction can be neglected for the vibration effect of VCNT.

Aicha *et al.* analysed the sandwich plates reinforced by carbon nanotubes for static as well as dynamic analysis with the help of FSDT theory. Two conditions were observed for this analysis: (1) Functionally graded core with uniformly distributed face sheets and (2) Functionally graded core with uniformly distributed face sheets. The findings suggested that the functionally graded face sheet sandwiched reinforced plate has a strong level of resistance to deflection in comparison to other types of reinforcement due to the concentration of carbon nanotube at the bottom and upper face sheet sandwich plate. However, for core-reinforced sandwich plate decrease in dimensionless natural frequency is the most noticeable. Due to the small dimensionless frequency, increasing aspect ratio (a/h) is caused by fundamental modes [7]. Wang *et al.* meshless approach is used to examine the irregular quadrilateral plate where they obtained results for a different side-to-thickness ratio with varying side angles. It was observed that the quadrilateral plate for a composite structure reinforced by carbon nanotubes was thermally affected in terms of vibration and buckling. It was concluded that the volume fraction of carbon nanotube, functionally grading distribution, geometry parameters, and temperature affect the frequency and deflection of skew symmetric plates. Initially the three modes of natural frequencies decrease as the temperature rises. Near the value of temperature at which critical buckling starts, the natural frequency mode of the first order approaches zero [8]. The value of frequency of the first order vibration mode approaches zero near critical buckling temperature. Rasool *et al.* studied the nanocomposite cylindrical structure reinforced with single wall carbon nanotube subjected to impact load to analyse the effects by mesh free process [9]. It was observed that the different grading of carbon nano tube, carbon nano tube volume fraction and structure thickness affects the stress flow and frequency in cylindrical structure. As the thickness is reduced, the first parameters of frequency are reduced and the stress propagation intensity is increased. The value of frequency and the wave of stress intensity propagation both increase as the volume fraction of carbon nanotubes increases. Kumar *et al.* studied the composite beam reinforced with the carbon nanotube and analysed its vibrational effects. It was concluded that the vibration frequency of the reinforced beam is dependent on the volume fraction of carbon nanotube & distribution pattern of reinforcement [10].

The chapter emphasises the natural frequency and central deflection of a quadrilateral sandwich plate with a functionally graded core, which is not very commonly studied in the literature. The core material is assumed to be functionally graded in the thickness direction, while the face plates are uniformly distributed in all the cases. The plate is assumed to be orthotropic, and four types of grading are considered, *i.e.*, F.GO, F.GX, F.GV, and uniformly distributed. To obtain the material properties of each layer, the volume fraction of the carbon nanotube (CNT) is varied from 0.11 to 0.17, and MATLAB is used to calculate the corresponding material properties. ANSYS R17.2 software is used to validate the obtained results and compare them with previously published papers.

The main objective of the study is to find the superior grading type for natural frequency and deflection by comparing the obtained results. The study will contribute to the understanding of the behavior of functionally graded sandwich plates and will help in the design of more efficient and cost-effective structures.

CHAPTER 19

Polymer Nanocomposites with Improved Electrical and Thermal Properties for Smart Electronic Material Applications

Tapan Kumar Patnaik[1,*], **Simadri Priyanka Achary**[1], **Jyoti Behera**[1] and **Sanjukta Mishra**[1]

[1] *Department of Physics, GIET University, Gunupur, Rayagada, Odisha, India*

Abstract: We know that in today's scenario, smart materials are in fame and are an important part of our daily life. Polymer nanocomposites (PNC) have attracted significant research and industrial interests due to their promising potential for versatile application. This nanocomposite technology has emerged from the field of engineering plastics and potentially expanded its application to structural materials, coatings, and packaging for medical products and electronic and photonic devices. The possibility of electrical and thermal conduction in a polymer matrix with low amounts of nanoparticles brings opportunities for highly demanding applications such as electrical conductors, heat exchangers, sensors, and actuators. The development of smart polymer nanocomposite (SPN) has been an area of high scientific and industrial interest in recent years, due to fantastic improvements achieved in these materials. SPN found potential applications in shape memory, self-healing, self-healing, self-cleaning, and energy harvesting. This paper mainly focuses on the most recent advances in polymer nanocomposites for everyday life applications, which are practically important and extremely useful. The applications of PNC are endless and still increasing rapidly due to their below-average cost and ease of manufacture. They make our lives more convenient and enjoyable. The main target is to study the applications of electrical and thermal properties of PNC for smart electronics materials.

