FUZZY RULE BASED OPTIMIZATION IN MACHINING OF GLASS FIBER REINFORCED POLYMER (GFRP) COMPOSITES

Thesis submitted in partial fulfillment of the requirements for the Degree of

Master of Technology (M. Tech.)

In

Production Engineering

By

RAJESH KUMAR VERMA
Roll No. 209ME2209

Under the Guidance of

Prof. SAURAV DATTA

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA 769008, INDIA

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA 769008, INDIA

Certificate of Approval

This is to certify that the thesis entitled **FUZZY RULE BASED OPTIMIZATION IN MACHINING OF GLASS FIBER REINFORCED POLYMER (GFRP) COMPOSITES** submitted by ***Sri Rajesh Kumar Verma*** has been carried out under my supervision in partial fulfillment of the requirements for the Degree of ***Master of Technology*** in ***Production Engineering*** at National Institute of Technology, NIT Rourkela, and this work has not been submitted elsewhere before for any other academic degree/diploma.

Dr. Saurav Datta

Assistant Professor
Department of Mechanical Engineering
National Institute of Technology, Rourkela

Rourkela-769008

Date:

Dedicated to my most loving family

Acknowledgement

This project seems to be the most significant accomplishment in my life and it would have been impossible without people who supported me and believed in me.

I would like to extend my gratitude and my sincere thanks to my honourable, esteemed supervisor ***Dr. Saurav Datta***, Assistant Professor and ***Prof. Siba Sankar Mahapatra***, Group Head (Production Specialization) and all the staff members of the Department of Mechanical Engineering, National Institute of Technology Rourkela, for their timely help and cooperation in completion of this work. ***Dr. Saurav Datta*** is not only a great teacher cum supervisor with deep visions but also most importantly a kind person. I sincerely thank for his exemplary guidance and encouragement. His trust and support inspired me in the most important moments of making right decisions and I am glad to work under his supervision. I am very much thankful to our Head of the Department, ***Prof. Kalipada Maity***, for providing us with best facilities in the department and his timely suggestions.

I would like to thank all my friends and especially my classmates specially ***Ranjeet Kumar Sahu***, ***Arpan Kumar Mandal***, ***Kumar Abhishek*** and ***Chitrasen Samantra***, research scholars of Production Specialization for all the thoughtful and mind stimulating discussions we had, which prompted us to think beyond the obvious. I've enjoyed their companionship so much during my stay at NIT, Rourkela.

Last but not the least I would like to thank my mother ***Smt. Rajkumari***, father ***Sri Narayan Das***, who has supported me mentally and was always with me and also who taught me the value of hard work by their own example. They rendered me enormous support being apart during the whole tenure of my stay in NIT Rourkela.

RAJESH KUMAR VERMA

Abstract

With the increasing use of Fiber Reinforced Polymer (FRP) composites outside the defense, space and aerospace industries; machining of these materials is gradually assuming a significant role. The current knowledge of machining FRP composites is in transition phase for its optimum economic utilization in various fields of applications. Therefore, material properties and theoretical mechanics have become the predominant research areas in this field. With increasing applications, economical techniques of production are indeed very important to achieve fully automated large-scale manufacturing cycles. Although FRP composites are usually molded, for obtaining close fits and tolerances and also achieving near-net shape, certain amount of machining has to be carried out. Due to their anisotropy, and non-homogeneity, FRP composites face considerable problems in machining like fibre pull-out, delamination, burning, etc. There is a remarkable difference between the machining of conventional metals and their alloys and that of composite materials. Further, each composite differs in its machining behavior since its physical and mechanical properties depend largely on the type of fibre, the fibre content, the fibre orientation and variabilities in the matrix material. Considerable amount of literature is readily available on the machinability of conventional metals/alloys and also polymers to some extent; with very limited work on FRP composites. Therefore, machining process optimization for all types FRP composites is still an emerging area of research.

In this context, the present research highlights a multi-objective extended optimization methodology to be applied in machining FRP-polyester/epoxy composites with contradicting requirements of quality as well as productivity. Attempt has been made to develop a robust methodology for multi-response optimization in FRP composite machining

for continuous quality improvement and off-line quality control. Design of Experiment (DOE) has been be selected based on Taguchi's orthogonal array design with varying process control parameters like: spindle speed, feed rate and depth of cut. Multiple surface roughness parameters of the machined FRP product along with Material Removal Rate (MRR) of the machining process have been optimized simultaneously. A Fuzzy Inference System (FIS) integrated with Taguchi's philosophy has been proposed for providing feasible means for meaningful aggregation of multiple objective functions into an equivalent single performance index (MPCI). This Multi-Performance Characteristic Index (MPCI) has been optimized finally. Detailed methodology of the proposed fuzzy based optimization approach has been illustrated in this reporting and validated by experiments.

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Chapter 1: Introduction

1.1. Overview of Composites

Mankind has been aware of composites materials since several hundred years before *Christ* and has been applied innovations to improve the quality of life. Contemporary composites resulting from research and innovation from the past few decades have progressed from glass fibre for automobiles bodies to particulate composites for aerospace and a range of other applications. The volume and number of applications of composite materials have grown steadily, penetrating and conquering new markets relentlessly. Modern composite materials constitute a significant proportion of the engineered materials market ranging from everyday products to sophisticated niche (hollow in a wall or statues) applications. While composites have already proven their worth as weight-saving materials, the current challenge is to make them cost effective. The efforts to produce economically attractive composite components have resulted in several innovative manufacturing techniques currently being used in the composites industry. Composites that form heterogeneous structures which meet the requirements of specific design and function with desired properties limit the scope for classification. Over, this lapse is made up for, by the fact that new types of composites are bring innovated all the time ,each with their own specific purpose like flake, particulate and laminar composites.

Composite materials (or composites for short) are engineering materials made from two or more constituent materials that remain separate and distinct on a macroscopic level while forming a single component.

1.2. What is Composite?

Composites are a combination of two or more materials yielding properties superior to those of the individual ingredients. One material is in the form of a particulate or fiber, called the reinforcement or discrete phase. The other is a formable solid, called the matrix or continuous phase. The region where the reinforcement and matrix meet is called the interface. Composite properties are determined by chemical and mechanical interaction of the combined materials. Wood and concrete are composites under this definition. This document is limited to the application of the subset of composites called Fiber Reinforced Polymer (FRP) that combine fibers of glass or other materials (the reinforcement) with thermoset and/or thermoplastic resins (the matrix).

Composites are made from two or more distinct materials that when combined are better (stronger, tougher, and/or more durable) than each would be separately.

A typical composite material is a system of materials composing of two or more materials (mixed and bonded) on a macroscopic scale. For example, concrete is made up of cement, sand, stones, and water. If the composition occurs on a microscopic scale (molecular level), the new material is then called an alloy for metals or a polymer for plastics.

Generally, a composite material is composed of reinforcement (fibers, particles, flakes, and/or fillers) embedded in a matrix (polymers, metals or ceramics). The matrix holds the reinforcement to form the desired shape; while the reinforcement improves the overall mechanical properties of the matrix. When designed properly, the new combined material exhibits better strength than would each individual material.

The most widely used meaning is the following one, which has been stated by ***Jartiz*** "Composites are multifunctional material systems that provide characteristics not obtainable from any discrete material. They are cohesive structures made by physically combining two or more compatible materials, different in composition and characteristics and sometimes in form". ***Kelly*** very clearly stresses that the composites should not be regarded simple as a combination of two materials. In the broader significance; the combination has its own distinctive properties. In terms of strength to resistance to heat or some other desirable quality, it is better than either of the components alone or radically different from either of them. ***Beghezan*** defines as "The composites are compound materials which differ from alloys by the fact that the individual components retain their characteristics but are so incorporated into the composite as to take advantage only of their attributes and not of their short comings", in order to obtain improved materials. ***Van Suchetclan*** explains composite materials as heterogeneous materials consisting of two or more solid phases, which are in intimate contact with each other on a microscopic scale. They can be also considered as homogeneous materials on a microscopic scale in the sense that any portion of it will have the same physical property.

The primary functions of the matrix are to transfer stresses between the reinforcing fibers/particles and to protect them from mechanical and/or environmental damage whereas the presence of fibers/particles in a composite improves its mechanical properties such as strength, stiffness etc.

1.3. What is FRP?

Fiberglass reinforced plastic, commonly known as fiberglass, was developed commercially after World War II. Since that time, the use of fiberglass has grown rapidly. The term 'fiberglass', can be described as a thermoset plastic resin that is reinforced with glass fibers. In this manual, the more general terms Fiber Reinforced Polymer/Composites or FRP/Composites will be used to describe these extremely useful material systems. Plastic resins come in two different classes: thermoset and thermoplastic. From a practical perspective, it's easy to remember that thermoset maintain their moulded shape at higher temperatures and cannot be melted and reshaped. Thermoplastics will melt at a given temperature and can be solidified into new shapes by cooling to ambient temperatures. Thermoset and thermoplastics are described with more detail in the Resin Systems section of this document. Reinforcing fibers include glass, carbon, aramid and other man-made and natural materials that are further described in the Reinforcement section of this document. These are used in a variety of forms and combinations to provide the required properties. The plastic resin systems determine chemical, electrical, and thermal properties. Fibers provide strength, dimensional stability, and heat resistance. Additives provide colour and determine surface finish, and affect many other properties such as weathering and flame retardance.

1.4. What Makes a Material a Composite?

Composite materials are formed by combining two or more materials that have quite different properties. The different materials work together to give the composite unique properties, but within the composite you can easily tell the different materials apart – they do not dissolve or blend into each other. Composites exist in nature. A piece of wood is a composite, with long fibres of cellulose (a very complex form of starch) held together by a much weaker substance called lignin. Cellulose is also found in cotton and linen, but it is the binding power of the lignin that makes a piece of timber much stronger than a bundle of cotton fibres.

The Composites are materials consist of two or more chemically distinct constituents on a macro scale having a distinct interface separating them and having bulk properties significantly different from those of any of the constituents.

A Composite Material consists of two phases:

1) Matrix phase

2) Reinforcement

Matrix phase

The primary phase having a continuous character is called matrix. Matrix is usually more ductile and less hard. It consists of any of three basic material types polymers, ceramics or metals. The matrix forms the bulk part.

Reinforcement

The secondary phase is embedded in the matrix in a discontinuous form. The dispersed phase is usually harder and stronger than the continuous phase and is called reinforcement. It serves to strengthen the composites and improves the overall mechanical properties of the matrix.

Much of the strength of FRP/Composites is due to the type, amount and arrangement of the fiber reinforcement. While over 90% of the reinforcements in use are glass fibers, other reinforcements have established a critical niche. E-glass is the most commonly used fiber reinforcement. It is strong, has good heat resistance, and high electrical properties. For more critical needs, S-Glass offers higher heat resistance and about one-third higher tensile strength (at a higher cost) than that of E-glass. Carbon Fibers (graphite) are available in a wide range of properties and costs. These fibers combine light weight with very high strength and modulus of elasticity. The modulus of elasticity is a measure of the stiffness or rigidity in a material. For high stiffness applications these reinforcements are hard to beat, with a modulus of elasticity that can equal steel. FRP/ Composites with carbon fiber reinforcement also have excellent fatigue properties. The primary use of carbon fibers is in aircraft and aerospace, in which weight savings are a major objective. While its cost limits carbon's use in commercial applications, it is used extensively where material content is low, such as sporting equipment. Aramid, or aromatic polyamide fibers (*Kevlar* or *Twaron*) provide high strength and low density (40% lower than glass) as well as high modulus. These fibers can be incorporated in many polymers and are extensively used in high impact applications, including ballistic resistance. Natural Fibers such as Sisal, Hemp and Flax have been used for many applications with low strength requirements. They are limited to applications not requiring resistance to moisture or high humidity. Arrangement of the glass fibers -how the individual strands are positioned -determines both direction and level of strength achieved in a moulded FRP/Composite. The three basic arrangements of glass fiber reinforcement are unidirectional, bidirectional and multidirectional. Unidirectional arrangements provide the greatest strength in the direction of the fibers. Unidirectional fibers can be continuous or intermittent, depending on specific needs determined by part shape and process used. This arrangement permits very high reinforcement loading for maximum strengths. The fibers in a bidirectional arrangement are in two directions – usually at 900 to each other, thus providing the highest strength in those directions. The same number of fibers need not necessarily be used in both directions. High fiber loading can be obtained in woven bidirectional reinforcements. Multidirectional or random arrangements provide essentially equal strength in all directions of the finished part.

1.5 Reinforcement

Reinforcements are supplied in several basic forms to provide flexibility in cost, strength, compatibility with the resin system, and process requirements. Regardless of the final form, all fiber reinforcements originate as single filaments. A large number of filaments are formed simultaneously and gathered into a strand. A surface treatment is then applied to facilitate subsequent processing, maintain fiber integrity, and provide compatibility with specific resin systems. After this treatment, the strands are further processed into various forms of reinforcements for use in moulding FRP/Composites.

Continuous strand roving

This basic form of reinforcement is supplied as untwisted strands wound into a cylindrical package for further processing. Continuous roving is typically chopped for spray-up, sheet moulding compounds. In the continuous form, it is used in pultrusion and filament-winding processes.

Woven roving

Woven from continuous roving, this is a heavy, drapable fabric available in various widths, thicknesses and weights. Woven roving costs less than conventional woven fabric and is used to provide high strength in large structural components such as tanks and boat hulls. Woven roving is used primarily in hand lay-up processing.

Woven fabrics

Made from fiber yarns, woven fabrics are of a finer texture than woven roving. They are available in a broad range of sizes and in weights. Various strength orientations are also available.

Reinforcing mat

Made from either continuous strands laid down in a swirl pattern or from chopped strands, reinforcing mat is held together with a resinous binder or mechanically stitched. These mats are used for medium strength FRP/Composites. Combination mat, consisting of woven roving and chopped strand mat bonded together, is used to save time in hand lay-up operations. Hybrid mats of glass and carbon and aramid fibers are also available for higher-strength reinforced products.

Surfacing mat

Surfacing mat or veil is a thin fiber mat made of monofilament and is not considered a reinforcing material. Rather, its purpose is to provide a good surface finish because of its effectiveness in blocking out the fiber pattern of the underlying mat or fabric. Surfacing mat is also used on the inside layer of corrosion-resistant FRP/Composite products to produce a smooth, resin-rich surface.

Chopped fibers

Chopped strands or fibers are available in lengths from 1/8” to 2”for blending with resins and additives to prepare moulding compounds for compression or injection moulding and other processes. Various surface treatments are applied to ensure optimum compatibility with different resin systems.

The matrix or resin is the other major component of an FRP/Composite. Resin systems are selected for their chemical, electrical and thermal properties. The two major classes of resins are thermoset and thermoplastics.

Thermoset resins

Thermosetting polymers are usually liquid or low melting point solids that can easily combine with fibers or fillers prior to curing. Thermoset feature cross-linked polymer chains that become solid during a chemical reaction or “cure” with the application of a catalyst and heat. The high level of cross-linking provides for reduced creep compared to thermoplastics. The thermoset reaction is essentially irreversible. Among the thermoset resins for FRP/Composites, the family of unsaturated polyesters is by far the most widely used. These resins are suitable for practically every moulding process available for thermoset. Polyesters offer ease of handling, low cost, dimensional stability, and a balance of good mechanical, chemical, and electrical properties.

