

**Study of Relationship of Mechanical Properties of Indian Wood
Species with Cutting Forces and Surface Finish in Slot Milling
using a High Speed 3-axis Vertical CNC Router System**

A Dissertation Report

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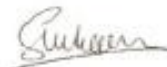
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ABSTRACT

Wood is an important natural material and being used for various applications since ages. The larger percentage of the timber wood is used for furniture making as well as a construction material in addition to being used as an engineering material. The wood as an engineering material possess anisotropic properties and some time has random defects. During manual wood machining operations one can take care of anisotropic nature of wood properties as well as the random defects but it is obtained at the cost of a lot of time. The CNC machining of wood can help us save a lot of machining time while simultaneously offer better machining accuracy, but it is desired that the relationship of machining parameters to be selected and the desired machined properties of the wood samples be studied to explore the full potential of using CNC wood machining systems. The wood as an engineering material has several mechanical properties but those mechanical properties which directly influence the machinability of wood are required to be studied.

In this thesis work the previously published literature has been studied in detail to identify the mechanical properties of wood which effect the machinability of wood. Further a systematic approach has been used to determine the values of these mechanical properties as per standard procedure available from the Bureau of Indian Standards as well as standard published standard procedures. The six Indian wood species are used in the present study where we have tried to establish a correlation between the mechanical properties of these wood species with the cutting forces observed in slot milling and the surface finish obtained in the bottom of the slotted cut.

It has been observed that the wood grain orientation is a key factor for machinability of wood because different slot milling orientation gives different measurable output of surface finish and cutting forces. Procedures to find out different mechanical properties are discussed and their averaged values are considered for analysis. A high rpm 3-axis vertical CNC router is used in the present study for slot and plunge milling while a force dynamometer is used for recording the magnitude of cutting forces thus produced. A stylus type surface roughness tester was then used to measure surface roughness of various machined samples. The results of different mechanical properties, various cutting forces and surface finish are thus analysed to identify the relationship among them. The literature surveyed for the present study, the procedure followed for determining the values of various measurable parameters and hence observed results and discussions have been presented systematically in this thesis report.

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ABBREVIATIONS

| | |
|-------------|--|
| CNC | COMPUTER NUMERICAL CONTROL |
| ASTM | AMERICAN SOCIETY FOR TESTING AND MATERIALS |
| MOE | MODULUS OF ELASTICITY |
| MOR | MODULUS OF RUPTURE |
| MCS | MAXIMUM CRUSHING STRENGTH |
| CAM | COMPUTER AIDED MANUFACTURING |
| RPM | REVOLUTION PER MINUTE |
| IS | INDIAN STANDARD |
| TS | TURKEY STANDARD |
| UTM | UNIVERSAL TESTING MACHINE |

CHAPTER 1

INTRODUCTION

1.1 Introduction

Wood is an important construction and engineering material which is being used in ornamental, furniture, building construction and number of applications since ages. There are various grades of wood depending upon their texture, mechanical properties and durability which are identified over a period of time. Many of the applications are done manually so various carpenters and artesian identified wood varieties which shows good machinability. When these woods are identified and these wood varieties are used in abundance. This results in increasing price of these wood varieties and facing some problem like shortage of these wood varieties because more trees are cut than plant. The government sometimes takes actions to defend the forest area where these wood varieties are planted. In this thesis work an attempt is being made to identify wood species which can be used instead of class I wood species and also an attempt is being made to correlate some required mechanical properties of wood species Vis-avis with cutting forces and surface finish.

1.2 Wood Varieties

There are millions of wood varieties in world and they are further classified into various categories depending upon their texture, mechanical properties, availability and some other parameters. A work has been carried out by Bansal et. al. 2013 in which author found some mechanical properties from literature that has good relationship with machinability and using MADM approach author graded some wood species. In the present work some wood species used are shown in Table 1.1.

Table 1.1: Wood species Nomenclature used for testing

| S.No. | Wood species | Technical name | Nomenclature used in this study |
|-------|--------------|--------------------|---------------------------------|
| 1. | Babool | Acacia nilotica | B |
| 2. | Dake | ----- | D |
| 3. | Jamoha | Sauder Shoal Creek | J |
| 4. | Mango | Mangifera indica | M |
| 5. | Neem | Azadirachta indica | N |
| 6. | Sheesham | Dalbergia sissoo | S |

1.3 Directional Properties of Wood

Wood is an anisotropic material and it has various directional properties. The grain direction of a wood samples is shown in figure 1.1. From literature it is found that Hardness, Density, Modulus of rupture, Modulus of elasticity and Maximum crushing strength are major contributors and affecting the machinability of wood as reported by Akyildiz & Kol, 2010, Gnanaharan & Dhamodaran, 1993, McKenzie et al., 2001, Eyma, Méausoone, & Martin, 2004, Shanavas & Kumar, 2006, Korkut & Guller, 2008, Akyildiz & Kol, 2010, Bal, 2014, Bansal et. al 2013. The machiability of different direction grains gives different output and wood is a composite material in which grains are there in matrix so while machining with wood grain direction is an important term. In this thesis work different directions are considered for machining and surface finish is measured.