Keywords: Actuators, Smart polymer nanocomposite, Self-healing polymer, Sensors.

INTRODUCTION

A polymer nanocomposite is a composite material comprising a polymer matrix and an inorganic dispersive phase that has at least one dimension, which is of nanometric scale [1]. Another highly potential application of polymer nanocomp-

* **Corresponding author Tapan Kumar Patnaik:** Department of Physics, GIET University, Gunupur, Rayagada, India; Email: tapanpatnaik@giet.edu

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

osite is for energy, which includes energy generation and energy storage. Among the types of mostly applied nanofiller for nanocomposite energy applications are metal oxides, Nano clays, carbon nanotubes, and graphenes. Some applications of polymer nanocomposites in biomedical applications are shown in Fig. (**1**).

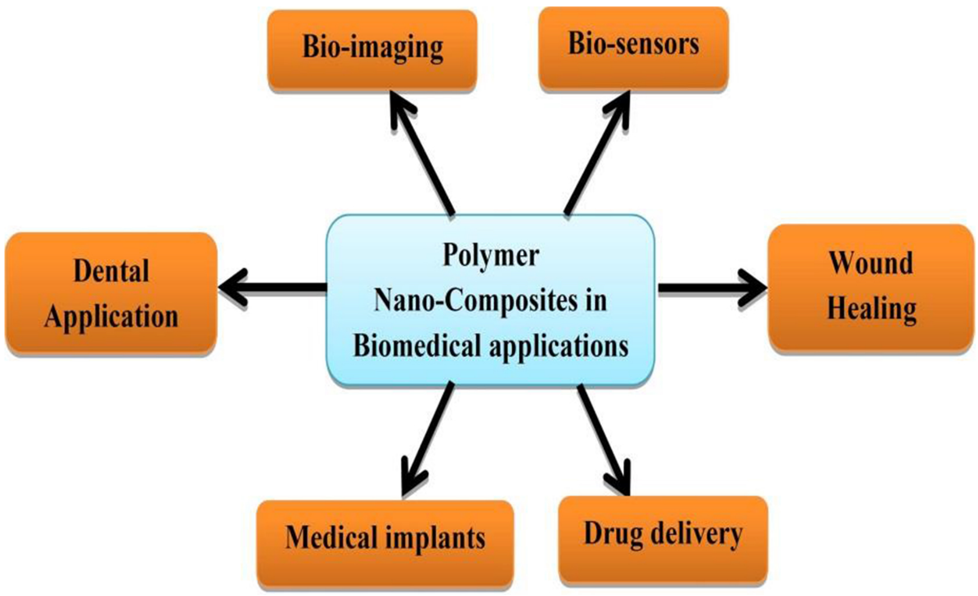

Fig. (1). Applications of polymer nanocomposites in biomedical applications [1].

The smartness of material development always comes from the inspiration and intelligence of nature. Smart materials can be defined as materials that incorporate the functions of sensing, actuation, and control. Smart materials are attracting increasing interest, especially in the era of the fourth industrial revolution and circular economy. Smart polymer nanocomposites (SPN) can be derived from shape memory polymers, stimuli-active polymers, smart electrorheological (ER) and magnetorheological (MR) polymers; self-healing polymer, self-cleaning polymer, self-healing polymer, self-sensing polymer, energy-harvesting and energy storage polymer are the latest hot research topics [2]. The addition of Nano filler can increase the performance of the SPN (*e.g.,* shape fixity, shape recovery, self-healing ability) due to their high specific surface area, nucleating effects, reinforcing effects, and inherent functionalities (*e.g.,* thermal conductivity, electrical conductivity). SPNs are widely used in various applications, for example, sensors and actuators, str*etc*hable electronics, wearable electronics, smart textiles, drug carriers and delivery, aircraft and aerospace applications. Ten years ago, Ratna and Karger-Kocsis documented a review on shape memory polymers and composites. When revisiting the ‘future outlook’ from Ratna and

Karger-Kocsis, they 'forecasted' that the blending and interpenetrating of network-based polymers in SMP could have led to the development of newer and novel SMPs. They also 'predicted' that SMPs are going to be the future materials for deployable structures for aircraft and spacecraft applications. And, nowadays, numerous research publications deal with SMP *via* blending and interpenetrating network strategies. This mini-research on smart polymer nanocomposite is mainly focused on the shape memory polymer (SMP) and self-healing polymer (SHP) [3], which is part of the 'heritage' of Professor Karger-Kocsis. This article provides a basic fundamental idea of how to fabricate SPN with different types of processing techniques. This could benefit researchers (especially 'beginners') looking for a feasible method to synthesize and prepare SPN, using as simple as solvent casting and melt blending, to some sophisticated methods (*e.g.,* electrospinning, 3D and 4D printing).