They can be formulated for high resistance to acids, weak alkalies and organic solvents. They are not recommended for use with strong alkalis. Other formulations are designed for low or high temperature processing, for room temperature or high-temperature cure, or for flexible or rigid end products. Vinylesters provide excellent resistance to water, organic solvents and alkalis, but less resistance to acids than polyesters. Vinylesters are stronger than polyesters and more resilient than epoxies. Moulding conditions for Vinylesters are similar to those for polyesters. Epoxies are another family of thermoset resins used in FRP/ Composites. They have excellent adhesion properties and are suited for service at higher temperatures – some as high as 500°F. Epoxy-matrix FRP/Composites are processed by any of the thermoset methods. Epoxies are more expensive than polyesters, and cure times are longer, but their extended range of properties can make them the cost/performance choice for critical applications. Epoxy/fiber structures have generally higher fatigue properties than polyesters. Polyurethanes are a family of resins that offer very high toughness, high elongation, faster cure times and good coupling to a variety of reinforcements. Polyurethanes are easily foamed in a controlled process to produce a wide range of densities. Additives are easily incorporated into resin systems to provide pigmentation, flame retardance, weather resistance, superior surface finish, low shrinkage and other desirable properties. Gel coats consisting of a special resin formulation provide an extremely smooth next-to-mould surface finish on FRP/Composites. They are commonly applied in hand lay-up and spray-up processes

to produce a tough, resilient, weather-resistant surface. Gel coats, which may be pigmented, are sprayed onto the mould before the reinforcement and resin are introduced. Other thermosetting resin systems, generally formulated with chopped strand or milled fiber reinforcement for compression or transfer moulding are:

Phenolics: Good acid resistance, good fire/smoke, and thermal properties.

Silicones: Highest heat resistance, low water absorption, excellent dielectric properties.

Melamines: Good heat resistance, high impact strength.

Diallyl phthalates: Good electrical insulation, low water absorption.

Thermoplastic resins

Thermoplastic polymers can soften and become viscous liquids when heated for processing and then become solid when cooled. The process is reversible allowing a reasonable level of process waste and recycled material to be reused without significant effect on the end product. Thermoplastic resins allow for faster moulding cycle times because there is no chemical reaction in the curing process. Parts may be formed as fast as heat can be transferred into and out of the moulding compound.

Polypropylene and polyethylene are the most common thermoplastic resins used in FRP/Composites. They have excellent resistance to acids and alkalies and have good resistance to organic solvents. Their relatively low melting points allow for rapid processing at lower cost. Nylon and Acetal are highly resistant to organic solvents and may also be used where increased mechanical properties are required

1.6 Classification of Composites

1.6.1 According to Geometry

Most composite materials developed thus far have been fabricated to improve mechanical properties such as strength, stiffness, toughness, and high temperature performance. It is natural to study together the composites that have a common strengthening mechanism. The strengthening mechanism strongly depends on the geometry of the reinforcement. Therefore, it is quite convenient to classify composite materials on the basis of the geometry of a representative unit of reinforcement. Figure 1.1 represents a commonly accepted classification scheme for composite materials.

Fibrous composite

A fibre is characterized by its length being much greater compared to its cross-sectional dimensions. The dimensions of the reinforcement determine its capability of contributing its properties to the composite. Fibers are very effective in improving the fracture resistance of the matrix since a reinforcement having a long dimension discourages the growth of incipient cracks normal to the reinforcement that might otherwise lead to failure, particularly with brittle matrices. Man-made filaments or fibers of non polymeric materials exhibit much higher strength along their length since large flaws, which may be present in the bulk material, are minimized because of the small cross-sectional dimensions of the fiber. In the case of polymeric materials, orientation of the molecular structure is responsible for high strength and stiffness.

Fibrous composites can be broadly classified as single layer and multi layer composites on the basis of studying both the theoretical and experimental properties.

Single layer composites may actually be made from several distinct layers with each layer having the same orientation and properties and thus the entire laminate may be considered a single layer composite. Most composites used in structural applications are *multilayered*; that is, they consist of several layers of fibrous composites. Each layer or lamina is a single layer composite and its orientation is varied according to design. Several identical or different layers are bonded together to form a multilayered composites usable for engineering applications. When the constituent materials in each layer are the same, they are called simply *laminates*. *Hybrid* laminates refer to multilayered composites consisting of layers made up of different constituent materials. Reinforcing fibers in a single layer composite may be short or long compared to its overall dimensions. Composites with long fibers are called *continuous fiber reinforced composites* and those with short fibers, *discontinuous fiber reinforced composites*. The continuous fibers in single layer composites may be all aligned in one direction to form a *unidirectional composite*. Such composites are fabricated by laying the fibers parallel and saturating them with resinous material. The *bidirectional reinforcement* may be provided in a single layer in mutually perpendicular directions as in a woven fabric. The bidirectional reinforcement may be such that the strengths in two perpendicular directions are approximately equal. The orientation of discontinuous fibers cannot be easily controlled in a composite material. So fibers can be either *randomly oriented* or *preferred oriented*. In most cases the fibers are assumed to be randomly oriented in the composites. However, in the injection moulding of a fiber reinforced polymer, considerable orientation can occur in the flow direction and which a case of preferred oriented fibers in the composites.

Particulate Composites

As the name itself indicates, the reinforcement is of particle nature (platelets are also included in this class). It may be spherical, cubic, tetragonal, a platelet, or of other regular or irregular shape, but it is approximately equiaxed. In general, particles are not very effective in improving fracture resistance but they enhance the stiffness of the composite to a limited extent. Particle fillers are widely used to improve the properties of matrix materials such as to modify the thermal and electrical conductivities, improve performance at elevated temperatures, reduce friction, increase wear and abrasion resistance, improve machinability, increase surface hardness and reduce shrinkage. Also, in case of particulate reinforced composites the particle can be either randomly oriented or preferred oriented.

1.6.2. According to Type of Matrix Material

1) Metal Matrix Composites (MMC)

2) Ceramic Matrix Composites (CMC)

3) Polymer Matrix Composites (PMC)

Metal matrix composites

Metal Matrix Composites have many advantages over monolithic metals like higher specific modulus, higher specific strength, better properties at elevated temperatures, and lower coefficient of thermal expansion. Because of these attributes metal matrix composites are under consideration for wide range of applications viz. combustion chamber nozzle (in rocket, space shuttle), housings, tubing, cables, heat exchangers, structural members etc.

Ceramic matrix composites

One of the main objectives in producing ceramic matrix composites is to increase the toughness. Naturally it is hoped and indeed often found that there is a concomitant improvement in strength and stiffness of ceramic matrix composites.

Polymer matrix composites

Most commonly used matrix materials are polymeric. The reasons for this are twofold. In general the mechanical properties of polymers are inadequate for many structural purposes. In particular their strength and stiffness are low compared to metals and ceramics. These difficulties are overcome by reinforcing other materials with polymers. Secondly the processing of polymer matrix composites need not involve high pressure and doesn’t require high temperature. Also equipments required for manufacturing polymer matrix composites are simpler. For this reason polymer matrix composites developed rapidly and soon became popular for structural applications.

Composites are used because overall properties of the composites are superior to those of the individual components for example polymer/ceramic. Composites have a greater modulus than the polymer component but aren’t as brittle as ceramics. Two types of polymer composites are: fiber reinforced polymer (FRP) and particle reinforced polymer (PRP).

Fiber reinforced polymer

Common fiber reinforced composites are composed of fibers and a matrix. Fibers are the reinforcement and the main source of strength while matrix glues all the fibers together in shape and transfers stresses between the reinforcing fibers. The fibers carry the loads along their longitudinal directions. Sometimes, filler might be added to smooth the manufacturing process, impact special properties to the composites, and / or reduce the product cost. Common fiber reinforcing agents include asbestos, carbon / graphite fibers, beryllium

beryllium carbide, beryllium oxide, molybdenum, aluminium oxide, glass fibers, polyamide, natural fibers etc. Similarly common matrix materials include epoxy, phenolic, polyester, polyurethane, peek, vinyl ester etc. Among these resin materials, epoxy is widely used for its higher adhesion and less shrinkage property.

Particle reinforced polymer

Particles used for reinforcing include ceramics and glasses such as small mineral particles, metal particles such as aluminium and amorphous materials, including polymers and carbon black. Particles are used to increase the modules of the matrix and to decrease the ductility of the matrix. Particles are also used to reduce the cost of the composites. Reinforcements and matrices can be common, inexpensive materials and are easily processed. Some of the useful properties of ceramics and glasses include high melting temperature, low density, high strength, stiffness, wear resistance, and corrosion resistance. Many ceramics are good electrical and thermal insulators. Some ceramics have special properties; some ceramics are magnetic materials; some are piezoelectric materials; and a few special ceramics are even superconductors at very low temperatures. Ceramics and glasses have one major drawback: they are brittle. An example of particle reinforced composites is an automobile tire, which has carbon black particles in a matrix of poly-isobutylene elastomeric polymer.

Based on the form of reinforcement, common composite materials can be classified as follows:

1. Fibers as the reinforcement (fibrous composites)
2. Random fiber (short fiber) reinforced composites

1.7. Structure of Composites

Structure of composite material determines its properties to a significant extent.

Properties

1) Nature of the constituent material (bonding strength)

2) The geometry of the reinforcement (shape, size)

3) The concentration distribution (vol. fraction of reinforcement)

4) The orientation of the reinforcement (random or preferred)

Good adhesion (bonding) between matrix phase and displaced phase provides transfer of load applied to the material to the displaced phase via the interface. Good adhesion is required for achieving high level of mechanical properties of composites. Very small particles less than 0.25 micrometer finely distributed in the matrix impede movement of dislocations and deformation of the material. They have strengthening effect. Large dispersed phase particles have low share load applied to the material resulting in increase of stiffness and decrease of ductility. Orientation of reinforcement:

1) Planar: In the form of 2-D woven fabric. When the fibers are laid parallel, the composite exhibits axistrope.
2) Random or Three Dimensional: The composite material tends to posses isotropic properties.
3) One Dimensional: Maximum strength and stiffness are obtained in the direction of fiber.

1.8. Benefits of Composites

Different materials are suitable for different applications. Advantages of composites over their conventional counterparts are the ability to meet diverse design requirements with significant weight savings as well as strength-to-weight ratio. Processing of FRP/Composites involves complex chemical reactions. Final properties are determined by many factors including the type, amount, and composition of the resin systems and reinforcements. In addition, the use of additives can greatly affect the FRP/Composite properties. When composites are selected over traditional materials such as metal alloys or woods, it is usually because of one or more of the following advantages:

- **Cost**
  - Prototypes
  - Mass production
  - Part consolidation
  - Maintenance
  - Long term durability
  - Production time
  - Maturity of technology

- **Weight**
  - Light weight
  - Weight distribution
  - Strength and Stiffness
  - High strength-to-weight ratio
  - Directional strength and/or stiffness

- **Dimension**
  - Large parts
  - Special geometry

- **Surface properties**
  - Corrosion resistance
  - Weather resistance
  - Tailored surface finish

- **Thermal properties**
  - Low thermal conductivity
  - Low coefficient of thermal expansion

- **Electric property**
  - High dielectric strength
  - Non-magnetic
  - Radar transparency

It is to be noted that there is no one-material-fits-all solution in the engineering world. Also, the above factors may not always be positive in all applications. An engineer has to weigh all the factors and make the best decision in selecting the most suitable material(s) for the project at hand. Table 1.1 shows few applications of composite material in different industry.

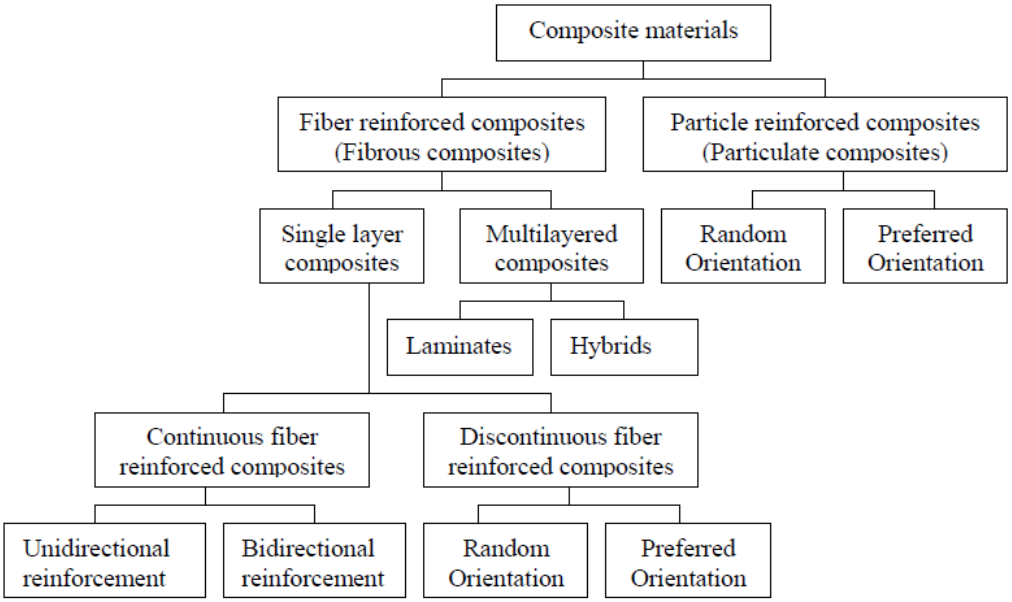


Figure 1.1: Classification of composite materials

Table 1.1: Application of composites

Industry	Examples	Comments
Aircraft	Door, elevators	20-35% Weight savings
Aerospace	Space Shuttle, Space stations	Great weight savings
Automotive	Body frames, engine components	High stiffness and damage tolerance
Chemical	Pipes, Tanks, Pressure vessels	Corrosion resistance
Construction	Structural and decorative panels, fuel tanks	Weight savings, portable

Chapter 2: Literature Review and Aim of the Work

2.1. Literature review

The purpose of this literature review is to provide previous information on the issues to be considered in this thesis and to emphasize the relevance of the present study. Composite materials are playing an important role in a wide range of application fields and replacing many traditional engineering materials. Glass fiber reinforced composite materials are a class of materials used in various products including aerospace, automobile, sporting goods, marine bodies, plastic pipes, storage containers, etc. The aim is of the present work is to present optimization aspects of machining of glass fibre reinforced polymers (GFRP) for improving material removal rate (MRR) and surface roughness of the finished product.

Machining of polymers/ composites (Evestine and Rogers, 1971; Alauddin et al., 1995) is employed when the quantity of items does not justify the cost for moulds, or when a product needs accurate dimensional accuracy, better surface finish. As high performance polymers have been increasingly used for a large number of industrial applications, the machining quality is becoming a predominant factor for the development of new processes and materials. Nevertheless, the knowledge about the polymer behaviour under machining is very limited, as well as the definition of suitable models for the prediction of cutting forces. In the scientific literature, machining of plastics is poorly treated. In the oldest references, an experimental approach is preferred, assuming that plastics behave as metals.