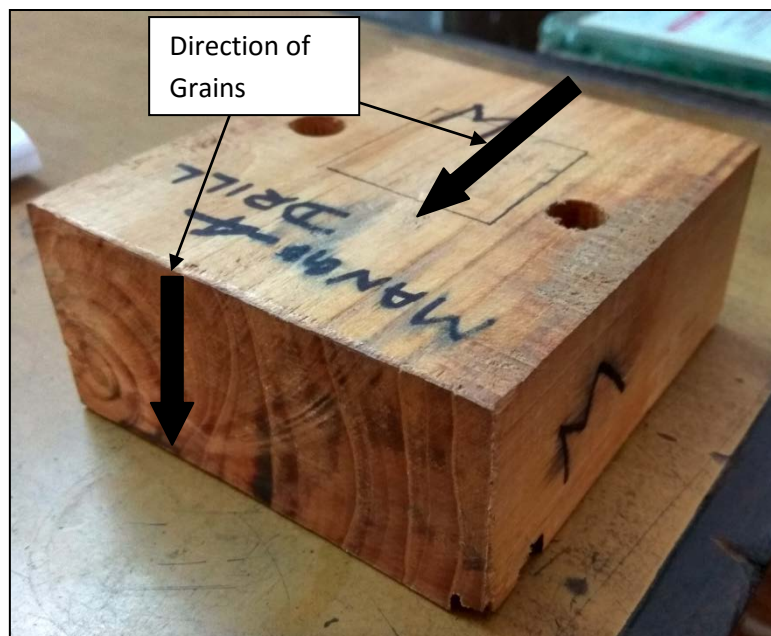


Figure: 1.1 Wood grain directions

1.4 Machining of Wood

Wood machining is an art of making ornamentals, statues and other important utensils from wood with the help of cutting tools and other mechanical equipments. Wood is a light and workable material, it has mechanical properties like tensile strength and its broken pieces can be joined very easily. It has some more physical properties like grain structure, different texture. Now a day's wood machining is done by CNC machines to remove human interference so that error can be reduced as possible. In wood machining selection of wood is very important because machining depends upon various mechanical properties of wood. For

example chipping is never required if chipping will occur sculpture is just a rejected product. Finishing of the product is also depend on its properties, its texture etc.

1.5 Methods of Wood Machining

Machining in different materials like metals, stone and wood has been done ever since ages. Different applications and based upon flavour of people at various places artisans used range of combinations of materials and craft designs to pull customers for their finished goods. The different ways of realizing art in wood have been used by different artisans in the region of the world, because workability and durability in wood permits any kind of complicated shape to be carved out of it. The wood machining process can be classified into following ways:

1.5.1 Manual Wood Machining

Traditional wood machining begins with selecting suitable plank of wood. The choice of type of wood depends upon details of machining to be realized, quality, cost and availability. Traditionally, selection of wood by sculptor begins with general shaping process to get a appropriate shape of raw stock for convenience of machining process. The manual machining process makes use of traditional cutting tools. The experienced machinist can very well avoid randomly occurring defects in wooden raw material which is nearly impossible if automatic CNC machining is used. After machining process is finished some textures improving processes like polishing or applying lacquer for longer lifetime of work material is done. The ancient way has its many disadvantages, like it is noisy, traditional tools being unsafe and it takes very long time to complete the job. Moreover, accuracy and repeatability of manual machining process is not very good. Additionally, often it takes several months for just a small sculpture or ornamental. The artist normally create outline of the design to be produced, and then create a master Figure/ template/ shape of raw skeleton, after this phase manufacturing/carving of the final product begins. For customized machining operations where the number of parts per order are very few or may be single unit, it takes much longer time that sometimes the orders gets cancelled and machinist have to suffer losses far more than expected returns.

1.5.2 Automated Wood Machining

The automation of machining process has been made possible by the invent of technologies like reverse engineering, 3D scanning, user friendly design automation techniques, rapid prototyping, special CAM packages which can create NC tool paths for complicated shapes and use of automated 3D dimensional CNC machining centres. The CNC machining centres can machine complicated shapes in metal, stone, synthetic/composite materials and wood

with high degree of precision and repeatability. The CAD packages along with suitable reverse engineering tools can be used as tools for assistance in creation of 3-dimensional designs for ornamental carvings. These designs can be used as input for creation of NC tool path data using suitable CAM packages. Once the tool path is ready for a particular cutting tool, we can use the CNC machining centres to machine the part. Using the simulation environment in CAM packages, the machining processes can be simulated under all operating conditions, which ensure that there is no milling cutter crash during simulation operations. Then, cutting and processing operation of the work pieces is started.

For automated machining of wood, special machines called CNC router tables are used. The router is one of the most commonly used power tools used in wood working. As in technical sight for wood machining the spindle should have high rpm and low torque. In wood machining low chip thickness is desired to avoid local burning, while maintaining the high material removal rates. This is possible using the wood router tables, which use high speed spindle having speed range from 5000 to 55000 rpm.

Moreover the design of high speed spindle is such that it throws air at high velocity over the cutting region so that the cutting tool remains cool, and it also helps removal of chips. The wood carving/cutting tools used with CNC routers are also having special shapes to get the required shapes cut in the wood, but the straight flute ball end mills have been extensively used for 3-dimensional carving in wood.

One of the main advantages of a CNC wood carving is that the special shaped cut-out stock, called initial carving skeleton, is not required before carving process can be started as need in manual carving, rather machine can cut out any desired shapes from the wood piece directly.