Smart Polymer Nanocomposite

Shape Memory Polymer

External stimuli can cause Shape Memory Polymer (SMP) to change shape temporarily, but it can then return to its original shape. The stimuli for shape memory alloy (SMA) is always limited to heat (*e.g.,* Joule heating) and magnetic field, whereas there are more 'triggering choice' for SMP, *e.g.,* light, water, solvent, pH, temperature, and electricity. Furthermore, compared with SMA, most of the SMP has more advantages, for example, low density, high elastic deformation, good biocompatibility, and bio-degradability, as well as fantastic tailor-ability. In general, SMP consists of permanent net points (a stable polymer network) and molecular switches of reversible nature [4]. The former memorizes the original shape, while the latter is used for setting the temporary shape. When molecules entangle, crystallize, cross-link, or intertwine in SMP, they create the permanent net points of SMP. There is a variety of thermosensitive SMP with physical (or chemical) network points that determine their original shape, while each temporary shape is fixed by switching domains associated with a thermal transition temperature (Ttrans), such as the crystallization/melting transition, the vitrification/glass transition, the liquid crystal anisotropic/isotropic transition, reversible molecule cross-linking, and supra molecular association/disassociation. The essential performance parameters for an SMP include Ttrans, shape fixity ratio (Rf), and shape recovery ratio (Rr) [4]. The viscoelastic and relaxation behaviors of SMP are attributed to the cooperative relaxation of each component. The working mechanism in the thermoresponsive SMP is governed by both the internal recovery stress and stored mechanical energy [5].

CHAPTER 20

An Investigation of Constant Amplitude Loaded Fatigue Crack Propagation of Virgin and Pre-Strained Aluminium Alloy

Chandra Kant[1] and **Ghulam Ashraf Harmain**[1,*]

[1] *Department of Mechanical Engineering, National Institute of Technology Srinagar, Jammu, and Kashmir, India*

Abstract: The article examines and explores the impact of pre-strain on resistance to fatigue crack propagation (FCP) *via* analytical models. Most of the materials during service and processing have gone through preexisting strain due to strain-invigorating processes. It is an utmost priority of any low-weight and high strength structural requirement. The numerical study is based on aluminum alloy 7475 with T7375 heat treatment, which is a candidate material for the aerospace industry due to its mechanical properties. In this paper, virgin and pre-strained Aluminum7475, 2.54 & 5% are explored in the time-invariant loading for load or stress ratio (R) of 0, 0.1, and 0.4 (minimum stress/maximum stress) *via* fatigue crack propagation model Paris and Crack annealing model. The model selected for the study is rooted in small-scale yielding theory which is based on linear elastic fracture mechanics (LEFM) without crack closure and accounting crack closure (CL). The emphasis on crack closure behavior before and after the pre-strain of material. Effects of load ratio 0, 0.1, and 0.4 have been studied *via* crack closure models- Elber, Newman, and Virtual crack annealing model. A comparative study of fatigue crack propagation Paris & Crack annealing model forecast has been presented for virgin and strained conditions. The predictions are validated *via* experimental data. Prediction error analysis has been presented in the forecast and actual data.

Keywords: Crack annealing model, Fatigue crack propagation, Pre-strained aluminium.

INTRODUCTION

In the automobile sector, a high strength-to-weight ratio is one of the primary criteria for structural material selection which influence fuel economy. In the case of the aviation industry, the lightweight-to-strength ratio is very crucial to meet

* **Corresponding author Ghulam Ashraf Harmain:** Department of Mechanical Engineering, National Institute of Technology Srinagar, Jammu & Kashmir, India; E-mail: gharmain@nitsri.net

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

the floating condition in a less dense medium (air). Structural integrity analysis of such materials considering actual manufacturing process parameter effects and loadings *etc*., is very much required for reliable design.