Kobayashi (1967) collected several experimental observations in his book '*Machining of plastics*'. This text has been considered as a reference for a long time in this field. Also the latest scientific reviews mention it to show the dependence of the cutting forces on process parameters. Roy and Basu (1977) defined generalized equations for evaluating the main cutting force and the surface roughness in terms of cutting speed, feed, depth of cut and tool-nose-radius in turning Nylon 6 and Teflon. Wu et al. (1985) examined that four facet, eightfacet, Jo-point, inverted cone and special geometry were some of the widely used tool designs in drilling composite materials. Konig (1985) investigated the phenomenon of machining of FRP composites using different processes like drilling, routing, milling, water jet cutting and laser cutting. The machining of FRP was seemed different from that of metal working in many aspects because of the inhomogeneous material behaviour, dependence on fiber and matrix properties, fiber orientation and the type of weave.

Hocheng et al. (1993) studied the machinability of some reinforced thermoset and thermoplastics for drilling operation. They discussed the chip characteristics and the specific cutting energy to reveal the mechanism of material removal. They observed that the level for fiber loading and the deformation behaviour of matrix polymer determined the extent of plasticity in chip formation and the chip length. In a further study, they also observed that, drilling fiber reinforced-thermoplastics, the edge quality was generally fine except in the case of concentrated heat accumulation at tool lips, which was generated by high cutting speed and low feed rate. An et al. (1997) reported that for the practical cutting of glass fiber, optimal cutting parameters should be taken into consideration to achieve less blade wear, good cutting quality, etc. During glass fiber cutting, the reduction of blade wear is a critical aspect. Long glass fibers were found to affect cutting quality significantly. Abrate (1997) stated that during machining of composite materials some damages may appear, like delamination, fibre pull-out, cracks or thermal degradation. These machining defects tend to cause a loss of the load carrying capacity of the laminate, which is really undesirable. Chen (1997) carried out experimental investigation on carbon/epoxy composite and recommended that high speed and low feed rate were key factors for producing delamination free and good surface finish holes. Increasing the cutting speed would certainly increase production rate. Eriksen (1999) studied the influence of cutting parameters on the surface roughness of machined short fiber reinforced thermoplastic. Lin and Shen (1999) analyzed drilling operation on FRP composites at high spindle speed and concluded that drill wear was the major problem at high speeds. Xiao and Zhang (2002) investigated the role of viscous deformation in machining of polymers. Palanikumar et al. (2003) highlighted machining of glass fiber reinforced composite pipes for cost effective implementation; the machinability became a major parameter. For successful application of these composites, the surface finish and surface integrity were seemed most important especially for surface sensitive parts subjected to fatigue or creep. Davim et al. (2004a, b) studied the influence of cutting parameters (cutting, velocity and feed) while machining GFRP with two different matrixes in order to study the influence of those parameters on delamination.

Khashaba (2004) studied the influence of material variables on thrust force, torque and delamination while drilling of GFRP composites with different types of fiber structures. They carried out the experiment with cross winding/polyester, continuous winding/polyester, woven polyester and woven/epoxy. It was found that woven epoxy showed best results in terms of torque, thrust force.

Tsao and Hocheng (2004) studied drilling operation of CFRP composite based on Taguchi's technique and Analysis of Variance (ANOVA). The main focus of this work was to have a correlation between drill diameter, feed rate and spindle speed. Results indicated that the drill diameter have a significant contribution to the overall performance. A considerable amount of investigations were directed towards the prediction and measurement of thrust forces. It has been found that the thrust force generated during drilling had a direct influence on the cutting of material. Wear on the tool, accuracy of the work piece dimensions and quality of the hole obtained in drilling were mainly influenced by the thrust force.

Singh et al. (2004) highlighted on drilling induced damage in FRP composite laminates for the high degree of intricacy in composite structures which necessitated special process to create holes in them for the purpose of assembly. Numerous methods were used, but conventional drilling still remained the unavoidable process for making holes in composite laminates. Kim et al. (2005) studied the effect of the consolidation process on drilling performance and machinability of PIXA-M and PEEK thermoplastic composites. They observed that the fabrication process could significantly affect the material machinability, as the induction-processed composite material produced equivalent or better holes than the autoclave processed composites. Moreover they also discussed unique chip characteristics during drilling both autoclaved and induction heat-pressed thermoplastic composites.

Mata et al. (2006) studied the physical cutting of polyamide composites by means of the theoretical model of Merchant's circle. Davim and Mata (2007a) reported the study of physical cutting of polyamide composites. Turning tests were carried out on large diameter rods (50 mm) of unfilled PA6 and 30 wt% glass fiber filled PA66. Palanikumar (2007) investigated towards modeling and analysis for surface roughness in machining glass fiber reinforced plastics using Response Surface Methodology (RSM). ANOVA was used to check the validity of the model for finding the significant parameters.

Davim and Mata (2007b) studied machinability of GFRP plastics using polycrystalline diamond and cemented carbide carbide (K15) tools; the GFRP was manufactured by hand layup method. A statistical technique using orthogonal array and ANOVA was employed to know the influence of cutting parameters on specific cutting pressure and surface roughness of machined composite product. Abrao et al. (2007) focused the effect of cutting tool geometry and material on thrust force and delamination produced while drilling GFRP composites. Dandekar et al. (2007) carried out an experimental study of comparing drilling characteristics of E-glass fabric reinforced polypropylene composite and aluminium alloy 6061-T6. Mohan et al. (2007) studied the influence of cutting parameters, drill diameter and thickness while machining GFRP composites and analyze the delamination. Camposrubio et al al. (2008) studied the influence of process parameters on delamination in drilling of composite materials at high speed using cemented carbide drills.

Durao et al. (2008a) studied the effect of drilling characteristics of hybrid carbon +glass/epoxy composites. They validated the influence of delamination in bearing stress of drilled hybrid carbon +glass/epoxy quasi-isotropic plates. Durao et al. (2008b) studied on drilling of fibre reinforced plastic laminates for unique machining process, characterized by the existence of two different mechanisms: extrusion by the drill chisel edge and cutting by the rotating cutting lips. Krishnaraj (2008) studied the effect of drill points on glass fibre reinforced plastic composite at high spindle speed. The most effective way of achieving good quality holes while drilling fibre reinforced plastics was found by reducing thrust as well as torque.

Kishore et al. (2009) focused on drilling of [(0/90)/0]S GFRP plastics using Taguchi method for examining significance of drill point geometry and the operating variables on drilling force and drilling induced damage. Singh et al. (2009) highlighted modelling and analysis of thrust force and torque in drilling GFRP composites by multi-facet drill using fuzzy logic using 8 facet solid carbide drills based on L_{27} orthogonal array. The process parameters investigated were spindle speed, feed rate and drill diameter. Fuzzy rule based model was developed to predict thrust force and torque in drilling of GFRP composites. The results indicated that the model could be effectively used for predicting the response variable by means of which delamination could be controlled. Latha and Senthilkumar (2009) successfully applied fuzzy logic for the prediction of delamination in drilling of glass fibre reinforced plastics.

Hussain et al. (2010) carried out investigations on machining of GFRP composites by carbide tools (K20) for development of a surface roughness prediction model using RSM.

2.2. Motivation and Aim of the Present Work

In recent era of globalization, manufacturers are putting more emphasis on customers' satisfaction. Therefore, modern quality programs being carried out by every manufacturing/production units are giving much importance to maintain required product quality along with productivity. For effective use of any machining process, it becomes necessary to find optimum process parameters to achieve improved quality as well as increased productivity.

Fiber Reinforced Plastic (FRP) (also fiber reinforced polymer) is a *composite material* made of a *polymer* matrix reinforced with fibers. The fibers are usually glass fiber, *carbon*, or *aramid*, while the polymer is usually an *epoxy*, *vinylester* or *polyester thermosetting plastic*. FRPs are commonly used in the aerospace, automotive, marine, and construction industries. Fiber reinforced plastics are best suited for any design problem that demands weight savings, precision engineering, finite tolerances, and the simplification of parts in both production and operation.

With the upcoming usage of fiber reinforced polymer (FRP) composites in various areas of applications, machining of these materials has become a major concern for the manufacturing industries. The current knowledge and state of art of machining FRP composites, unfortunately, is seemed inadequate for its optimal economic utilization. This research presents an optimization study made on machining of randomly oriented glass fiber reinforced (GFRP) polymer composite rods with different process environment. Two case studies have been presented here on selection of optimal machining parameters to ensure high productivity as well as satisfactory surface quality of machined glass fiber reinforced polyester as well as glass fiber reinforced epoxy composites. An expert system based on fuzzy rule based modelling approach combined with Taguchi's robust optimization philosophy has been adopted to evaluate optimal process parameters thereby satisfying conflicting requirements of *material removal rate (MRR)* and surface roughness *(roughness average)* of the machined composite product. Effectiveness of the proposed model has been illustrated in later parts of the thesis.

2.3. Bibliography

1. Evestine G.C., and Rogers T.G. (1971) ‘A theory of machining of fiber-reinforced materials’, *Journal of Composite Materials*, Vol. 5, pp. 94-106.
2. Alauddin M., Choundhury I.A., Baradie El, and Hashmi M.S.J. (1995) ‘Plastics and their machining: A review’. *Journal of Materials Processing Technology*, Vol. 54, pp. 40–46.
3. Kobayashi A. (1967) ‘Machining of plastics’, *McGraw-Hill*, New York.
4. Roy P.K., and Basu S.K. (1977) ‘Evaluation of processing factors on turning of thermoplastics’, *Polymer Engineering and Science*, Vol. 17, pp. 751–757.
5. Wu S.M, Multifacet drills (1985), In: Robert I. King, Editor, Handbook of High-speed Machining Technology, London, Chapman and Hall, pp.305-316.
6. Konig W. (1985) ‘Machining of fiber reinforced plastics’: *Annals of CIRP*, Vol. 34, pp. 537-548.
7. Hocheng H., Pwu H.Y., and Yao K.C. (1993) ‘On drilling characteristics of fiber-reinforced thermoset and thermoplastics’, *Materials and Manufacturing Processes*, Vol. 8, pp. 653–682.
8. An S.O., Lee E.S., and Noh S.L. (1997) ‘A study on the cutting characteristics of glass fiber reinforced plastics with respect to tool materials and geometries’, *Journal of Materials Processing Technology*, Vol. 68, No. 1, pp. 60-67.
9. Abrate S. (1997) ‘Machining of composite materials’, Composites Engineering Handbook, P. K. Mallick, *Marcel Dekker*, New York, pp. 777-809.

10. Chen W.-C. (1997) 'Some experimental investigation in the drilling of carbon fiber reinforced plastic (CFRP) composite laminates', *International Journal of Machine Tools and Manufacture*, Vol. 37, No. 8, pp. 1097-1108.
11. Eriksen E. (1999) 'Influence from production parameters on the surface roughness of a machined short fibre reinforced thermoplastic', *International Journal of Machine Tools and Manufacture*, Vol. 39, pp. 1611–1618.
12. Lin S.-C., and Shen J.-M. (1999) 'Drilling unidirectional glass fiber-reinforced composite materials at high speed', *Journal of Composite Materials*, Vol. 33, No. 9, pp 827-851.
13. Xiao K.Q., and Zhang L.C. (2002) 'The role of viscous deformation in the machining of polymers', *International Journal of Mechanical Sciences*, Vol. 44, pp. 2317–2336.
14. Palanikumar K., Karunamurthy L.,Vinoth C., and Muthu S.V. (2003) "On the machining of glass fiber reinforced composite Pipes', *Proceedings of the International Conference on Mechanical Engineering (ICME2003)*, pp. 26- 28, Dhaka, Bangladesh
15. Davim J.P., Reis, P., and Antonio, C.C. (2004a) 'Experimental study of drilling glass fiber reinforced plastics manufactured by hand layup', *Composite Science and Technology*, Vol. 64, pp.289-297.
16. Davim J.P., Reis, P., and Antonio, C.C. (2004b) 'Drilling fiber reinforced plastics manufactured by hand lay-up: Influence of matrix (VIAPAL VUP 9731 and ATLAC 382-05)', *Journal of Materials Processing Technology*, Vol. 155-156, pp.1828-1833.
17. Khashaba U.A. (2004) 'Delamination in drilling GFRP thermoset composites', *Composite Structures*, Vol.63, pp. 313-327.
18. Tsao C.C., and Hocheng, H. (2004) 'Taguchi analysis of delamination associated with various drill bits in drilling of composite material', *International journal of Machine tools and manufacture*, Vol.44, pp. 1085-1090.

19. Singh I., Nayak D., Saxena R., and Bhatnagar N. (2004) 'Drilling induced damage in FRP composite laminates', *Journal of Engineering for Industry*, Vol. 85, pp. 37-40.

20. Kim D., Ramulu M., and Doan X. (2005) 'Influence of consolidation process on the drilling performance and machinability of PIXA-M and PEEK thermoplastic composites', *Journal of Thermoplastic Composite Materials*, Vol. 18, pp. 195–217.

21. Mata F., Reis P., Davim J.P. (2006) 'Physical cutting model of polyamide composites (PA66 GF30)', *Materials Science Forum*, Vol. 514–516, pp. 643–647.

22. Davim J.P., and Mata F. (2007a) 'A comparative evaluation of the turning of reinforced and unreinforced polyamide', International Journal of Advanced Manufacturing Technology, Vol. 33, pp. 911–914.

23. Palanikumar K. (2007) 'Modelling and analysis for surface roughness in machining glass fibre reinforced plastic using RSM methodology', *Material and Design*, Vol. 28, pp. 2611-2618.

24. Davim J.P., and Mata. F. (2007b) **'**New machinability of GFRP plastics using polycrystalline diamond and cemented carbide carbide (K15) tools', *Material and design*, Vol. 28, pp. 1050-1054.

25. Abrao A.M., Faria P.E., Campos R.J.C., and Davim J.P. (2007) 'Drilling of fiber reinforced plastics: a review', *Journal of Materials Processing Technology*, Vol. 186, pp.1-7.

26. Dandekar C., Orady E., and Mallick P.M. (2007) 'Drilling characteristics of an e-glass fabric–reinforced polypropylene composite and an aluminum alloy: A comparative study', *Journal of American Society of Mechanical Engineering*, Vol.129, pp.14-18.

27. Mohan. N.S., Kulkarni S.M, and Ramachandra A. (2007) 'Delamination analysis in drilling process of glass fiber reinforced plastics (GFRP) composite materials', *Journal of Material Processing Technology*, Vol. 186, pp.265- 271.