1.5.3 Use of CNC Router for Automated Carving

The CNC router is very useful machine tool for process like rapid prototyping, ornamental carving, some art work etc. and it use special cutters for material removal compared to conventional machine tools. Of course CNC router tables can be used for machining of other softer materials like plastic based materials, aluminium, and brass etc. with controlled machining parameters like feed speed and depth of cut. A conventional general purpose router table used for machining of softer metals and special router used exclusively for wood. The general CNC router machining mechanism working on the Cartesian coordinate system for 3D motion control, which means the cutting tool, can be moved along any one or more than one controlled axis (X-axis, or Y-axis, or Z-axis) simultaneously.



Figure 1.2: CNC router for milling

The CNC carving router having 3-axis simultaneous control can execute the carving operations very effectively. And major advantage of using CNC router for wood carving is that it cuts at higher rpm which help in chiselling of wooden material without burning and affecting the global or local properties of wooden stock.

1.6 Engineering Properties of Wood Species

Wood can be defined as an orthotropic material that is it has randomly and different mechanical properties are in the three different directions as shown in figure 1.3. It shows 3 axis named radial, tangential and longitudinal. The longitudinal axis is in the direction of grain, radial axis is normal to growth rings and tangential axis is perpendicular to fibre direction.

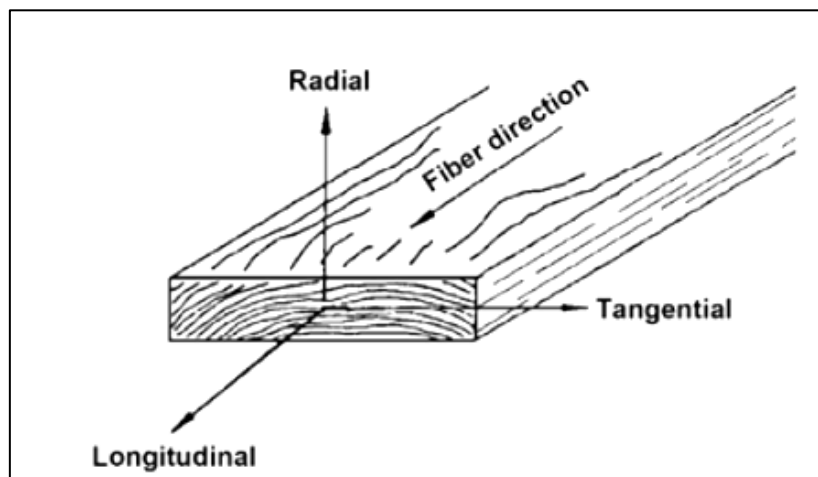


Figure-1.3. Three main axis of wood grain

- **Elastic Properties**

There are twelve constraints which is used to define the behaviour of wood species. In twelve constraints three are used for modulus of elasticity, three are used for modulus of rigidity and remaining six are used for poisson's ratio.

$$\frac{U_{ij}}{E_i} = \frac{U_{ji}}{E_j}, i \neq j, i, j = I, R, T$$

Poisson's ratio and modulus of elasticity is correlated in the way of equations. In the anisotropic elasticity you can find relation of different anisotropic substances in the terms of stress and strain.

- **Modulus of Elasticity**

The basic rule of elasticity is that when ever low load is applied at a material it changes to some extent but when load is removed then it should be recover in its original position but if a heavy load is applied then material goes into plastic deformation phase. As shown in figure 1.3 three modulus of elasticity is E_L for longitudinal, E_R for radial and E_T for tangential. It is determined by compression test.

- **Modulus of Rigidity**

Modulus of rigidity can be defined as the resistance to deflection when load is applied in the form of shear stress. It can also be called as shear modulus.

- **Modulus of rupture**

Modulus of rupture can be defined as capacity of load carrying in bending direction. It is not considered as a true stress because the expression derived is only applicable to elastic limit.

- **Compressive strength parallel to grain**

Compressive strength can be defined as an ability of wood species to withstand with load parallel to their grains.

- **Compressive stress perpendicular to grain**

Compressive strength can be defined an ability of wood species to withstand with load perpendicular to their grains.

- **Shear strength parallel to grain**

Shear strength is an ability of wood or material in which resist slipping of grain to another grain.

- **Impact bending**

The impact bending consist of a beam and hammer of some weight when the weight is thrown from some height the rupture may occur in beam if rupture is not occur than height will be increased and this process is carried out till rupture occur in beam. So it defines ability of material to withstand with sudden shocks.

- **Hardness**

Hardness is determined with Janka hardness tester or Rockwell hardness tester. It is a property in material to resist any mark or scratch on its outer surface. As hardness is increased it is difficult to carve on wood but surface finish will be good as compare soft woods.

1.7 Present Work

The wood is an anisotropic material and is being used for construction, furniture, ornamental things around the world. There are millions of varieties but according to different applications different wood species are preferable. In the present work, an attempt has been made to correlate mechanical properties with cutting forces and surface finish. There are several mechanical properties but out of those which directly affect the machinability of wood are identified from literature. Different standard procedures to determine these properties reported by different authors are also discussed in chapter 2. Out of those procedures suitable procedures have been adopted to determine the values of mechanical properties discussed in chapter 3. Wood grain direction is also a factor for optimising the machinability of wood so in present work different grain direction is considered for milling slots which are along the grain, across the grain, inclined the grain and axial to the grain. Six Indian woods species are selected in the present work. CNC router is used for slot milling in different wood species and a dynamometer is used for recording the cutting forces produced in slot milling. A stylus type surface roughness tester is used for measuring the surface of slots milled in different grain directions. Results of mechanical properties, cutting forces and surface finish are systematically presented in chapter 4 results and discussion.