Aluminum alloy – 7475 with T-7351 heat treatment is a candidate material for aviation vehicle structures (frames, ribs & spares) as it shows design suitable strength with load and shows aversion to oxidation (corrosion) [1]. Alloy 7474-T7351 is a modified form of Al- alloy 7075, which shows good fracture toughness and corrosion resistance which makes it a candidate material for aviation structures. During service, aviation vehicle continuously encounters cyclic loading, which makes fatigue analysis of such material inexorable.

Plastic deformation accumulated during the manufacturing process of various parts influences the microstructure, mechanical properties, *etc*. accumulated plastic deformation is termed pre-strained material [2, 3]. Accounting for the influence of pre-strain on mechanical properties (tensile strength, compressive strength, fatigue crack propagation resistance, *etc*.) is inevitable for the reliable structural integrity of the structure made of it. Plastic deformation, environmental conditions (temperature, humidity, *etc*.), load ratio (R), microstructure, and grain size influence fatigue crack propagation resistance [4]. Almost 90% of the mechanical structure fails due to fatigue loading; hence analysis of the fatigue crack propagation behaviour of the structure is essential for better reliability of the structural design.

For an accurate assessment of the life of a structure experiencing cyclic loading and rate of fatigue crack growth (FCP) for ductile material, crack closure analysis is inevitable, which has been reported by several researchers [5 - 11]. The crack closure phenomenon is identified and reported in [12 - 14], which incorporates the effect of plasticity, roughness, and oxidation-induced obstructions in crack flank opening and closing. Generally, the effect of plasticity-governed crack closure (PGCC) is influenced by load ratio & environmental conditions (temperature, pressure, humidity, test chamber, and gaseous compositions, *etc*.).

This article presents the influence of pre-strain (0%, 4%, and 5%) on fatigue crack propagation rate *via* an *in-situ* experimental study, and also, the influence of varying stress ratios (0, 0.1, and 0.4) is simulated *via* crack closure models. Crack propagation rate versus stress intensity factor data is modeled *via* linear elastic fracture mechanics based Paris model [15]. The crack annealing model [16], Elber model [12], and Newman model [17] are used to imitate fatigue crack growth rate (FCGR) in the cycle *via* cycle method.

The article is systematized as follows – Section 2 discusses the mechanical properties of Al-7475, the prerequisite process for straining the material, and also discusses the apparatus used briefly. Section 3 gives the details of the experimental procedure, and discusses the process parameters and sample geometry. Next, Section 4 discusses crack propagation models used in this study. Section 5 presents the results. This study is concluded in section 6.

MATERIALS AND METHODOLOGY

For the current study, aluminum alloy 7475-t7375 is used to examine the influence of accumulated plastic strain on FCP behavior in the Paris zone (stable fatigue crack propagation zone). The material has been prominently used in aerospace and automobile structure construction due to its good mechanical properties, such as fracture toughness and corrosion resistance which qualifies the material as an optimal choice for reliable structural design in such industries [18].

Table. **1** gives the Chemical constituents of the material used for this study. Mechanical properties of the material are determined from a tensile test at 27^0C using a 100 KN Tinius-Olsen universal testing machine (UTM) with a 50 mm gauge length extensometer. Table. **2** provides a tensile stress-strain response of the Al-7475 with t-7375 heat treatment. Material has been subjected to pre-strain on UTM, where the strain was measured *via* an axial extensometer.

Table 1. Elements of Al-7475

Alloy wt.%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
7475	0.1%	0.12%	1.4%	0.06%	2.3%	0.22	5.9%	0.06%	Balance

Table 2. Mechanical property of virgin and pre-strained Al-7475-T7531

Material condition	Yield strength (σy) (MPa)	Ultimate tensile strength UT (MPa)
Virgin	396	469.15
2.54% strained	405.18	475.14
5% strained	409.71	476.5

EXPERIMENTAL PROCEDURE

The fatigue crack propagation (FCP) test is conducted on the quarter compact sample in compliance with the standard ASTM-647 [19]. FCP sample, used for this analysis, is prepared *via* electric discharge machining (EDM) from (50*50*6.15) mm sheet.