28. Camposrubio A.M. Abrao, Faria P.E., Coreeia A. Esteves, and Davim. J.P. (2008) ‘Effects of high speed in drilling of glass fibre reinforced plastic: Evaluation of delamination factor’, *International Journal of Machine Tools and Manufacture*, Vol. 48, pp.715-721.
29. Durao L.M.N., Magalhaes A.G., Manuel J Tavares R.S., and Marques A.T. (2008a) ‘Analyzing objects in images for estimating the delamination influence on load carrying capacity of composite laminates’, *Electronic Letters on computer Vision and Image Analysis*, Vol. 7, No. 2, pp.11-21.
30. Durao L.M.N., Magalhaes A.G., Marques A.T., Baptista A.M., and Figueired M. (2008b) ‘Drilling of fibre reinforced plastic laminates’, *Materials Science Forum*, Vol. 587-588, pp. 706-710.
31. Krishnaraj V. (2008) ‘Effects of drill points on glass fibre reinforced plastic composite while drilling at high spindle speed’, *Proceedings of the World Congress on Engineering 2008 Vol II WCE 2008*, July 2 - 4, 2008, London, U.K.
32. Kishore R.A., Tiwari R., and Singh I. (2009) ‘Drilling of [(0/90)/0]S GFRP plastics using Taguchi Method’, *International Journal of Advances in Production Engineering and Management*, Vol. 4, No. 1-2, pp. 37-46.
33. Singh R.V.S., Latha B., and Senthilkumar V.S. (2009) ‘Modeling and analysis of thrust force and torque in drilling GFRP composites by multi-facet drill using fuzzy logic’, *International Journal of Recent Trends in Engineering*, Vol. 1, No. 5, pp. 66-70.
34. Latha. B., and Senthilkumar V.S. (2009) ‘Fuzzy rule based modeling of drilling parameters for delamination in drilling GFRP composites’, *Journal of Reinforced Plastics and Composites*, (Online Version available) DOI: 10.1177/0731684407087570.

35. Hussain S.A., Pandurangadu V., and Palanikumar K. (2010) 'Surface roughness analysis in machining of GFRP composites by carbide tools (K20)', *European Journal of Scientific Research*, Vol. 41, No. 1, pp. 84-98.

Websites

36. *www.whitebuffalobeadsandstones.com*
37. *www.ia.ucsb.edu*
38. *www.wikipedia.com/Composite material.html*
39. *www.structsource.com/pdf/composite.pdf*
40. *www.emba.uvm.edu/iatridis/me257/Introduction.html*
41. *www.engr.sjsu.edu/sgleixner/PRIME/FRP.pdf*
42. *www.autospeed.com/composites.html*

Chapter 3

Optimization in Machining Glass Fiber Reinforced Polyester Composites

3.1. Introduction: Prior State of Art and Problem Formulation

FRP (Fiber Reinforced Polymer) Composite is a mixture of materials that include special polymers reinforced with fibers designed to carry loads much stronger than a regular plastic or ordinary fiberglass. Other materials include resins, fillers and additives. Polymer is plastic, and fibers are added to reinforce it. Each material has its own purpose and contribution to the strength and durability of the product being manufactured. When combined in the proper manner, the result is the best in strength, light weight as well as cost effectiveness.

FRP Composite itself has many benefits over other common materials:

- It has a high strength to weight ratio
- It does not contract or expand due to temperature changes
- It does not rust or absorb water
- It is non-flammable
- It does not conduct electricity
- It is generally chemical resistant

Santhanakrishnam et al. (1988) carried out face turning trials on glass fiber reinforced polymers (GFRP), carbon fiber reinforced polymers (CFRP) and kevlar fiber reinforced polymers (KFRP) cylindrical tubes to study their machined surfaces for possible application as friction surfaces. The surface roughness obtained and the observed morphology of the machined surfaces of fiber reinforced polymer (FRP) composites was compared. The mechanisms of material removal and tool wear were also discussed. The cutting forces encountered during machining of composites were also reported. El-Sonbaty et al. (2004) investigated the influence of cutting speed, feed, drill size and fiber volume fraction on the thrust force, torque and surface roughness in drilling processes of fiber reinforced epoxy composite materials. Davim and Mata (2005a) presented an optimization study of surface roughness in turning FRPs tubes manufacturing by filament winding and hand lay-up, using polycrystalline diamond cutting tools. Optimal cutting parameters were identified to obtain a certain surface roughness (*Ra* and *Rt/R*max), corresponding to international dimensional precision (ISO) IT7 and IT8 in the FRP work pieces, using multiple analysis regression (MRA). Additionally, the optimal material removal rates were identified. Mohan et al. (2005) outlined the Taguchi optimization methodology, which is applied to optimize cutting parameters in drilling of glass fiber reinforced composite (GFRC) material followed by Analysis of Variance (ANOVA); to study the effect of process parameters on machining process. The drilling parameters and specimen parameters evaluated were speed, feed rate, drill size and specimen thickness. A series of experiments were conducted to relate the cutting parameters and material parameters on the cutting thrust and torque. An orthogonal array, signal-to-noise ratio were employed to analyze the influence of these parameters on cutting force and torque during drilling. Analysis of the Taguchi method indicated that among the all-significant parameters, speed and drill size were found to impose more significant influence on cutting thrust than the specimen thickness and the feed rate. Davim and Mata (2005b) studied on the machinability in turning processes of fiber reinforced polymers (FRPs) using polycrystalline diamond cutting tools. A statistical technique, using orthogonal arrays and ANOVA, was employed to investigate the influence of cutting parameters on specific cutting pressure and surface roughness. The objective was to evaluate the machinability of these materials as a function of manufacturing process (filament winding and hand lay-up). A new machinability index was proposed by the authors. Jawali et al. (2006) fabricated a series of short glass fiber-reinforced nylon 6 composites with different weight ratios of glass contents by melt mixing. The fabricated nylon 6 composites have been characterized for physical-mechanical properties such as specific gravity, tensile properties, and wear resistance. A marginal improvement in tensile strength and tensile modulus was observed with increase in high modulus fiber. Wear resistance was increased with the increase in rigid glass fiber content in the nylon matrix. The dimensional stability of the composite was found improved with the increase in fiber content. The acoustic behavior of these composites was measured using acoustic emission technique. The surface morphological behaviour of the composites was investigated by scanning electron microscopy (SEM). Bagci and Işık (2006) carried out orthogonal cutting tests on unidirectional glass fiber reinforced polymers (GFRP), using cermet tools. During the tests, the process variables: depth of cut, feed rate and cutting speed were varied, whereas the cutting direction was held parallel to the fiber orientation. Turning experiments were designed based on statistical three level full factorial experimental designs. An artificial neural network (ANN) and response surface (RS) model were developed to predict surface roughness on the turned part surface. In the development of predictive models, cutting parameters of cutting speed, depth of cut and feed rate were considered as model variables. The required data for predictive models were obtained by conducting a series of turning test and measuring the surface roughness data. Good agreement was observed between the predictive models results and the experimental measurements. The ANN and RSM models for GFRPs turned part surfaces were compared with each other for accuracy and computational cost. Palanikumar et al. (2006a) attempted to assess the influence of machining parameters on the machining of GFRP composites. Full factorial design of experiments concept was used for experimentation. The machining experiments were conducted on all geared lathe using coated cermet tool inserts with two level of factors. The factors considered were cutting speed, work piece fiber orientation angle, depth of cut and feed rate. A procedure was developed to assess and optimize the chosen factors to attain minimum surface roughness by incorporating: (i) response table and response graph; (ii) normal probability plot; (iii) interaction graphs; (iv) Analysis of Variance (ANOVA) technique. Palanikumar et al. (2006b) discussed the application of the Taguchi method with fuzzy logic to optimize the machining parameters for machining of GFRP composites with multiple characteristics. A multi-response performance index (MRPI) was used for optimization. The machining parameters viz., work piece (fiber orientation), cutting speed, feed rate, depth of cut and machining time were optimized with consideration of multiple performance characteristics viz., metal removal rate, tool wear, and surface roughness. The results from confirmation runs indicated that the determined optimal combination of machining parameters improved the performance of the machining process. Palanikumar et al. (2006c) developed a mathematical model to predict the surface roughness of machined glass fiber reinforced polymer (GFRP) work piece using regression analysis and analysis of variance (ANOVA) in order to study the main and interaction effects of machining parameters, viz., cutting speed, work piece fiber orientation angle, depth of cut, and feed rate. The adequacy of the developed model was verified by calculating the correlation coefficient. This model could be effectively used to predict the surface roughness of the machined GFRP components. Davim and Mata (2007) investigated the machinability in turning processes of glass fiber reinforced plastics (GFRPs) manufactured by hand lay-up. A plan of experiments was performed on controlled machining with cutting parameters prefixed in work piece. A statistical technique, using orthogonal arrays and analysis of variance (ANOVA), were employed to know the influence of cutting parameters on specific cutting pressure and surface roughness. The objective was to evaluate the machinability of these materials in function of cutting tool (polycrystalline diamond and cemented carbide tools). A new machinability index has been proposed by the authors. Palanikumar and Davim (2007) derived a mathematical model to predict the tool wear on the machining of GFRP composites using regression analysis and analysis of variance (ANOVA) in order to study the main and interaction effects of machining parameters, viz., cutting speed, feed rate, depth of cut and work piece fiber orientation angle. The adequacy of the developed model was verified by using coefficient of determination and residual analysis. This model could be effectively used to predict the tool wear on machining GFRP components within the ranges of variables studied. The influences of different parameters in machining GFRP composite were also analyzed. Palanikumar (2007) attempted to model the surface roughness through response surface method (RSM) in machining GFRP composites. Four factors five level central composite, rotatable design matrix was employed to carry out the experimental investigation. Analysis of Variance (ANOVA) was used to check the validity of the model. For finding the significant parameters student's t-test was used. Also, an analysis of the influences of the entire individual input machining parameters on the response were carried out and presented in this study. Karnik et al. (2008) presented application of artificial neural network (ANN) model to study the machinability aspects of unreinforced polyetheretherketone (PEEK), reinforced polyetheretherketone with 30% of carbon fibers (PEEK CF 30) and 30% of glass fibers (PEEK GF 30) machining. A multilayer feed forward ANN was employed to study the effect of parameters such as tool material, work material, cutting speed and feed rate on two aspects of machinability, namely, power and specific cutting pressure. The input-output patterns required for training were obtained from the experiments planned through full factorial design. The analysis reveals that minimum power results from a combination of lower values of cutting speed and feed rate for all work-tool combinations. However, higher values of feed rate were required to achieve minimum specific cutting pressure. The investigation results exhibited that, K10 tool provided better machinability for PEEK and PEEK CF 30 materials, while PCD tool was found preferable for PEEK GF 30 material. Palanikumar (2008a) discussed the use of Taguchi and response surface methodologies for minimizing the surface roughness in machining glass fiber reinforced (GFRP) plastics with a polycrystalline diamond (PCD) tool. The experiments were conducted using Taguchi's experimental design technique. The cutting parameters used were cutting speed, feed and depth of cut. The effect of cutting parameters on surface roughness was evaluated and the optimum cutting condition for minimizing the surface roughness was determined. A second-order model was established between the cutting parameters and surface roughness using response surface methodology. The experimental results revealed that the most significant machining parameter for surface roughness was feed followed by cutting speed. Basheera et al. (2008) presented an experimental work on the analysis of machined surface quality on Al/SiCp composites leading to an artificial neural network-based (ANN) model to predict the surface roughness. The predicted roughness of machined surfaces based on the ANN model was found to be in very good agreement with the unexposed experimental data set. Palanikumar et al. (2008) presented a study of influence of cutting parameters on surface roughness parameters such as Ra, Rt, Rq, Rp and R3z in turning of glass fiber reinforced composite materials. Empirical models were developed to correlate the machining parameters with surface roughness. Analysis of experimental results was carried out through area graphs and three-dimensional surface plots. Palanikumar (2008b) discussed the use of fuzzy logic for modeling machining parameters in machining glass fiber reinforced plastics by poly-crystalline diamond tool. The Taguchi method was used for conducting the experiments, which in turn reduced the number of experiments. An orthogonal array was used to investigate the machining process. The cutting parameters selected were cutting speed, feed, and depth of cut. The output responses considered for the investigation were surface roughness parameters such as arithmetic average height (Ra) and maximum height of the profile (Rt). Fuzzy rule based models were developed for correlating cutting parameters with surface roughness parameters. The model predicted values and measured values were fairly close to each other. The confirmation test results proved the fact that the developed models were effectively representing the surface roughness parameters Ra and Rt in machining of GFRP composites. Davim et al. (2009) reported on the better understanding of the machinability of PA 66 polyamide with and without 30% glass fiber reinforcing, when precision turning at different feed rates and using four distinct tool materials. The findings indicated that the radial force component presented highest values, followed by the cutting and feed forces. The PCD tool gave the lowest force values associated with best surface finish, followed by the ISO grade K15 uncoated carbide tool with chip breaker when machining reinforced polyamide. Continuous coiled micro-chips were produced, irrespectively of the cutting parameters and tool material employed. Palanikumar and Davim (2009) attempted to assess the factors influencing tool wear on the machining of GFRP composites. The factors considered were cutting speed, fibre orientation angle, depth of cut and feed rate. A procedure was developed to assess and optimize the chosen factors to attain minimum tool wear by incorporating (i) response table and effect graph; (ii) normal probability plot; (iii) interaction graphs; (iv) Analysis of Variance (ANOVA) technique. The results indicated that cutting speed is a factor, which had greater influence on tool flank wear, followed by feed rate. Also the determined optimal conditions reduced the tool flank wear on the machining of GFRP composites within the ranges of parameters studied. Kilickap (2010) investigated the influence of the cutting parameters, such as cutting speed and feed rate, and point angle on delamination produced when drilling a GFRP composite. The damage generated associated with drilling GFRP composites were observed, both at the entrance and the exit during the drilling. The author obtained optimum cutting parameters for minimizing delamination at drilling of GFRP composites. This paper presented the application of Taguchi method and Analysis of Variance (ANOVA) for minimization of delamination influenced by drilling parameters and drill point angle. The optimum drilling parameter combination was obtained by using the analysis of signal-to-noise ratio. The conclusion revealed that feed rate and cutting speed were the most influential factor on the delamination, respectively. The best results of the delamination were obtained at lower cutting speeds and feed rates. Kini and Chincholkar (2010) studied the effect of varying machining parameters in turning on surface roughness and material removal rate (MRR) for ±30^0 filament wound glass fiber reinforced polymers (GFRP) in turning operations using coated tungsten carbide inserts under dry cutting conditions. The authors described the development of an empirical model for turning GFRP utilizing factorial experiments. Second order predictive model covering speed, feed, depth of cut and tool nose radius was developed at 95% confidence interval for surface roughness and material removal rate. Hussain et al. (2010) studied on development of a surface roughness prediction model for the machining of GFRP pipes using Response Surface Methodology (RSM). Experiments were conducted through the established Taguchi's Design of Experiments (DOE) on an all geared lathe using carbide (K20) tool. The cutting parameters considered were cutting speed, feed, depth of cut, and work piece (fiber orientation). A second order mathematical model in terms of cutting parameters was developed using RSM. The effect of different parameters on surface roughness was also analyzed. Hussain et al. (2010) studied of machinability of GFRP composite tubes of different fiber orientation angle vary from 30^0 to 90^0. Machining studies were carried out on an all geared lathe using three different cutting tools: namely Carbide (K-20), Cubic Boron Nitride (CBN) and Poly-Crystalline Diamond (PCD). Experiments were conducted based on the established Taguchi's Design of Experiments (DOE) L_{25} orthogonal array on an all geared lathe. The cutting parameters considered were cutting speed, feed, depth of cut, and work piece (fiber orientation). The performances of the cutting tools were evaluated by measuring surface roughness (Ra) and Cutting force (Fz). A second order mathematical model in terms of cutting parameters was developed using RSM. Sait et al. (2008) presented a new approach for optimizing the machining parameters on turning glass-fiber reinforced polymer (GFRP) pipes. Optimization of machining parameters was done by an analysis called desirability function analysis. Based on Taguchi's L_{18} orthogonal array, turning experiments were conducted for filament wound and hand layup GFRP pipes using K20 grade cemented carbide cutting tool. The machining parameters such as cutting velocity, feed rate and depth of cut were optimized by multi-response considerations namely surface roughness, flank wear, crater wear and machining force. A composite desirability value was obtained for the multi-responses using individual desirability values from the desirability function analysis. Based on composite desirability value, the optimum levels of parameters were identified, and significant contribution of parameters was determined by ANOVA. Thus, the application of desirability function analysis in Taguchi technique proved to be an effective tool for optimizing the machining parameters of GFRP pipes.