CHAPTER 2

LITERATURE REVIEW

In this thesis work a work is carried out for finding out the engineering properties of wood for machining application which will have direct effect on machinability, surface finish and cutting forces. Then from literature surveyed same work has been figure out which represent the relationship between developed engineering properties of various woods which directly influence machinability. Subsequently in the same chapter some methodologies have been further identified which have been used to figure out those properties. Aim is to establish relationship between engineering properties and machinability.

2.1 Different Types of Wood and Their Engineering Properties

Gnanaharan & Dhamodaran, 1993 Investigated the Engineering properties of rubberwood which is grown to 35 year old farm in Kerala. The engineering properties of air-dried rubberwood since a 35 year old farm in the central region of Kerala were found. It was found that the mechanical properties tested, namely, modulus of elasticity (MOE) maximum compressive stress (MCS) and modulus of rupture (MOR), were high for the 35-y-old stuff than for lower age material reported in the literature. These properties were similar with those of other conventional timbers grown in Kerala. The study showed that rubberwood possesses medium strength properties.

Obataya, Ono, & Norimoto, 2000 Worked on The dynamic loss tangent ($\tan \delta_L$) along the grain and Young's modulus (E'_L) and, dynamic shear modulus (G'_L) and loss tangent ($\tan \delta_S$) in the straight up section, and density (ρ) of a hundred spruce wood species specimens used for the soundboards of musical instruments were found. By using a cell wall model, those sound factors were expressed with the physical properties of the cell wall constituents. This form predicted that the necessary requirement for an excellent soundboard is lower fibril angle of the cell wall, which yields upper α and upper β . On the other hand, the effects of chemical treatments on the α and β of wood were clarify experimentally and analyzed theoretically. It was recommended that the α and β of wood cannot be better at the same time by chemical treatment.

Davim, 2001 studied the effect of cutting environment on the surface roughness in the turning operation. With the help of Taguchi's method different iterations for experiments were planned and after applied to know the behaviour of surface finish in turning. The cutting parameters like feed rate, depth of cut and cutting velocity and surface finish parameters like Ra and Rz etc. The objective of this study was to find a correlation between these parameters.

McKenzie et al., 2001 investigated for edge cutting, the dissimilarity within a single medium density fibre board across the thickness and in different cutting directions in the plane of board. Material properties of concentration were friction coefficient and specific gravity. In slow linear cutting on a customized milling machine, carbide router inserts cut the boundaries of layers cut from an average density fibre board. Friction coefficient values, approximate both from rubbing forces and from cutting forces during revisit, varied about a value of 0.23, with no major difference between layers.

Yang & Evans, 2003 determined engineering properties modulus of elasticity and modulus of rupture with the help of static central point bending test. After MOE and MOR their density and microfibrill angle was determined using a technique of silviscan. It was analysed that MFA participated 87% for the variation of modulus of elasticity whereas density participated only 81% and if density and MFA is combined than the effect on MOE is increases to 92%.

Barbosa & Fearnside, 2004 compared the basic densities of wood species in open savannas with Amazonian forests. After comparison it is found that open savannas (0.404 g/cm^3) had less density than Amazonian forests (0.680 g/cm^3).

Eyma, Méausoone, & Martin, 2004 obtained the models which is considered density and mechanical properties to analysis the cutting forces. The mechanical properties are the important factor to correlate with machinability of different wood species and it can improve the machinability of wood.

Hansson & Antti, 2006 investigated that operations carried out for remove moisture content affects the hardness of wood species. For this a microwave is used for gaining different temperature level and it gives a comparison of air dried wood with microwave dried wood. It is found that microwave drying samples had more hardness than air dried samples.

Hernández, 2006 studied the compression strength is dependent on the equilibrium moisture content and also density is participated in this factor because as wood is denser than its response will be more.

Kilic, Hiziroglu, & Burdurlu, 2006 investigated the effect of different machining techniques on the surface roughness of wood species beech and aspen. Different operations like sawn, planned and sanded are carried out and after surface roughness is measured with the contact stylus method and their parameters are Ra, Rz and Rq etc. The readings are taken from tangential and radial but result shows that no important variations found.

Malkoçoğlu & Ozdemir, 2006 determined that different rake angle gives different surface finish and depending upon wood species high or low rake angles which angle should be

preferred? So answer is hardwood requires low rake angle and for softwoods high rake angle can be used for better surface finish.

Ratnasingam & Scholz, 2006 performed a plan of experiments in which different samples are sanded with different grit size paper. And after surface finish is measured for each samples and it has been found that 240 grit size gives best surface finish among all. So it is good for furniture making manufacturer that they can accept it for better surface finish.