EDM technique was chosen to minimize the machining-induced residual stress to be able to test the actual behavior of the material. The sample is prepared in

CHAPTER 21

Principle and Application of Smart Material in the Biosensing Field

Tapan Kumar Patnaik[1,*], **Asheem Putel**[1], **Rakesh Kumar Rout**[1] and **Sudhanshu Shekhar Parida**[1]

[1] *Department of Physics, GIET University, Gunupur, Rayagada, Odisha, India*

Abstract: Biosensors are analytical devices that are broadly used for the detection of chemical substances like tissue, organelles, cell receptors, enzymes, antibodies, *etc*. Smart materials respond to the external impulse, and convert the impulse to readable signals. Nowadays, smart materials are used in every requirement of a human being. The various kinds of smart materials are the subject of extensive investigation. This chapter examines the fundamental idea and practical use of smart materials in the biosensing industry.

Keywords: Applications, Biosensors, Smart material.

INTRODUCTION

Smart or Intelligent Materials

Smart materials are a vital research area in the field of material physics. Smart materials exhibit observable changes in response to an external effect or environmental impulse [1]. Temperature, pressure, electric flow, light, mechanical, heat, stress, moisture, electric field, magnetic field, and pH are a few examples of the external impulses or stimuli. Due to the popularity of color-changing shirts and other smart materials, there is an increased use of smart material-based products in everyday life today. Smart materials are used in many fields like aerospace, material, bionics, medical, technologies., civil, engineering and automobiles. A structure that is made from smart material is known as a smart structure.

* **Corresponding author Tapan Kumar Patnaik:** Department of Physics, GIET University, Gunupur, Rayagada, India; E-mail: tapanpatnaik@giet.edu

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

Smart materials are composite materials, i.e., smart materials are the combination of two or more materials. When compared to standard materials, these materials have various benefits, including reduced weight, immunity to corrosion, and a longer lifespan. Our world's design actively incorporates smart materials. It involves designing things like clothing, buildings, vehicles like cars or planes, bikes, and goods for the house [2].

TYPES OF SMART MATERIALS

There are different types of smart materials. Some of those are as follows:

Biomimetic Materials

Biomimetic materials are capable of sensing their environment, processing the data, and responding instantly. These materials are used in the restoration of natural functions where the original material is not performing well. These materials are used in a very wide range in the biosensing field as it sustains an optimally conducive environment, tissue growth, biomolecular assays, and biotechnology-based manufacturing. Some of these materials are shown in Fig (**1**).

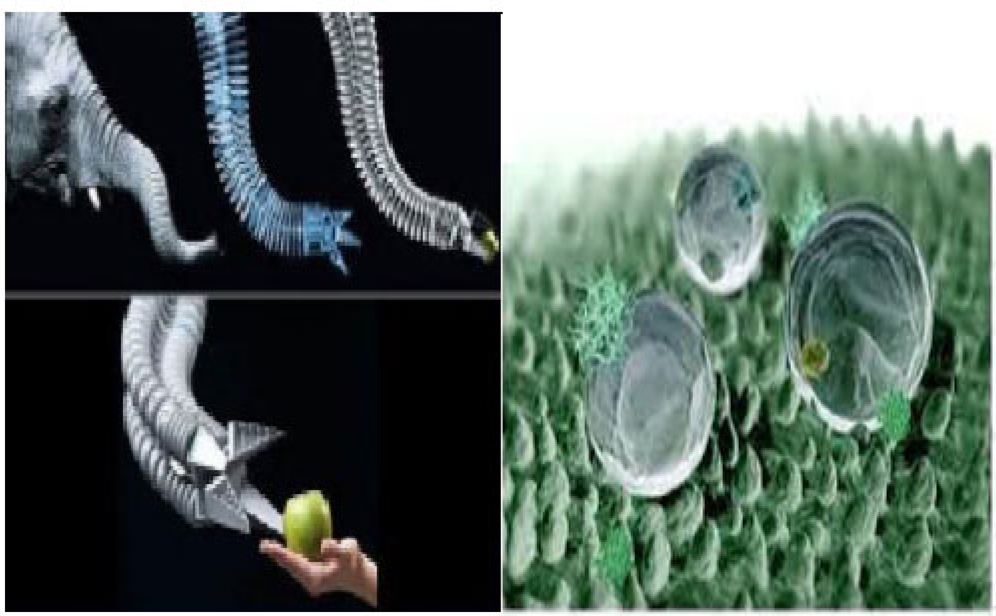

Fig. (1). Biomimetic Materials.

Smart Gels

Smart gels are the gels that change their structure after getting external stimuli like temperature, pH, light, magnetic field, etc.