Literature depicts that efforts have been made by previous researchers in understanding various aspects of composite machining. Machinability aspects with a variety of tool-work material combination have been addressed and well documented in literature. Issues of tool wear, surface roughness, and involvement of cutting forces have been investigated as well. Predictive models haves also been developed using regression modelling, response surface modeling as well as neural network. Optimization aspects have been attempted but to a limited extent.

In parametric optimization, Taguchi method has been found extensive application as it explores statistically designed experiments (orthogonal array) and the concept of signal-to-noise (SN) ratio. The approach is advantageous from economic point of view as it requires well balanced (limited number of experiments) experimental runs resulting reliable prediction outcome. Moreover, Taguchi approach follows optimal search at discrete levels of process parameters in the prescribed domain which can easily be adjusted in the experimental setup. The limitation of the traditional Taguchi approach is the incapability in addressing optimization issues of multiple conflicting objectives. Desirability function was reported (Sait et al., 2008) to combine multiples responses into overall desirability value which was finally optimized by Taguchi method.

However, these optimization approaches were based on the assumption of negligible response correlation; while in practical situation definitely some correlations exist among output responses. Secondly, uncertainty arises in assigning individual response priority weights. Degree of importance of individual responses is represented by the priority weights decided by the decision maker which may vary according to individual's discretion. These create uncertainty, vagueness in the solution. To avoid this fuzzy logic has come into picture. Rajasekaran et al. (2011) attempted to develop a fuzzy model to predict the cutting force thereby cutting power and specific cutting force in machining CFRP composites. The developed models offered satisfactory performance on comparison with the experimental results and hence these models could be effectively used to predict cutting forces in machining of carbon fiber-reinforced plastic composites. In order to bypass various shortcomings of aforesaid traditional optimization approaches, fuzzy linguistic reasoning has been adopted in the present work. Using Fuzzy Inference System (FIS) multiple responses (objectives) have been aggregated into a single quality index: Multi-Performance Characteristic Index (MPCI) which has been finally optimized by Taguchi method. The study demonstrates a case study on selecting an optimal process environment for GFRP composite machining (turning) in which conflicting requirements of (i) material removal rate (MRR in the process) and (ii) surface roughness of the machined product have been satisfied simultaneously. As material removal rate is directly related to productivity and product surface roughness dictates the aspect of product quality; the present problem is reduced to a situation of quality-productivity optimization. It is felt that there must be an optimal compatible balance between quality and productivity.

3.2. Experimentation

The present study has been done through the following plan of experiments.

[1] Checking and preparing the centre lathe ready for performing the machining operation.

[2] Cutting GFRP bars and performing initial turning operation in lathe to get desired dimension ($\phi 50 \times 150$) of the work pieces.

[3] Calculating weight of each specimen by the high precision digital balance meter before machining.

[4] Performing straight turning operation on specimens in various cutting environments involving various combinations of process control parameters like spindle speed, feed and depth of cut.

[5] Calculating weight of each machined GFRP bars again by the digital balance meter.

[6] Calculating MRR of the process for each experimental run.

[7] Measuring surface roughness (R_a) of the machined surface for each experimental run.

Fiber Reinforced Polyester composite has been selected as work piece material. The specifications of the work piece material are shown in Table 3.1. Carbide tool (K20) has been has been used for this investigation. In the present study, spindle speed (N, rpm), feed rate (f, mm/min) and depth of cut (d, mm), have been selected as design factors while other parameters have been assumed to be constant over the experimental domain. The process variables (design factors) with their values at different levels have been listed in Table 3.2. It is known that the selection of the values of the variables is limited by the capacity of the machine used in the experimentation as well as the recommended specifications for different work piece and tool material combinations. Therefore, three levels have been selected for each of the aforesaid three factors. In the present investigation, Taguchi's L_9 orthogonal array (OA) design (without factorial interaction) has been considered for experimentation (Table

3.3). The machine used for turning is PINACHO manually operated lathe. The surface roughness parameters have been measured using the stylus-type profilometer, Talysurf (Taylor Hobson, Surtronic 3+). The definitions of surface roughness average (R_a), selected in the present study, along with MRR selected in the present study have been given below. The values of measured roughness parameter (average of trials) R_a along with material removal rate (MRR) has been shown in Table 3.4.

R_a (arithmetic average height)

Roughness average R_a is the arithmetic average of the absolute values of the roughness profile ordinates. R_a is the arithmetic mean roughness value from the amounts of all profile values.

$$R_a = \frac{1}{l}\int_0^l |Z(X)|\,dx \tag{3.1}$$

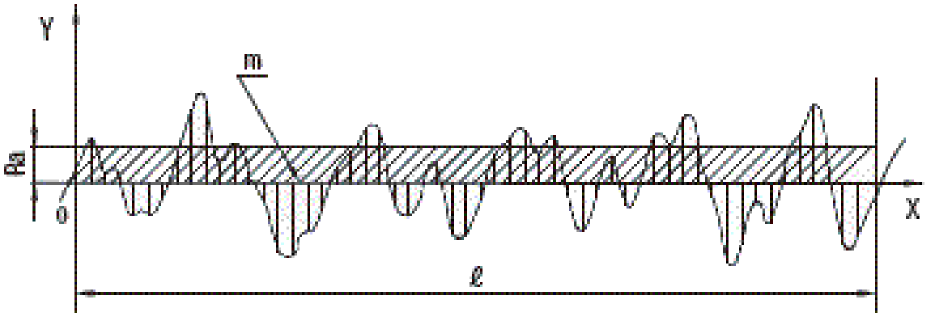


Figure 3.1: Measurement of R_a

Material Removal Rate (MRR)

Material removal rate (MRR) has been calculated from the difference in weights of the work pieces before and after experiment.

$$MRR = \frac{W_i - W_f}{\rho . t_m} \left(mm^3 / \min \right) \tag{3.2}$$

Here, W_i is the initial weight of the work piece in gm

W_f is the final weight of the work piece in gm

ρ is the density of work material (2 gm/cm^3 for GFRP polyester) and

t_m is the machining time in minute.

3.3. Fuzzy Inference System (FIS)

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves the following elements: Membership Functions, Logical Operations, and If-THEN Rules. Most commonly two types of fuzzy inference systems can be implemented: *Mamdani* type and *Sugeno* type. These two types of inference systems vary somewhat in the way outputs are determined [28-43].

Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision. Because of its multidisciplinary nature, fuzzy inference systems are associated with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply (and ambiguously) fuzzy systems.

Mamdani's fuzzy inference method is the most commonly viewed fuzzy methodology. Mamdani's method was among the first control systems built using fuzzy set theory. It was proposed in 1975 by Ebrahim Mamdani (Mamdani, 1976; 1977) as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators.

Mamdani type inference expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It is possible, and in many cases much more efficient, to use a single spike as the output membership functions rather than a distributed fuzzy set. This type of output is sometimes known as a *singleton* output membership function, and it can be thought of as a pre-defuzzified fuzzy set. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of a two-dimensional function. Rather than integrating across the two-dimensional function to find the centroid, weighted average of a few data points is used. Sugeno-type systems support this type of model. In general, Sugeno-type systems can be used to model any inference system in which the output membership functions are either linear or constant. The basic structure of FIS is shown in the following diagram (Figure 3.2). The fuzzy inference process has been described below in Figure 3.3.

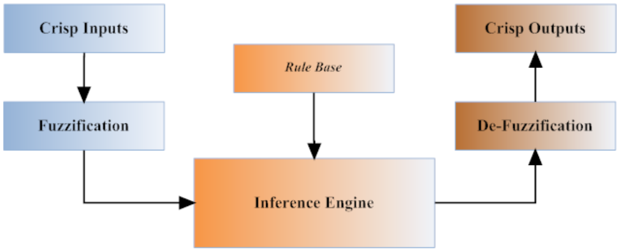


Figure 3.2: Basic structure of FIS

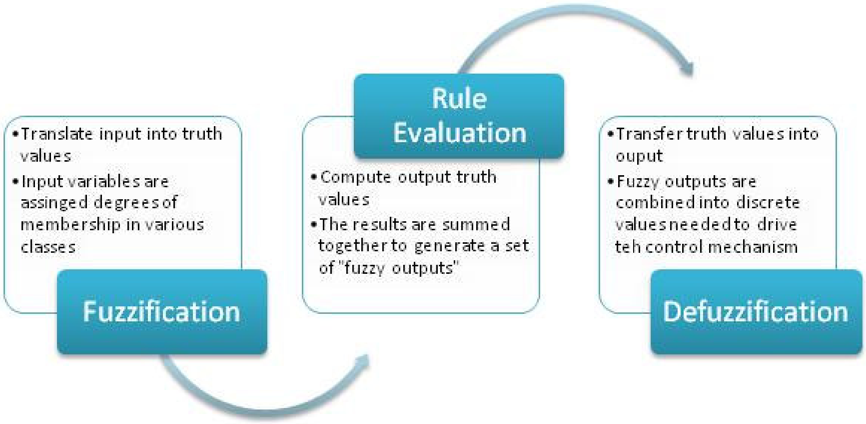


Figure 3.3: Operation of fuzzy inference system

3.4. Parametric Optimization: Results and Discussions

Experimental data (corresponding to Table 3.4) have been converted into corresponding SN ratios using Eqs 3.3-3.4. For surface roughness parameter R_a, a Lower-the-Better (LB) criterion and for MRR, a Higher-the-Better (HB) criterion has been selected.

The SN ratio with a Lower-the-Better (LB) characteristic can be expressed as:

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n} y_{ij}^2\right) \tag{3.3}$$

The SN ratio with a Higher-the-Better (HB) characteristic can be expressed as:

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n} \frac{1}{y_{ij}^2}\right) \tag{3.4}$$

Here, y_{ij} is the ith experiment at the jth test, n is the total number of the tests.

Computed SN ratios have been furnished in Table 3.4. These SN ratios have then been normalized (Table 3.5) based on Higher-the-Better (HB) criteria using Eq. 3.5.

For Higher-the-Better (HB) criterion, the normalized data can be expressed as:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{3.5}$$

Here, $x_i(k)$ is the value of the response (SN ratio) k for the i^{th} experiment, $\min y_i(k)$ is the smallest value of $y_i(k)$ for the k^{th} response (SN ratio), and $\max y_i(k)$ is the largest value of $y_i(k)$ for the k^{th} response (SN ratio).

Normalized SN ratios (Table 3.5) of the responses (R_a and MRR) have been fed as inputs in Fuzzy Inference System (FIS) (Figure 3.4). FIS explores fuzzy rule base (Table 3.6). The output of the fuzzy inference system has been defined as MPCI (Table 3.7). This Multi-Performance Characteristic Index (MPCI) has been finally optimized by using Taguchi methodology. Higher- the- Better (HB) criterion has been used for optimizing (maximizing) the MPCI (Eq. 3.5).

In calculating MPCI in FIS system, various membership functions (MFs) (Figures 3.5-3.6) have been assigned to the input variables: (i) normalized SN ratio of MRR and (ii) normalized SN ratio of R_a. The selected membership functions for input variables are given below.

$MRR_{\text{Normalized SN ratio}}$: “Low”, “Medium” and “High”.

$R_{a\ \text{Normalized SN ratio}}$: “Low”, “Medium” and “High”

Five membership functions have been selected for MPCI: “Very Small”, “Small”, “Medium”, “Large”, and “Very Large” (Figure 3.7). Nine fuzzy rules (Table 3.6) have been explored for fuzzy reasoning (Fig. 8). Fuzzy logic converts linguistic inputs into linguistic output. Linguistic output is again converted to numeric values (MPCI) by defuzzification method. Numeric values of MPCIs have been tabulated in Table 3.7 with corresponding SN ratio. SN ratios of MPCIs have been calculated using Higher-the-Better (HB) criterion. Figure 3.9 represents optimal parametric combination ($N_3\ f_2\ d_2$). Optimal result has been validated by satisfactory confirmatory test. Predicted value of SN ratio of MPCI has been found 1.92944 (higher than all entries of SN ratios in Table 3.7). In confirmatory experiment the value came 1.8913. So, it can be concluded that quality and productivity have improved using the said optimal setting. Table 3.8 represents mean values table of MPCIs. The degree of influence of various factors on MPCI can be estimated from this table. It shows that spindle speed is the most significant factor on influencing MPCIs followed by depth of cut and feed rate.

3.5. Conclusions

In this study, fuzzy rule based expert system has been adopted using two input variables with single output i.e. MPCI. By this way a multi-response optimization problem has been converted into an equivalent single objective optimization problem which has been further solved by Taguchi philosophy. The proposed procedure is simple, effective in developing a robust, versatile and flexible mass production process. Response correlations need not to be revealed and eliminated. In the proposed model it is not required to assign individual response weights. FIS can efficiently take care of these aspects into its internal hierarchy. Degree of influence of various process control factors can be investigated easily. Accuracy in prediction of the model analysis can be subsequently increased by assigning adequate fuzzy rules as well as by increasing number of membership functions in the fuzzy inference system. This approach can be recommended for continuous quality improvement and off-line quality control of a process/product in any manufacturing/ production environment.

3.6. Bibliography

1. Santhanakrishnam G., Krishnamurthy R., and Malhotra S.K. (1988) 'Machinability characteristics of fibre reinforced plastics composites', *Journal of Mechanical Working Technology*, Vol. 17, pp. 195-204.
2. El-Sonbaty I., Khashaba U.A., and Machaly T. (2004) 'Factors affecting the machinability of GFR/epoxy composites', *Composite Structures*, Vol. 63, pp. 329-338.
3. Davim J.P., and Mata F. (2005a) 'Optimization of surface roughness on turning fibre-reinforced plastics (FRPs) with diamond cutting tools', *International Journal of Advanced Manufacturing Technology*, Vol. 26, pp. 319–323.