Shanavas & Kumar, 2006 evaluated the wood properties of three locally important fast growing tree species (*Acacia auriculiformis*, *Grevillea robusta* and *Acacia mangium*,) occurring as scattered and boundary planted trees on the agricultural lands of Kerala. Species and specimens positions exerted a profound influence on the mechanical and physical properties of wood species. Wood density of *A. auriculiformis* was greater than that of *A. mangium* and *G. robusta*, while moisture content followed a repeal sequence: *G. robusta*, *A. mangium*, *A. auriculiformis*.

Lourenço et al., 2007 evaluated the compression strength with the help of non-destructive and destructive testing for chestnut wood species. The result shows a good correlation between compression strength to non-destructive testing.

Ruelle et al., 2007 found that it can be possible to determine the some mechanical properties with the help of wood species growth strains. In this study as expected tensile growth strains was high in tension wood zone.

Aslan et al., 2008 studied the surface finish of planed and sanded of wood species Taurus cedar samples. From result analysis it has been found that cutting ways affect the surface finish of Taurus cedar. It is also found that cutting in radial direction gives more surface finish than other directions.

Korkut & Guller, 2008 Compared the physical properties of samples to determine air dry density, oven dry density and swelling properties. A contact stylus method is used to determine the surface finish of these samples. Readings were taken at perpendicular to fiber.

Aknouche et al., 2009 examined the various forces produced while routing process for Aleppo wood species. The main objective of this study to gain knowledge about tool wear rate with cutting forces. Dynamometer is used to record cutting forces in various directions and a carbide tool is used for this process. After analysis the results it was found that there is correlation between cutting forces and computed angle.

Akyildiz & Kol, 2010 determined some mechanical and physical properties of *Paulownia tomentosa* wood grown-up in Turkey. The specimen's trees harvested from Kargi in Corum. Physical properties including oven-dry density, air-dry density, density, shrinkage, swelling,

air-dry thermal conductivity coefficients and oven-dry and mechanical properties including modulus of elasticity, bending strength, hardness, compression strength parallel to grain, bonding strength were analyzed.

Chomsamutr & Jongprasithporn, 2010 proposed research methodology for turning operation design parameters, Taguchi's method is used to analysis. In this study machining parameters are considered depth of cut, feed rate and spindle rpm. The parameters are further divided into three categories high, medium and low level. The result shows that only feed rate is the parameter which affects the surface finish.

Cristovao et al., 2011 studied the relationship between chemical and physical properties with tool wear rate for not so popular wood species. Results shows that silica content in wood species affects the tool wear rate. The mechanical properties like density is not so important for analysing tool wear rate. At last only one parameter is not enough to determine tool wear rate.

Hiziroglu, Zhong, & Ong, 2014 evaluated the bonding strength of wood species namely pine, white oak and nyatoh. Samples free from defect is sanded with 80, 100 and 240 grade sand paper and after that surface finish is measured using surface roughness tester.

Machado et al., 2014 analysed the difference in wood species density and mechanical properties with site, tree and within tree were studied for blackwood grown in four sites in Portugal. Twenty trees were randomly selected (40cm diameter breast height class, 33–51 years of age), specimens at three different stem height levels (5%, 35% and 65% of tree height) and for three radial positions (10%, 50% and 90% of radius). They were ahead tested for air dry density at 12% equilibrium moisture content, bending strength (MOR), compression strength parallel to grain (CS) and modulus of elasticity (MOE).

Tiryaki & Hamzaçebi, 2014 predicted the MOR and MOE of the heat-treated wood by artificial neural networks. For this purpose, specimens were prepared from beech wood and spruce wood. The specimens were exposed to heat treatment at different temperatures (125, 150, 175 and 200°C) for different durations (3, 5, 7 and 9 hours). As per results, the mean absolute percentage errors were found as 0.74%, 1.01% and 1.04% in prediction of Moduls of rupture values, and 1.14%, 2.21% and 2.13%, in forecast of Modulus of elasticity values for training, confirmation and testing data sets.

Yoon et al., 2014 found that the power efficiency varied regardless of machining scales or specific energy consumed, and also can differ widely in terms of the peripheral devices used. Moreover, for the case of laser-assistant machining, the current power efficiency metric gets lower as the cutting load decreased.

2.2 Procedures to Find Mechanical Properties

Table 2.1 Important references to determine density:

| S.No. | Standard | Method/Procedure | Reference |
|-------|---------------|---|-------------------------|
| 1. | ASTM-D143 | <p>Samples are taken from each log to determine density. After seasoning for many months some moisture content should be there in samples so for removing 100% moisture content samples are kept in a oven with a constant temperature of $103\pm 2^{\circ}\text{C}$. After gaining 0% moisture content measurements are taken of samples with a digital Vernier calliper.</p> $D_0 = M_0/V_0 \times 100$ <p>Where D_0 is oven dried density, M_0 is mass and V_0 is volume of samples.</p> | Kiaei & Samariha (2011) |
| 2. | TS 2472, 1976 | <p>The density experiment was performed on the lumber of paulownias. The experimental region is held on a nearby altitude of 450m. Basic density D_b was found by using the following formula:</p> $D_b = M_0/V_g$ <p>Where M_0 is the oven dried weight of the samples (g) and V_g is the green volume of the samples (cm^3)</p> | Akyildiz & Kol, (2010) |
| 3. | IS:1708-2 | <p>Density in both the air dry and green form was determined from the mass of samples in the green state and their measurements in the green state, and in the same way the air dry weight and air dries volume (at 12% equilibrium moisture content) respectively.. The numbers of samples occupied to find out for density in air-dry and green states were 578 and 531 respectively.</p> <p>The formula to evaluate density is as follow:</p> $W_1/V_1 \times 100$ | Shukla et al., (2007) |