Researchers are interested in smart hydrogens, a sort of smart gel, not only for their stunning behavior under external stimuli but also for a broad array of applications, such as industrial or biological, to which they may be used [3]. Drug delivery methods, tissue engineering solutions and injectable biomaterials have all made use of these materials. Some examples of smart gels are shown in Fig 21.2.

Fig. (2). Smart Gel.

Piezo-electric Materials

Piezoelectric smart materials produce electric voltage when stress is applied and vice versa. Applying the electric voltage throughout this material shows some changes in shape. Some of the naturally piezoelectric occurring materials are berlinite, cane sugar, quartz, Rochelle salt, topaz, and tourmaline [3, 4]. A piezo-electric smart material is shown in Fig. (**3**).

Piezo-electric materials possess:

- High strain constants, permittivity and coupling constant
- The low mechanical quality factor
- High strain output for large displacement at modest voltage

CHAPTER 22

Experimental Investigation Of Tribological Behavior Of Tin-Based Babbitt And Brass Material

Rohit Kumar Babberwal[1,*] and **Raosaheb Bhausaheb Patil**[1]

[1] *Department of Mechanical Engineering, Army Institute of Technology, Pune-411015, Maharashtra, India*

Abstract: The aim of the experiment is to investigate the tribological behavior of Brass and tin-based babbitt materials. The experiment is conducted on a pin-on-disk wear test machine at room temperature to analyze their effect on tribological behavior. The experiment is conducted at various operating factors like load, sliding time and sliding velocity under dry and lubrication conditions. Application of these materials is mostly found in automobile bearing, precise instrument, railway bearing, aerospace and heavy duty application. After conducting the experiment, it was noticed that tribological behavior slightly changes at elevated temperatures. The use of oil lubricant improves the tribological performance as compared to dry conditions by 18.56 times for tin-based babbitt alloy and by 2.19 times for brass material. Thus the performance of Brass under oil lubrication is superior to tin-based Babbitt due to its hardness. Under dry conditions, the wear rate of brass material is approximately four times that of wear in tin-based Babbitt; thus, the service life of tin-based Babbitt is longer than brass material under dry conditions.

Keywords: Brass, Temperature, Tin based babbitt, Tribology, Wear.

INTRODUCTION

Nowadays, various materials with different compositions are used in industry, such as steel, Aluminum, Copper, Nickel, Titanium, Bronze, Nickel, etc., to reduce wear and friction and improve the performance or service life of the component. But these materials and their combination have wear and friction problems, and their available tribological data is also limited, so it is difficult to predict the actual tribological behavior of these materials. The Selection of the correct material is of great concern in the design of components [1]. In this experi-

* **Corresponding author Rohit Kumar Babberwal:** Department of Mechanical Engineering, Army Institute of Technology, Pune-411015, Maharashtra, India; Email: rkbabberwal01@gmail.com

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

mental investigation, tin-based Babbitt and Brass are selected to analyse their tribological performance. These materials show good compatibility with other materials such as steel; also, they have a good anti-frictional properties and the ability to embed

foreign particles. These materials are mostly used in various industrial applications, such as bearing, gear, cam, and follower. Earlier studies have shown that wear and friction depend on various factors such as normal load, sliding speed, surface condition, specimen geometry, system rigidity, sliding time, type of material in contact, etc. Out of these factors, sliding speed and normal load are the main factors that play a significant role in the change in tribological performance. So, this experimental investigation focuses on examining the tribological performance of babbitt alloy and brass material with different working parameters under dry and oil lubricating (SAE 50) conditions. This research paper aims to investigate tribological behavior of tin-based Babbitt and brass material under various operating conditions.

Dongya *et al.* [1] studied the tribological performance of Babbitt (ZSnSb11Cu6) alloy with PU polymer coating with dry sliding and oil lubricating conditions. It is observed from the result that Babbitt with polyurethane coating shows better tribological performance than bare Babbitt. The coefficient of friction of bare Babbitt is more than Babbitt with PU coating. Goudarzi *et al.* [2] study about tribological properties of white metal (Sn-Sb-Cu) as a journal bearing. It also investigates the heating effect and cooling rate on white metal. The result shows that under heavy load application, the tribological performance of WM5 is better than WM2 because of alloying materials. It also noticed that under the same working condition, the amount of wear in WM2 is more compared to WM5. Feyzullahoglu *et al.* [3] investigated the tribological behavior of Brass (CW 619), SAE (7% Sb), and Sn-Sb-Cu (20% Sb) for heavy duties application. The experiment was conducted using Tecquipment HFN type 5 journal-bearing equipment. It notices that increase in tin content in WM5 increase results in an increase in hardness. Chowdhury *et al.* [4] investigated the effect of normal load, sliding velocity, and relative humidity on wear and friction of Brass (disc) sliding against mild steel and stainless steel (pin). It has been observed from the experiment that the wear rate of SS 202, SS314 and MS is affected by sliding velocity and perpendicular load. Also, study the wear properties of different grade steel [5, 6] and other material pairs [7].