4. Mohan N.S., Ramachandra A., and Kulkarni S.M. (2005) 'Influence of process parameters on cutting force and torque during drilling of glass–fiber polyester reinforced composites', *Composite Structures*, Vol. 71, pp. 407-413.
5. Davim J.P., and Mata F. (2005b) 'A new machinability index in turning fiber reinforced plastics', *Journal of Materials Processing Technology*, Vol. 170, pp. 436-440.
6. Jawali N.D., Siddeswarappa B., Siddaramaiah (2006) 'Physicomechanical properties, machinability, and morphological behavior of short glass fiber-reinforced nylon 6 composites', Journal of Reinforced Plastics and Composites, Vol. 25, No. 13, pp. 1409-1418.
7. Bagci E., and Işık B. (2006) 'Investigation of surface roughness in turning unidirectional GFRP composites by using RS methodology and ANN', *International Journal of Advanced Manufacturing Technology*, Vol. 31, pp. 10-17.
8. Palanikumar K., Karunamoorthy L., and Karthikeyan R. (2006a) 'Assessment of factors influencing surface roughness on the machining of glass fiber-reinforced polymer composites', *Materials and Design*, Vol. 27, pp. 862–871.
9. Palanikumar K., Karunamoorthy L., Karthikeyan R., and Latha B. (2006b) 'Optimization of machining parameters in turning GFRP composites using a carbide (K10) tool based on the Taguchi method with fuzzy logics', *Metals and Materials International*, Vol. 12, pp. 6, pp. 483-491.
10. Palanikumar K., Karunamoorthy L., and Manoharan N. (2006c) 'Mathematical model to predict the surface roughness on the machining of glass fiber reinforced polymer composites', *Journal of Reinforced Plastics and Composites*, Vol. 25, No. 4, pp. 407-419.
11. Davim J.P., and Mata F. (2007) 'New machinability study of glass fibre reinforced plastics using polycrystalline diamond and cemented carbide (K15) tools', *Materials and Design*, Vol. 28, pp. 1050–1054.

12. Palanikumar K., and Davim J.P. (2007) 'Mathematical model to predict tool wear on the machining of glass fibre reinforced plastic composites', *Materials and Design*, Vol. 28, pp. 2008–2014.
13. Palanikumar K. (2007) 'Modeling and analysis for surface roughness in machining glass fibre reinforced plastics using response surface methodology', *Materials and Design*, Vol. 28, pp. 2611–2618.
14. Karnik S.R., Gaitonde V.N., Mata F., and Davim J.P. (2008) 'Investigative study on machinability aspects of unreinforced and reinforced PEEK composite machining using ANN model', *Journal of Reinforced Plastics and Composites*, Vol. 27, No. 7, pp. 751-768.
15. Palanikumar K. (2008a) 'Application of Taguchi and response surface methodologies for surface roughness in machining glass fiber reinforced plastics by PCD tooling', *International Journal of Advanced Manufacturing Technology*, Vol. 36, pp. 19–27.
16. Basheera A.C., Dabadea U.A., Joshia S.S., Bhanuprasad V.V., and Gadreb V.M. (2008) 'Modeling of surface roughness in precision machining of metal matrix composites using ANN', *Journal of Materials Processing Technology*, Vol. 197, pp. 439–444.
17. Palanikumar K., Matab F., and Davim J.P. (2008) 'Analysis of surface roughness parameters in turning of FRP tubes by PCD tool', *Journal of Materials Processing Technology*, Vol. 204, pp. 469-474.
18. Palanikumar K. (2008b) 'Surface roughness model for machining glass fiber reinforced plastics by PCD tool using fuzzy logics', *Journal of Reinforced Plastics and Composites*, Vol. 00, No. 00/2008, DOI: 10.1177/0731684408092009.
19. Davim J.P., Silva L.R., Festas A., and Abrão A.M. (2009) 'Machinability study on precision turning of PA66 polyamide with and without glass fiber reinforcing', *Materials and Design*, Vol. 30, pp. 228–234.

20. Palanikumar K., and Davim J.P. (2009) ‘Assessment of some factors influencing tool wear on the machining of glass fiber-reinforced plastics by coated cemented carbide tools’, *Journal of Materials Processing Technology*, Vol. 209, pp. 511–519.
21. Kilickap E. (2010) ‘Optimization of cutting parameters on delamination based on Taguchi method during drilling of GFRP composite’, *Expert Systems with Applications*, Vol. 37, pp. 6116–6122.
22. Kini M.V., and Chincholkar A.M. (2010) ‘Effect of machining parameters on surface roughness and material removal rate in finish turning of $\pm 30^0$ glass fibre reinforced polymer pipes’, *Materials and Design*, Vol. 31, pp. 3590–3598.
23. Hussain S.A., Pandurangadu V., and Palanikumar K. (2010) ‘Surface roughness analysis in machining of GFRP composites by carbide tool (K20)’, *European Journal of Scientific Research*, Vol. 41, No. 1, pp. 84-98.
24. Sait A.N., Aravindan S., and Haq A.N. (2008) ‘Optimisation of machining parameters of glass-fibre-reinforced plastic (GFRP) pipes by desirability function analysis using Taguchi technique’, *International Journal of Advanced Manufacturing Technology*, (Published Online) DOI: 10.1007/s00170-008-1731-y
25. Rajasekaran T., Palanikumar K., and Vinayagam B.K. (2011) ‘Experimental investigation and analysis in turning of CFRP composites’, *Journal of Composite Materials*, (Published Online), DOI: 10.1177/0021998311410500.
26. Mamdani E.H. (1976) ‘Advances in the linguistic synthesis of fuzzy controllers’, *International Journal of Man-Machine Studies*, Vol. 8, pp. 669-678.
27. Mamdani E.H. (1977) ‘Applications of fuzzy logic to approximate reasoning using linguistic synthesis’, *IEEE Transactions on Computers*, Vol. 26, No. 12, pp. 1182-1191.
28. Bezdec J.C. (1981) ‘Pattern Recognition with Fuzzy Objective Function Algorithms’, *Plenum Press*, New York.

29. Dubois D., and Prade H. (1980) ‘Fuzzy Sets and Systems: Theory and Applications’, *Academic Press*, New York.

30. Jang J.-S. R., and Sun C.-T. (1997) ‘Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligence’, *Prentice Hall.*

31. Sugeno M. (1985) ‘Industrial applications of fuzzy control’, *Elsevier Science Pub. Co.*

32. Wang L.-X. (1994) ‘Adaptive fuzzy systems and control: design and stability analysis’, *Prentice Hall.*

33. Yager R., and Filev D. (1994) ‘Generation of fuzzy rules by mountain clustering’, *Journal of Intelligent and Fuzzy Systems*, Vol. 2, No. 3, pp. 209-219.

34. Zadeh L.A. (1965) ‘Fuzzy sets, Information and Control’, Vol. 8, pp. 338-353.

35. Zadeh L.A. (1973) ‘Outline of a new approach to the analysis of complex systems and decision processes’, *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 3, No. 1, pp. 28-44.

36. Zadeh L.A. (1989) ‘Knowledge representation in fuzzy logic’, *IEEE Transactions on Knowledge and Data Engineering*, Vol. 1, pp. 89-100.

Websites

37. *http://www.codeproject.com/KB/recipes/Fuzzinator.aspx*

38. *http://www.scielo.br/scielo.php?pid=S0103-17592003000400005&script=sci_arttext*

39. *http://www.mathworks.com/help/toolbox/fuzzy/fp351dup8.html*

40. *http://binoybnair.blogspot.com/2007/03/fuzzification-and-defuzzification.html*

41. *http://www.codeproject.com/KB/recipes/Seshi_FuzzyLogic.aspx*

Table 3.1: Specifications of work material

Resin used	Polyester resin
Fiber orientation	Random
Method of preparation	Hand molding method
Composition	75:25 (Resin: Fiber)
Weight percentage of hardener	5%
Density	2 gm/cm^3

Table 3.2: Machining parameters (domain of experiments)

Parameters	Notation and Unit	Level Values		
		Level 1	Level 2	Level 3
Spindle Speed	N (RPM)	530	860	1400
Feed Rate	f (mm/rev)	0.298	0.308	0.331
Depth of cut	d (mm)	3.0	4.0	5.0

Table 3.3: Design of experiments (L_9 orthogonal array)

Sl. No.	Factor setting (coded form)		
	N	f	d
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3.4: Experimental data, corresponding SN ratios

Sl. No.	MRR (mm^3/min)	Ra (µm)	SN Ratio of MRR (dB)	SN Ratio of Ra (dB)
1	13767.7	5.1333	82.7773	-14.2079
2	13843.4	5.8533	82.8248	-15.3480
3	18525.7	5.9933	85.3555	-15.5533
4	30763.1	5.2933	89.7606	-14.4745

5	27686.8	4.9533	88.8454	-13.8979
6	14648.2	4.5400	83.3157	-13.1411
7	37492.5	5.0200	91.4789	-14.0141
8	28794.2	5.2800	89.1861	-14.4527
9	35762.1	5.2066	91.0685	-14.3311

Table 3.5: Normalized SN ratios

Sl. No.	Normalized SN Ratio of MRR	Normalized SN Ratio of Ra
1	0.00000	0.55774
2	0.00500	0.08510
3	0.29660	0.00000
4	0.80260	0.44722
5	0.69750	0.68260
6	0.06230	1.00000
7	1.00000	0.63080
8	0.73660	0.45626
9	0.95280	0.50671

Table 3.6: Fuzzy rule matrix

Rule No.	**IF** Normalized SN Ratio of MRR is:	**AND** Normalized SN Ratio of Ra is:	**THEN** MPCI is:
1	LOW	LOW	VERY SMALL
2	MEDIUM	LOW	SMALL
3	HIGH	LOW	MEDIUM
4	LOW	MEDIUM	SMALL
5	MEDIUM	MEDIUM	MEDIUM
6	HIGH	MEDIUM	LARGE
7	LOW	HIGH	MEDIUM
8	MEDIUM	HIGH	LARGE
9	HIGH	HIGH	VERY LARGE

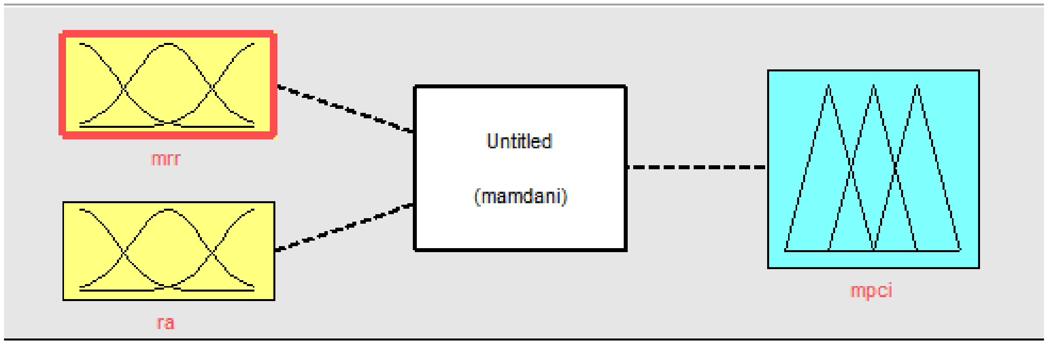
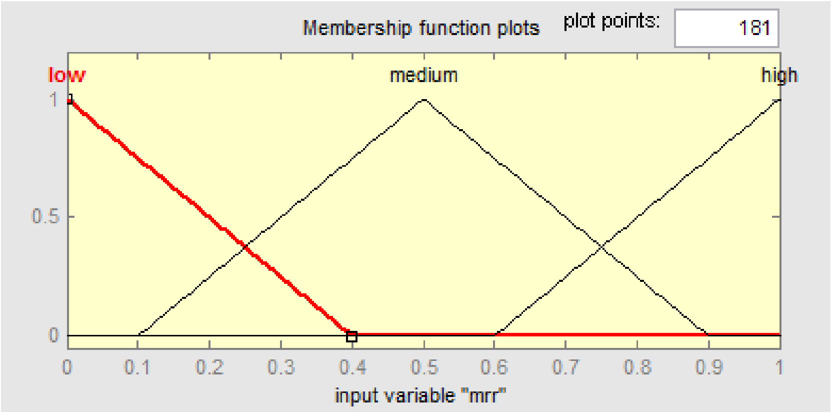
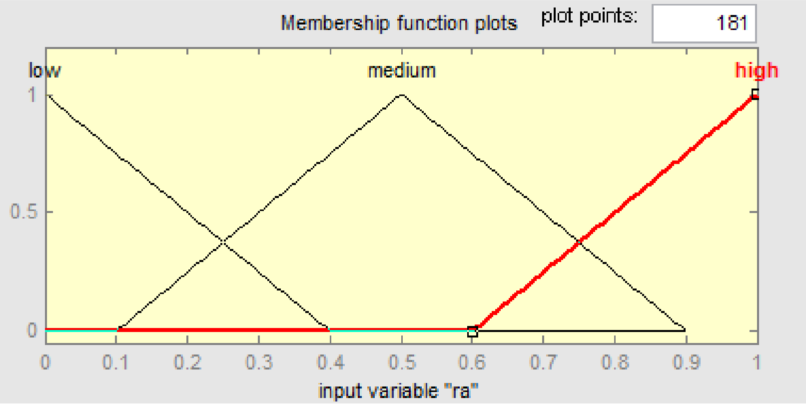


Figure 3.4: Proposed fuzzy inference system



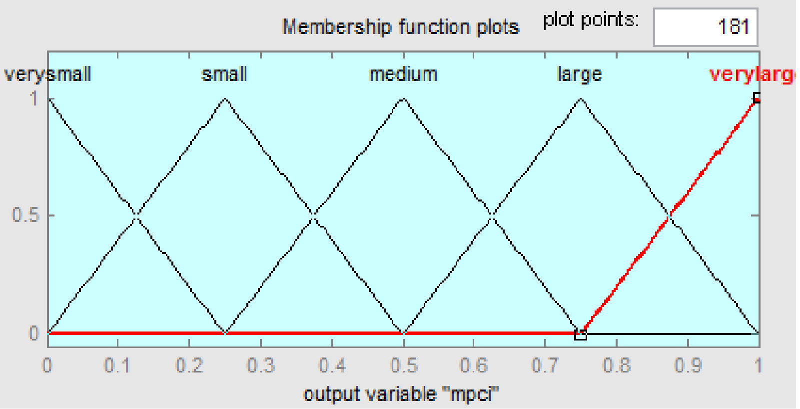
plot points: 181

Figure 3.5: Membership functions (MFs) for MRR (normalized SN ratio of MRR)



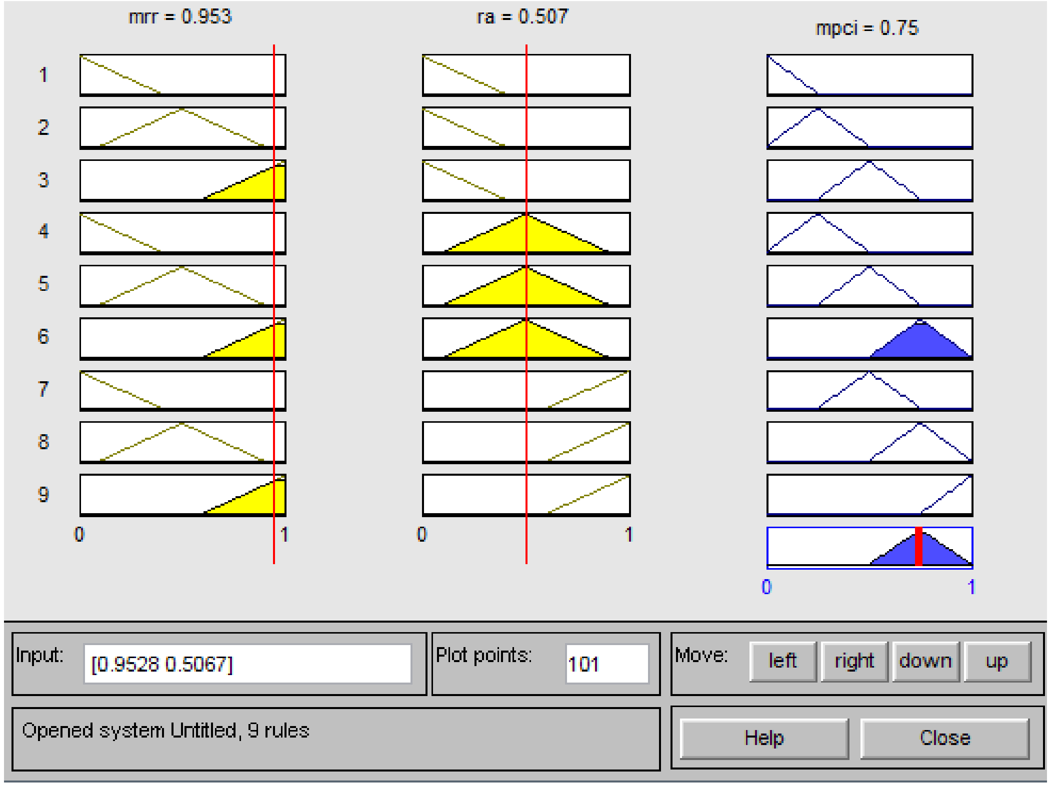
plot points: 181

Figure 3.6: Membership functions (MFs) for Ra (normalized SN ratio of Ra)



plot points: 181

Figure 3.7: Membership functions (MFs) for MPCI


mrr = 0.953

ra = 0.507

mpci = 0.75

Input: [0.9528 0.5067]