| | | | |
|----|------------------|---|-----------------------------|
| 4. | DIN 52182 (1978) | First of all after tree logging specimens were made as per German standard 52180(1994). 30 specimens (Ten samples per tree) of every 14 wood species are prepared for density experiment. The equation for using basic density is dry mass divided by green volume. In this research the author has been used this standard on that species of wood which is used for constructive, decorative and energy purposes. | Carrillo et al.(2011) |
| 5. | DIN 52182 | In this standard after seasoning of three months, small specimens are prepared and kept for 12 weeks in normal climate conditions where temperature ranges from 19°C to 21°C and relative humidity ranges from 62% to 68%. After this samples are kept in an oven to gain 0% moisture content. | Mantanis & Birbilis, (2010) |

ASTM D143 has been used in present work to find out density of wood samples because Majid kiaei & Ahmad Samariha (2011) considered density as the important property in their research for both solid wood and fibre products.

Table 2.2 Important reference to determine hardness:

| S.No. | Standard | Method/Procedure | Reference |
|-------|---------------|--|-----------------------|
| 1. | TS 2479, 1976 | The Brinell hardness values of the specimens were determined as per the procedures described in the standard. The surface of the specimens was depressed with a 10 mm diameter hardened steel ball with a weight of 5000 N for 15 seconds. A microscope was used for found the indentation diameter left in the samples. The Brinell hardness number was determined by dividing the mass applied by the surface area of the indentation. | Akyildiz & Kol (2010) |
| 2. | IS:1708-10 | The size of specimens was 50mm × 50mm × 50mm. As per procedure a steel ball having diameter of 1.128 cm is to penetrate in it at a depth of 0.564 cm with a uniform loading of 6mm/min. The process should be free from splitting and chipping. | Shukla et al., (2007) |

| | | | |
|----|---------|---|-----------------------------|
| 3. | EN 1534 | Brinell hardness was determined by using Llyod testing machine. The readings were taken with a steel ball of 10 mm dia and weight of 3 kN. the load was fixed for 25 seconds, and after that the load continuously decreased to zero within 15 seconds. The diameter of the left over indentation mark of the sphere was calculated with a Brinell microscope. Twenty injection molded specimens were tested to determine Brinell hardness. | Kaymakci & Ayrimlis, (2014) |
|----|---------|---|-----------------------------|

IS-1708-10 has been used in present work to find out hardness of wood samples because Shukla et al., (2007) in their paper compare same species of wood at different ages and in result said that this species can be used for making tool handles or in industry where less diameters with high strength is required. Scale B is used for softer material like wood in Rockwell hardness tester and the equipment is available in Mechanical lab at TU.

Table 2.3 Important references to determine maximum crushing strength (MCS):

| S.No. | Standard | Method/Procedure | Reference |
|-------|--------------|--|-------------------------|
| 1. | ASTM D143-94 | As per this standard samples are placed in a control condition room in which temperature is 20°C and relative humidity ranges from 60% to 70% until specimen gain 12% moisture content. Test is performed on a universal testing machine and rate of loading is 100kN/minute. The following formula is used to determined the MCS: $\sigma_{cpl} = P_{max}/A$ Where σ_{cpl} = Maximum Crushing Strength (MPa), P_{max} = maximum compressive load load at fracture point (KN) and A = area of section of the samples on which load was applied (mm ²). | Kiaei & Samariha (2011) |
| 2. | IS:1708-8 | The size of samples was 20mm × 20mm × 80mm in length, testing is done on a universal testing machine with a rate of loading 0.6 mm/min. Number of samples used for determination of MCS for green and air dry are 124 and 156. The MCS (Parallel to grain) was determined by the following equation: | Shukla et al., 2007 |

| | | | |
|----|-----------|--|----------------------------|
| | | $\sigma_{cpl} = P_{max}/A$ <p>Where σ_{cpl} = Maximum crushing strength (MPa), A = sectional area of the samples on which load is applied (mm^2) and P_{max} = crushing load at break point (kN).</p> | |
| 3. | IS:1708-8 | <p>For determination of mechanical properties, five defect-free teak trees having each age of 35 years were harvested. The samples were air-dried to 12% equilibrium moisture content. 90 numbers of samples were used in this testing. Maximum crushing strength was determined on a Universal Testing Machine (Zwick, Germany) having capacity of 200KN. Rate of loading was 1 mm/min. The formula to determine MCS is as follows:</p> $\sigma_{cpl} = P_{max}/A$ <p>Where σ_{cpl} = Maximum crushing strength (MPa), A = Sectional area of the specimen on which force was applied (mm^2) and P_{max} = maximum crushing load at break point (kN).</p> | Thulasidas & Bhat (2012) |
| 4. | DIN 52185 | <p>According to this standard samples are placed in a control condition room where temperature ranges from 19°C to 21°C and relative humidity ranges from 62% to 68%. Testing is performed on a UTM with a rate of loading 2 mm/min. The following formula is used to evaluate MCS:</p> $\sigma_{cp} = F_{max}/A$ <p>Where F_{max} the maximum compression in force and A is area of the surface.</p> | Mantanis & Birbilis (2010) |

In all standards, the formula to evaluate MCS is a ratio of maximum load to the area of the cross-section of samples. In Standard 1708-8 the rate of loading is 0.6mm/min and it comes in the range of our available equipment.