MATERIALS AND METHODOLOGY

The pin specimen used in the experiment is made up of tin-based Babbitt and brass material, whereas the disc is made up of E8 steel material. Pin specimen is cylindrical in shape with a flat surface. It is manufactured by extraction process followed by machining on a lathe machine to get the desired dimension of 6mm diameter and 28mm height. Chemical analyses using a spectrometer show that the composition of tin-based Babbitt is 81.74% tin, 12.13% antimony, 5.05% copper, and 0.22% lead, whereas brass chemical composition is 55.77% copper, 41% zinc, 2.42% lead, and 0.33% tin. The experimental setup with pin specimen is shown in Figs. (**1**-**2**) [8].

Fig. (1). Tin based babbitt pin.

Fig. (2). Brass pin.

Experiment

The experiment was performed on Pin on disc (POD) machine according to the G99 ASTM test standard to find wear and friction properties of babbitt alloy and brass material. The experiment was conducted, by considering working parameters like normal load (10N, 20N, and 30N), and sliding velocity (200, 300, and 400rpm) into the account. The experiment was carried out for 20 minutes

SUBJECT INDEX

Amar Patnaik, Albano Cavaleiro, Malay Kumar Banerjee, Ernst Kozeschnik & Vikas Kukshal (Eds.)

D

E

Amar Patnaik

Prof. Amar Patnaik is associate professor of mechanical engineering at Malaviya National Institute of Technology Jaipur, India. Dr. Patnaik has more than 14 years of teaching experience and has taught a broad spectrum of courses at both the undergraduate and graduate levels. He has guided 27 PhD's and several M.Tech theses. He has published a number of research articles and book chapters in reputed journals, edited books and filed 7 patents out of which 1 is granted. He is a life member of Tribology Society of India, Electron Microscope Society of India and ISTE.

Albano Cavaleiro

Prof. Albano Cavaleiro is a professor at the Mechanical Engineering Department of the Coimbra University, Portugal. He has supervised numerous master's and Ph.D. thesis, teaches basic and advanced university courses and has authored and co-authored more than 100 scientific papers, 60 of them in International Journals of the Science Citation Index. He has participated in more than 60 international events, such as congresses, conferences, work-shops and exhibitions. He has delivered talks at national and international scientific events. He has participated in more than 25 projects.

Malay Kumar Banerjee

Prof. Malay Kumar Banerjee served as former ministry of steel chair professor in the department of Metallurgical and Material Engineering at Malaviya National Institute of Technology Jaipur, India. He has over 43 years of experience in academia. He received many research grants from DST India, Ministry of Steel India, ISRO, DRDO, UGC, DMRL, AICTE, IIF, CPCB, NMRL, MHRD, and BRNS. He has published a number of research articles in journals of repute, presented papers in conferences, contributed book chapters, edited books, and filed a few patents.

Ernst Kozeschnik

Prof. Ernst Kozeschnik is the head of the Institute of Materials Science and Technology at TU Wien since 2009. He has supervised numerous master and Ph.D. thesis. He is the author of the textbook "Modeling precipitation kinetics". He has authored and co-authored more than 140 scientific papers. Prof. Kozeschnik is the lead developer of the MatCalc software package, which is used in many different universities and research centers. He is head of the Scientific Advisory Board of MatCalc Engineering GmbH. Prof. Kozeschnik was awarded a "Christian Doppler Laboratory" in 2007, which is one of the most renowned mid-term scientific funds in Austria.

Vikas Kukshal

Prof. Vikas Kukshal is assistant professor in the Department of Mechanical Engineering, NIT Uttarakhand, India. He has more than 10 years of teaching experience. He has authored and co- authored a number of articles in journals and conferences, and contributed book chapters. He is the editor of a few books of international repute. He is a life member of Tribology Society of India, The Indian Institute of Metals and The Institution of Engineers. His research area includes material characterization, composite materials, high entropy materials, simulation and modelling.