Plot points: 101

Opened system Untitled, 9 rules

Figure 3.8: Fuzzy reasoning rule base

Table 3.7: Computed MPCI and corresponding SN ratio

Sl. No.	MPCI	SN Ratio of MPCI (dB)
1	0.250	-12.0412
2	0.836	-1.5559
3	0.238	-12.4685
4	0.666	-3.5305
5	0.594	-4.5243
6	0.500	-6.0206
7	0.752	-2.4756
8	0.614	-4.2366
9	0.750	-2.4988

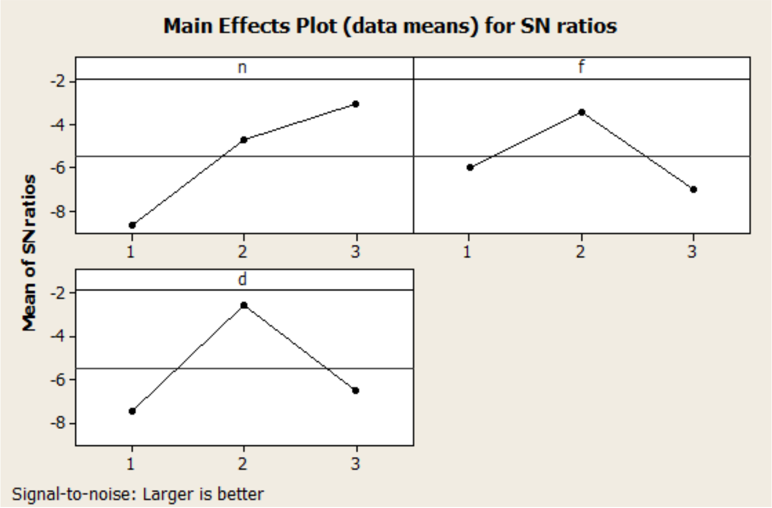


Figure 3.9: Evaluation of optimal setting (SN ratio plot of MPCIs)

Table 3.8: Mean response table (SN ratio of MPCIs)

Level	N	f	d
1	-8.689	-6.016	-7.433
2	-4.692	-3.439	-2.528
3	-3.070	-6.996	-6.489
Delta (max.-min.)	**5.618**	**3.557**	**4.904**
Rank	**1**	**3**	**2**

Chapter 4

Optimization in Machining Glass Fiber Reinforced Epoxy Composites

4.1. State of Art Understanding and Problem Formulation

Glass fiber reinforced epoxy is a composite material made of a polymer matrix (epoxy) reinforced with fibers which are commonly used in the aerospace, automotive, marine, and construction industries. With upcoming worldwide application of composites, machining and machinability aspects of composites are important areas of research. Effect of machining parameters on various quality aspects of the machined composite product are seemed to be studied in detail. Apart from quality; productivity is another important feature which needs to be improved as well. There should be a compatible balance between quality and productivity.

Davim and Mata (2005) studied on the machinability in turning processes of fiber reinforced plastics (FRPs) using polycrystalline diamond cutting tools. A statistical technique, using orthogonal arrays and ANOVA, was employed to investigate the influence of cutting parameters on specific cutting pressure and surface roughness. Mohan et al., (2005) outlined the Taguchi optimization methodology, which was applied to optimize cutting parameters in drilling of glass fiber reinforced composite (GFRC) material followed by Analysis of Variance (ANOVA); to study the effect of process parameters on machining process. Palanikumar, (2008) discussed the use of Taguchi and response surface methodologies for minimizing the surface roughness in machining glass fiber reinforced (GFRP) plastics with a polycrystalline diamond (PCD) tool. Sait et al., (2008) presented a new approach for optimizing the machining parameters on turning glass-fiber reinforced plastic (GFRP) pipes. Optimization of machining parameters was done by an analysis called desirability function (DF) analysis. Basheera et al. (2008) proposed the artificial neural network (ANN) model for predicating the surface roughness and to analyze the machined surface quality during the machining of Al/SiCp composites. Palanikumar and Davim (2009) examined the effect of machining parameters viz. cutting speed, orientation angle, feed rate and depth of cut on tool wear during the machining of GFRP composites with aid of ANOVA technique.

Literature depicts that efforts have been made by previous researchers in understanding various aspects of composite machining. Machinability aspects with a variety of tool-work material combination have been addressed and well documented in literature. Predictive models have also been developed using regression modelling, response surface modelling as well as neural network. Optimization aspects have been attempted to some extent. However, application of traditional Taguchi based optimization methodologies (Tong and Su, 1997; Yang and Tang, 1998) seems not reliable enough as these do not take care of response correlation. Moreover, these approaches assume individual response priority weights depending on the perception of decision-makers. These create uncertainty, imprecision on the optima selection. In order to avoid these shortcomings utility concept embedded with fuzzy logic along with fuzzy logic has been applied to optimize material removal rate and surface roughness in machining glass fiber reinforced epoxy composites. The detailed description of the methodology followed by application feasibility has been described in later part.

4.2. Experimentation

Work Material

Glass fiber reinforced epoxy bar $(\phi 50\times 70)$ of cutting length 30 mm has been used as the work-piece material.

Cutting Tool

Single point carbide cutting tool (Indolov SHRIRAM IK-20) has been used for machining purpose.

Experimental Setup

The machining of GFRE samples has been performed on the PINACHO manually operated lathe.

Design of Experiment (DOE)

Here, machining parameters viz. cutting speed, feed rate and depth of cut has been varied into three different levels (Table 4.1). L_9 Orthogonal array (OA) design has been adopted in the present study (Table 4.2).

Response Measurements

Average surface roughness (R_a) of the machined glass fiber reinforced epoxy has been measured using the stylus-type profilometer, Talysurf (Taylor Hobson, Surtronic 3+).

Material removal rate (MRR) has been calculated from the difference in weights of the work pieces before and after experiment.

$$MRR = \frac{W_i - W_f}{\rho . t_m} \quad mm^3 / \min \tag{4.1}$$

Here, W_i is the initial weight of the work piece in gm

W_f is the final weight of the work piece in gm

ρ is the density of work material (1.75 gm/cm^3 for GFRE polyester) and

t_m is the machining time in minute.

4.3. Proposed Methodology

Utility theory has been used to convert individual response features (i.e. Roughness average and MRR in the present case) into corresponding preference number called individual utility degree. These have been fed to a fuzzy inference system (FIS). Based on fuzzy logic reasoning FIS combines multiple inputs into single output. The crisp value of the output is termed as MPCI (Multi-Performance Characteristic Index). MPCI has been finally optimized by Taguchi method. The procedural steps have been described as follows:

Step 1: Computation of utility degree (preference number) of individual responses

In the present context, the, the utility index for each response has been assessed. The utility theory has been described in paper by [Mishra et al., 2010; Kaladhar et al., 2011].

For evaluating preference number of MRR

Utility index

$$A = \frac{9}{\log \frac{X_{\max}}{X_{\min}}} \tag{4.2}$$

The preference number P_i can be expressed on a logarithmic scale as follows:

$$P_i = A \times \log\left(\frac{X_i}{X_{\min}}\right) \tag{4.3}$$

For evaluating preference number of roughness average

$$A = \frac{9}{\log \frac{X_{\min}}{X_{\max}}} \tag{4.4}$$

The preference number P_i can be expressed on a logarithmic scale as follows:

$$P_i = A \times \log\left(\frac{X_i}{X_{\max}}\right) \tag{4.5}$$

All usual notations define the proper meaning as described in [Mishra et al., 2010; Kaladhar et al., 2011].

The collected response for each experimental run has been shown in the Table 4.3. The utility index for each input response has been assessed and treated as input data in fuzzy inference system which has been tabulated in Table 4.4.

Step 2: Application of fuzzy logic [11-21]

Individual preference numbers (for MRR and roughness average) have been fed as inputs to the FIS (Figure 4.1). In assessing the output MPCI, each input factor has been expressed using seven linguistic variables viz. “very low (vl)”, “low (l)”, “fairly low (fl)”, “medium (m)” “fairly high (fh)”, “high (h)”, “very high (vh)” (Figure 4.2-4.3). In present study, the *Gaussian membership function* has been used to convert crisp inputs into fuzzy values. On the basis of fuzzy rules (Table 4.5), the *Mamdani* implication method has been employed for fuzzy inference reasoning. To obtain a rule,

$R_i : if x_1 is A_{i1}, x_2 is A_{i2}, and x_s is$

Then y_i is C_i, $i = 1,2,..........,M$

The linguistic terms in Gaussian membership function has been given as the following

$$\mu_{A^i}(x) = \exp\left(-\frac{(c_i - x)^2}{2\sigma^2}\right) \tag{4.6}$$

Here c_i and σ_i are the centre and width of the i^{th} fuzzy set A^i, respectively.

The output $u_{agg}(y)$ of *Mamdani- type* fuzzy inference system has to be expressed by a crisp value for the next operation of the fuzzy controller. Centre of gravity (COG) method has been adapted for the defuzzification.

$$Y_0 = \frac{\sum_{i=1}^{m} y_i u_{agg}(y_i)}{\sum_{i}^{m} u_{agg}(y_i)} \tag{4.7}$$

The fuzzy set comprises for each input variable as a symmetric Gaussian membership function. The Fuzzy based rule matrix has been shown in Table 4.5. The MPCI value has been evaluated from FIS output (Table 4.6).

Step 3: Taguchi robust optimization technique

The optimal machining condition has been determined by using S/N ratio plot of MPCI. For computing the S/N ratio, Higher-the-Better (HB) criterion has been adopted.

$$\eta_{ij} = -10\log\left(\frac{1}{n}\sum_{j=1}^{n}\frac{1}{y_{ij}^2}\right) \tag{4.8}$$

Here, y_{ij} is the ith experiment at the jth test, n is the total number of the tests.

Figure 4.5 represents the optimal parameter combination $N_3F_2D_2$. The mean response table for S/N ratio of MPCIs has been furnished in Table 4.7. The predicated S/N ratio of MPCI (18.7204) has been evaluated which has been seemed highest among all calculated S/N ratios of MPCIs in Table 4.6.

4.4. Conclusions

In this study, utility concept based fuzzy rule based model has been developed towards optimizing roughness average and MRR in machining glass fiber reinforced epoxy composites. FIS model has been constructed to work on two input variables (preference number of individual responses) with single output i.e. MPCI. By this way a multi-response optimization problem has been converted to an equivalent single objective optimization problem which has been further solved by Taguchi philosophy. The proposed procedures are simple, effective in developing a robust, versatile and flexible mass production process. In the proposed models it is not required to assign individual response weights; no need to check for response correlation. FIS can efficiently take care of these aspects into its internal hierarchy thereby overcoming various limitations/ assumptions of existing optimization approaches. Degree of influence of various process control factors can be investigated easily. Accuracy in prediction of the model analysis can be subsequently increased by assigning adequate fuzzy rules as well as by increasing number of membership functions in the fuzzy inference system. This approach can be recommended for continuous quality improvement and off-line quality control of a process/product in any manufacturing/ production environment.

4.5. Bibliography

1. Davim, J.P., and Mata, F. (2005) ‘Optimization of surface roughness on turning fibre reinforced plastics (FRPs) with diamond cutting tools’, *International Journal of Advanced Manufacturing Technology*, Vol. 26, pp. 319–323.
2. Mohan N.S., Ramachandra A., and Kulkarni S.M. (2005) ‘Influence of process parameters on cutting force and torque during drilling of glass–fiber polyester reinforced composites’, *Composite Structures*, Vol. 71, pp. 407-413.
3. Palanikumar K. (2008) ‘Application of Taguchi and response surface methodologies for surface roughness in machining glass fiber reinforced plastics by PCD tooling’, *International Journal of Advanced Manufacturing Technology*, Vol. 36, pp. 19–27.
4. Sait A.N., Aravindan S., and Haq A.N. (2008) ‘Optimisation of machining parameters of glass-fibre-reinforced plastic (GFRP) pipes by desirability function analysis using

Taguchi technique', *International Journal of Advanced Manufacturing Technology*, (Published Online) DOI: 10.1007/s00170-008-1731-y

5. Basheera A.C., Dabadea U.A., Joshi S.S., Bhanuprasad, V.V. and Gadreb V.M. (2008) 'Modeling of surface roughness in precision machining of metal matrix composites using ANN', *Journal of Materials Processing Technology*, Vol. 197, pp. 439–444.
6. Palanikumar K., and Davim J.P. (2009) 'Assessment of some factors influencing tool wear on the machining of glass fiber-reinforced plastics by coated cemented carbide tools', *Journal of Materials Processing Technology*, Vol. 209, No. 1, pp. 511–519.
7. Tong L.-I., and Su C.-T. (1997) 'Optimizing multi-response problems in the Taguchi method by fuzzy multiple attribute decision making', *Quality and Reliability Engineering International*, Vol. 13, pp. 25–34.
8. Yang W.H., and Tang, Y.S. (1998) 'Design optimization of cutting parameters for turning operations based on the Taguchi method', *Journal of Material Processing and Technology*, Vol. 84, pp. 122-129.
9. Mishra A., Verma R.K., Datta S., and Mahapatra S. S. (2010) 'Utility theory in Taguchi based multi-response optimization: a case study', *2nd International Conference on Production and Industrial Engineering (CPIE 2010)*, December 3-5, 2010, organized by Department of Industrial and Production Engineering, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar-144011.
10. Kaladhar M., Subbaiah, K.V., Rao Ch. Srinivasa and Rao K. Narayana (2011) 'Application of Taguchi approach and utility concept in solving the multi-objective problem when turning AISI 202 austenitic stainless steel', *Journal of Engineering Science and Technology Review*, Vol. 4, No. 1, pp. 55-61.