Table 2.4 Important references to determine modulus of elasticity (MOE):

| S.No. | Standard | Method/Procedure | Reference |
|-------|--------------|--|-------------------------|
| 1. | ASTM D143-94 | According to this standard samples are placed in a control condition where temperature is at 20°C and relative humidity range is from 60 to 70% until specimens gained | Kiaei & Samariha (2011) |

| | | | |
|----|------------------|---|----------------------------|
| | | moisture content approximate 12%. Test is performed on a universal testing machine and the formula to evaluate Modulus of elasticity is as follows: $M.O.E. = P \times l^3 / 4 \times D \times b \times h^3$ Where P = load (kN), l = Span length(mm), D = Deflection(mm), b = breadth(mm) and h = height (mm) | |
| 2. | IS:1708-5 | The size of specimen was 20mm × 20mm × 30mm having span length of 280mm. The load rate as per standard is 1 mm/min. The both samples air dry and green can be used in this experiment. The formula is as follows to determine modulus of elasticity: $M.O.E. = P \times l^3 / 4 \times D \times b \times h^3$ Where P = load (kN), l = Span length (mm), D = Deflection(mm), b = breadth(mm) and h = height (mm) | Shukla et al., 2007 |
| 3. | DIN 52186 (1978) | As per this standard size of samples are 100mm x 5mm x 10mm. Samples are kept in control conditions where temperature ranges from 17 to 24°C and relative humidity ranges from 60 to 70%. Test is performed on universal testing machine and 5 mm/min rate of loading is specified in this standard. | Carrillo et al.(2011) |
| 4. | DIN 52186 | According to this standard samples are kept in controlled climatic conditions in which temperature ranges from 19 to 21°C and humidity of 62 to 68%. Test is performed on UTM and 5 mm/min rate of loading is applied. | Mantanis & Birbilis (2010) |

IS:1708-5 standards is used in present work because in literature of Thulasidas & Bhat 2012 determined Modulus of elasticity with a specified uniform rate of 1mm.min⁻¹ and this comes in our equipment range.

Table 2.5 Important references to determine modulus of rupture (MOR):

| S.No. | Standard | Method/Procedure | Reference |
|-------|--------------|---|-------------------------|
| 1. | ASTM D143-94 | The prepared samples (For each species N= 50) were after that conditioned in a room at a temperature of 20°C and 65 ± 5% relative humidity until the samples gained an equilibrium moisture | Kiaei & Samariha (2011) |

| | | | |
|----|-----------|---|--------------------------|
| | | <p>content of about 12%.The moisture content of all specimens was 12-13% in this test. Test is performed on a universal testing machine and the formula to evaluate MOR is as follows:</p> $MOR = 3 \times P_{max} \times l / 2 \times b \times h^2$ <p>Where P = load at the limit of proportionality (kN); P_{max} = maximum load (KN), l = span of the test specimen (mm), b = breadth of the test specimen (mm), h = depth of the test specimen (mm).</p> | |
| 2. | IS:1708-5 | <p>The size of samples was 2 cm × 2 cm × 30 cm with a span length of 28 cm. The loading was applied at a steady rate of 1.0 mm min⁻¹ on the tangential surface of the specimen. The numbers of samples used in green and air-dry states were 159 and 162 in that order. The formula is as follows to determine Modulus of rupture:</p> $MOR = 3 \times P_{max} \times l / 2 \times b \times h^2$ <p>Where P = load at the limit of proportionality (kN); P_{max} = maximum load (kN), l = span of the test specimen (mm), b = breadth of the test specimen (mm), h = depth of the test specimen (mm)</p> | Shukla et al., 2007 |
| 3. | IS:1708-5 | <p>The testing is performed on a span length of 280 mm. The loading was applied at a steady rate of 1.0 mm/min on the tangential surface of the specimen. The numbers of samples used in testing is 90. The formula is as follows to determine MOR:</p> $MOR = 3 \times P_{max} \times l / 2 \times b \times h^2$ <p>Where P = load at the limit of proportionality (kN); P_{max} = maximum load (kN), l = span of the test specimen (mm), b = breadth of the test specimen (mm), h = depth of the test specimen (mm)</p> | Thulasidas & Bhat (2012) |

| | | | |
|----|---------------------|--|----------------------------|
| 4. | DIN 52186 (1978) | MOR was determined using 30 samples from each species (ten specimens per tree), measuring 100 × 5 × 10 mm. The MOR test was performed on a universal Tinius Olsen machine once specimens gained constant weight at 65% moisture content and 20±3°C, using three-point static bending where annual rings were leaning horizontally, The rate of loading was 5 mm/min in the direction of the narrow side at the centre of the sample span. MOR was evaluated during using the ultimate load at the break point as the condition of rupture. | Carrillo et al.(2011) |
| 5. | DIN 52186 | The Modulus of elasticity of Tamarix aphylla wood was evaluated on specimens free from defects under normal climatic conditions (65±3% RH and 20±1°C). The static modulus of elasticity was evaluated on 15 samples by testing static bending strength with a Zwick-Roell Z020 testing machine. The load was applied at a rate of 5 mm/min | Mantanis & Birbilis (2010) |

IS:1708-5 standards is used in present work because in literature of Thulasidas & Bhat 2012 determined Modulus of rupture with a specified uniform rate of 1mm.min⁻¹ and this comes in our equipment range.