11. Mamdani E.H. (1976) ‘Advances in the linguistic synthesis of fuzzy controllers’, *International Journal of Man-Machine Studies*, Vol. 8, pp. 669-678.
12. Mamdani E.H. (1977) ‘Applications of fuzzy logic to approximate reasoning using linguistic synthesis’, *IEEE Transactions on Computers*, Vol. 26, No. 12, pp. 1182-1191.
13. Bezdec J.C. (1981) ‘Pattern Recognition with Fuzzy Objective Function Algorithms’, *Plenum Press*, New York.
14. Dubois D., and Prade H. (1980) ‘Fuzzy Sets and Systems: Theory and Applications’, *Academic Press*, New York.
15. Jang J.-S. R., and Sun C.-T. (1997) ‘Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligence’, *Prentice Hall.*
16. Sugeno M. (1985) ‘Industrial applications of fuzzy control’, *Elsevier Science Pub. Co.*
17. Wang L.-X. (1994) ‘Adaptive fuzzy systems and control: design and stability analysis’, *Prentice Hall.*
18. Yager R., and Filev D. (1994) ‘Generation of fuzzy rules by mountain clustering’, *Journal of Intelligent and Fuzzy Systems*, Vol. 2, No. 3, pp. 209-219.
19. Zadeh L.A. (1965) ‘Fuzzy sets, Information and Control’, Vol. 8, pp. 338-353.
20. Zadeh L.A. (1973) ‘Outline of a new approach to the analysis of complex systems and decision processes’, *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 3, No. 1, pp. 28-44.
21. Zadeh L.A. (1989) ‘Knowledge representation in fuzzy logic’, *IEEE Transactions on Knowledge and Data Engineering*, Vol. 1, pp. 89-100.

Table 4.1: Domain of Experiments

Sl. No.	Factors	Notation	Unit	Level 1	Level 2	Level 3
1	Cutting speed	N	m/min	360	530	860
2	Feed rate	F	mm/rev	0.083	0.166	0.331
3	Depth of cut	D	mm	2	3	4

Table 4.2: L_9 orthogonal array

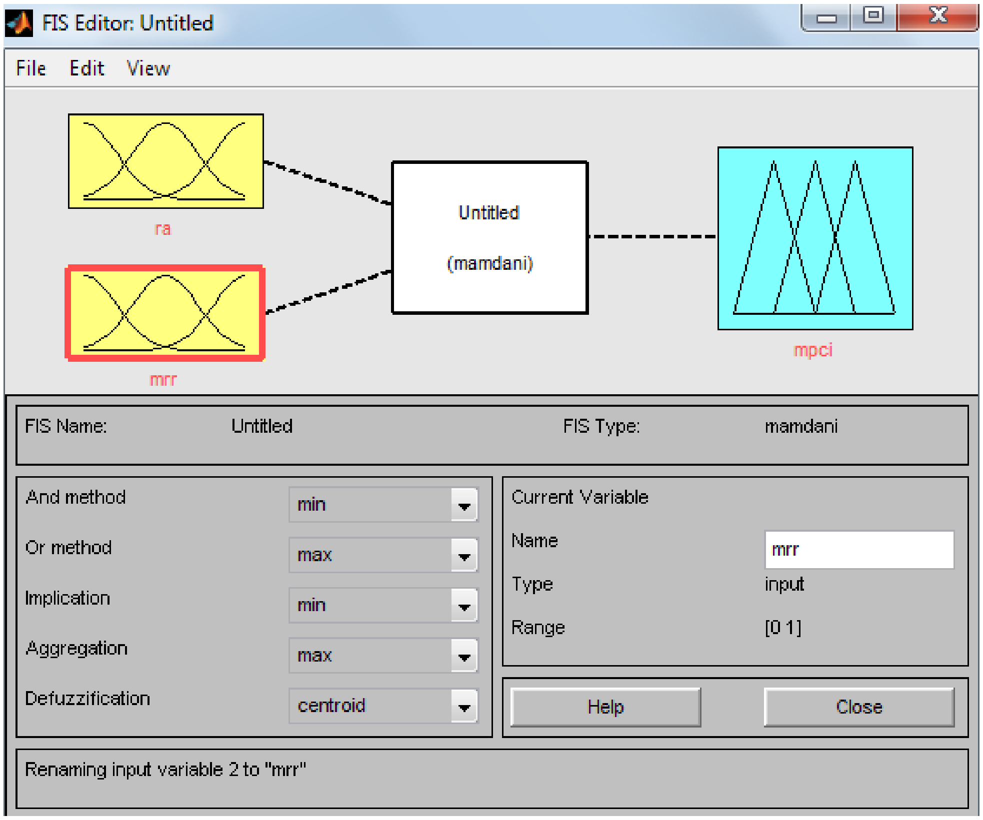
Sl. No.	N	F	D
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 4.3: Experimental data

Sl. No.	MRR (mm^3/min)	R_{a1} (µm)	R_{a1} (µm)	R_{a1} (µm)	R_{avg} (µm)
1	3713.5430	7.4	5.6	8.8	7.2667
2	15303.06184	6.2	3.6	6.4	5.4
3	41777.35881	8.2	6.8	8.2	7.733
4	9348.7795	6.2	6.8	5.4	6.133
5	21813.81905	3.6	8.4	6.8	6.2667
6	29604.46872	11.6	7.0	7.0	8.533
7	22648.53152	14	7.6	8.4	10
8	22413.0998	6.8	6.0	5.0	5.933
9	63660.73724	5.8	8.4	7.4	7.27

Table 4.4: Individual utility value (preference number) for each response

Sl. No.	U_{MRR}	$U_{R_{avg}}$
1	0	4.6609
2	4.4849	9.0
3	7.6658	3.75244
4	2.9241	7.13705
5	5.60774	6.8262
6	6.57496	2.3159
7	5.72668	0
8	5.6935	7.6210
9	9.0	4.7955



FIS Name: Untitled

FIS Type: mamdani

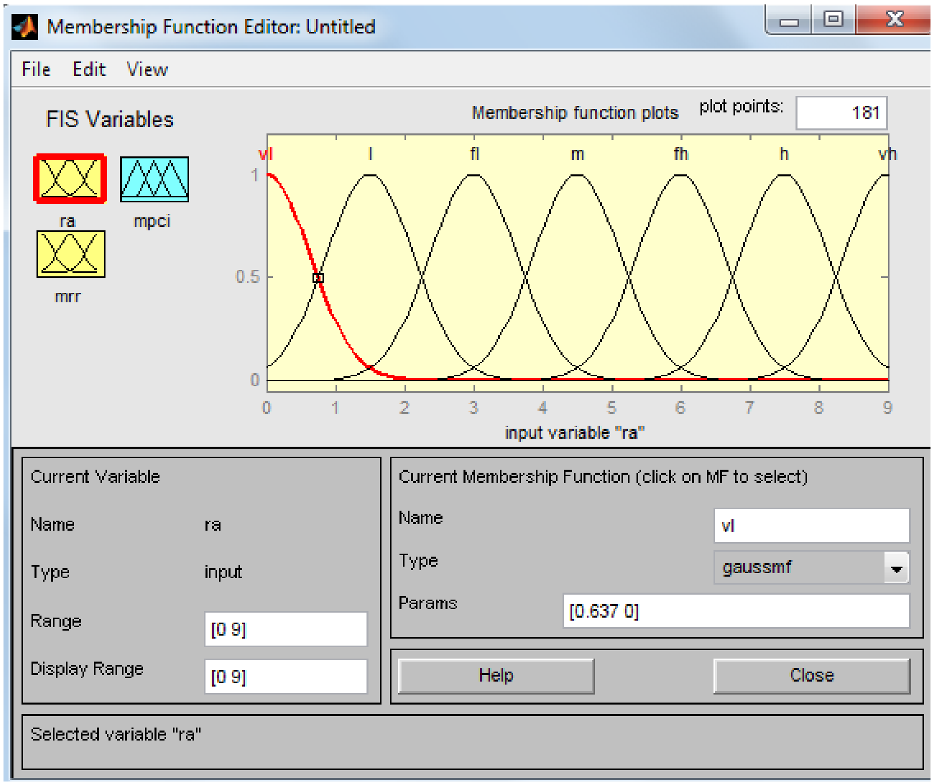
And method	min
Or method	max
Implication	min
Aggregation	max
Defuzzification	centroid

Current Variable

Name	mrr
Type	input
Range	[0 1]

Renaming input variable 2 to "mrr"

Figure 4.1: Proposed fuzzy inference system



plot points: 181

Current Variable

Name ra

Type input

Range [0 9]

Display Range [0 9]

Current Membership Function (click on MF to select)

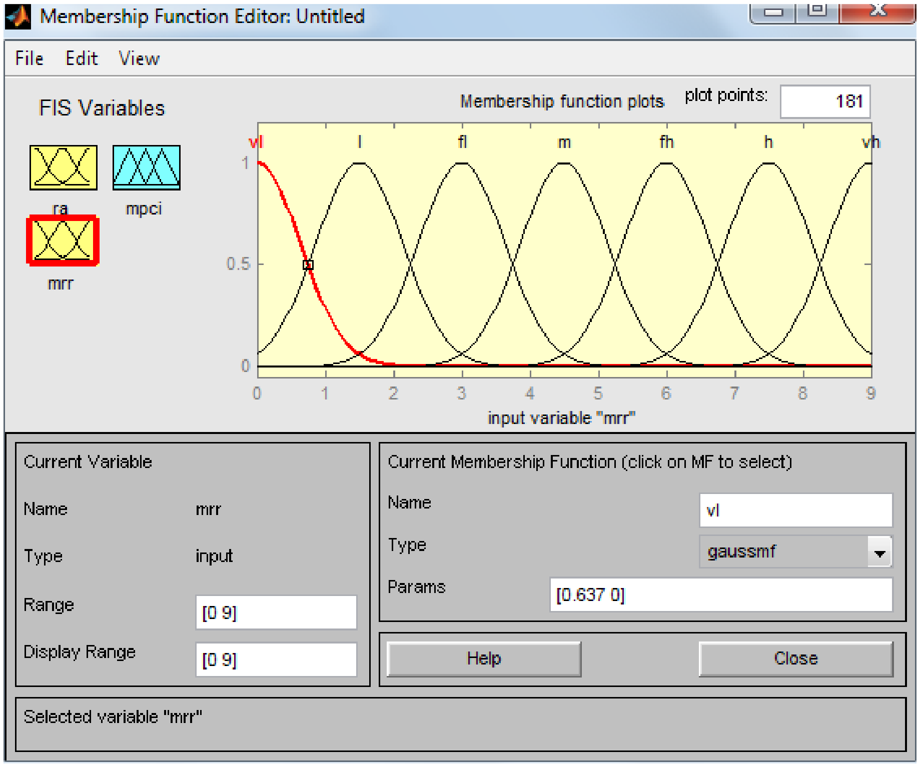
Name vl

Type gaussmf

Params [0.637 0]

Selected variable "ra"

Figure 4.2: Membership function for R_a



plot points: 181

Current Variable

Name mrr

Type input

Range [0 9]

Display Range [0 9]

Current Membership Function (click on MF to select)

Name vl

Type gaussmf

Params [0.637 0]

Selected variable "mrr"

Figure 4.3: Membership function for MRR

Table 4.5: Fuzzy rule base reasoning

MPCI		MRR						
		VL	L	FL	M	FH	H	VH
Ra	VL	VL	VL	L	L	FL	FL	M
	L	VL	VL	L	FL	FL	M	M
	FL	L	L	FL	FL	M	M	FH
	M	L	L	FL	M	M	FH	H
	FH	L	FL	FL	M	FH	H	H
	H	L	FL	M	FH	FH	H	VH
	VH	FL	FL	M	FH	H	H	VH

Table 4.6: Computed MPCI and corresponding S/N ratios

Sl. No.	MPCI	S/N Ratio
1	1.65	4.3497
2	5.96	15.5049
3	5.48	14.7756
4	4.25	12.5678
5	5.56	14.9015
6	3.83	11.6640
7	2.78	8.8809
8	6.09	15.6923
9	7.27	17.2307

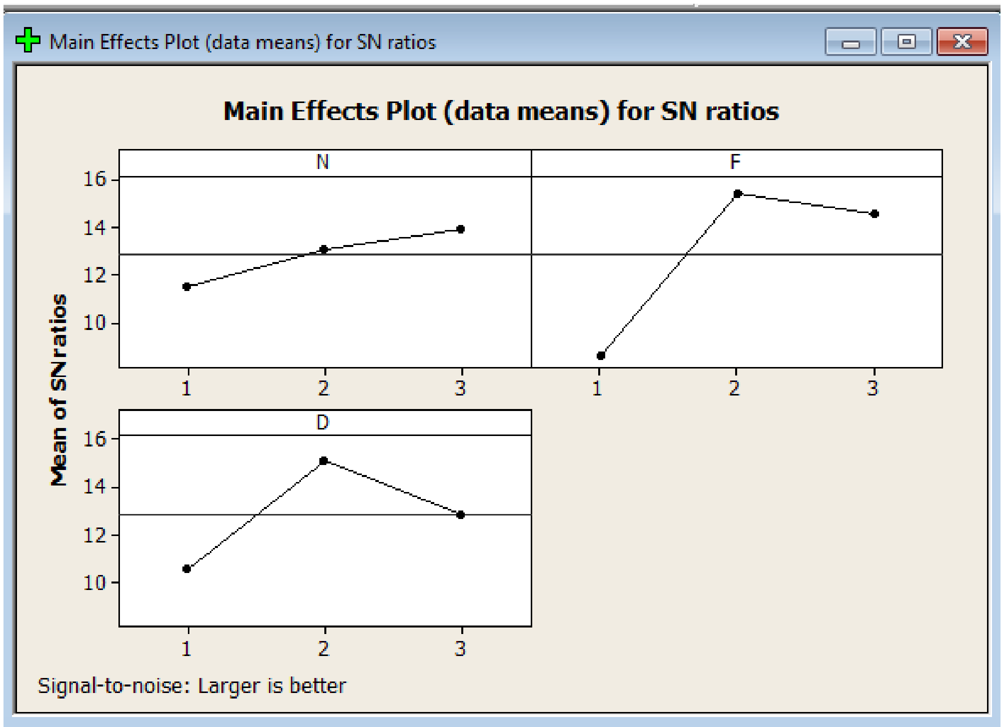


Figure 4.5: Evaluation of optimal setting

Table 4.7: Mean response table (SN ratio of MPCIs)

Level	**N**	**F**	**D**
1	11.543	8.599	10.569
2	13.044	15.366	15.101
3	13.935	14.557	12.853
Delta	**2.391**	**6.767**	**4.532**
Rank	**3**	**1**	**2**

<u>Publication Status</u>

1. **Rajesh Kumar Verma**, Kumar Abhishek, Saurav Datta, Siba Sankar Mahapatra, "*Fuzzy Rule Based Optimization in Machining of FRP Polyester Composites*", **Turkish Journal of Fuzzy Systems**, **An Official Journal of Turkish Fuzzy Systems Association**. (**Accepted**)
2. Kumar Abhishek, **Rajesh Kumar Verma**, Saurav Datta, Siba Sankar Mahapatra, "*Utility concept and Fuzzy rule based optimization in machining glass fiber reinforced epoxy composites*", **The 9th International Conference on Enterprise Systems, Accounting and Logistics 2012** (9th ICESAL 2012), scheduled to be held in **Chania**, **Crete Island**, **Greece,** on **June 3-5, 2012**. (**Communicated**)