2.3 Summary of Literature Surveyed

As discussed above it is evident from the published literatures that various physical and mechanical properties are individually investigated but no effort is done to relate the mechanical properties with machining parameters and the measurable output that is surface finish. Moreover such a study will helpful to find the best parameters values for optimise the machining and surface finish.

CHAPTER 3

METHODOLOGIES

In this thesis work correlation was found between different mechanical properties of wood with forces produced in slot milling and surface finish of slot cut. There are several mechanical properties of wood but Hardness, Density, Modulus of rupture, Modulus of elasticity and Maximum crushing strength are directly correlated with machinability of wood as reported by Akyildiz & Kol, 2010, Gnanaharan & Dhamodaran, 1993, McKenzie et al., 2001, Eyma, Méausoone, & Martin, 2004, Shanavas & Kumar, 2006, Korkut & Guller, 2008, Akyildiz & Kol, 2010, Bal, 2014. The six wood species were selected for experiments named Dake, Mango, Sheesham, Babool, Jamoha and Neem. Wood species which was selected for experiment is a class II wood species because these wood species are not used for carving operations and class I wood species are costly. Procedures to find out these properties and equipments are also discussed in the section below. Since wood is an anisotropic material thus it exhibits direction dependent measurable responses like cutting forces and surface finish etc. In this present study slot milling had been performed on router with respect to different direction of grains of wood to study the relation between the machinability parameters vis-à-vis type wood variety and direction of grain. Dynamometer was used for recording cutting forces in machining. A stylus type roughness tester was used for measuring surface roughness of slot milled.

3.1 Mechanical Properties of Wood

3.1.1 Hardness

Hardness is ability of a material to resist indent or scratches on its surface. Hardness can be measured into three types (i) Scratch (ii) Indentation (iii) Rebound. Most common method used to determine hardness is Rockwell hardness and Brinell hardness tester. Wood hardness is one of the most important and desirable property in carving application because higher hardness prevents splitting of wood leading to better surface finish. More the hardness, better the carving will be and vice versa. Hardness of the sample is direction dependent.

3.1.2 Density

Density of a material is its mass per unit volume. Different materials have different densities. It depends upon the atomic mass, size and structure of the material. Hardness depends on the density of a material. Wood is a hygroscopic material so density depends upon two factors one is the basic substance wood and another is weight of moisture reserved in wood. Wood density is an important property for both fibre products and solid wood. Range of densities

for wood species varies from 160 kg/m^3 to 961 kg/m^3 . It is independent of the direction of the fibre.

3.1.3 Modulus of Rupture

Modulus of rupture is also known as flexural strength of a material. It is defined as ultimate stress in a substance before it ruptures in flexural test. The bending test is mostly applied with specimens of circular or flat cross section. Modulus of rupture is not a true stress because the equation or formula used to compute is valid only for elastic limit.

3.1.4 Modulus of Elasticity

Elasticity is defined as the recovery of original shape of an object after removing the load. But when the load is at high level, plastic deformation or failure occurs. This is an index of stiffness of a material. The three Moduli of elasticity of timber are denoted by E_L , E_R and E_T for longitudinal, radial and tangential respectively.

3.1.5 Maximum Crushing Strength

Maximum crushing strength is also known as compressive strength parallel to grain. It is ability of timber to withstand with compressive force. Applications of crushing strength are outdoor uses such as bridges and decks because its capability to absorb plenty of water and don't warp.

3.2 Sample Cutting From Log of Wood

Measurement of the relevant properties was carried out in accordance with pertinent standard codes and procedures which necessitate samples with different sizes and cross section. Samples of the required sizes were taken out from the logs of wood variety samples with the help of sawing machine. For the testing of different mechanical properties the samples of wood should be defect free like warp, knot. The cutting of wood samples was carried out by the saw machine, planner machine etc.

3.3 Procedures Used to Determine Mechanical Properties

3.3.1 Hardness

Rockwell Hardness testing machine (shown in figure 3.1) was used to measure the hardness of the samples. For softer material like wood, aluminium the scale B is preferred. Samples measuring $20 \text{ mm} \times 20 \text{ mm} \times 20 \text{ mm}$ of various wood varieties were prepared as shown in figure 3.2. Sample is appropriately mounted on the machine and load (in kN) is applied at a load rate of 6 mm/min by penetrating the steel ball of diameter 1.128 cm up to a depth of 0.564 cm . Hardness is measured along the different directions of the grains i.e. the radial, tangential and end faces while avoiding splitting or chipping during the procedure.



Figure-3.1: Avery make Rockwell hardness tester



Figure-3.2: Specimens for Hardness Testing

3.3.2 Density

As per ASTM D-143 samples measuring 20mm x 20mm x 20 mm were prepared as shown in figure 3.3. It was not possible to prepare exact samples with said dimension but samples were prepared as close as possible. Five readings were taken for each dimensions and after averaged. For dimension accuracy digital caliper was used having least count of 0.01 mm. Density is measured with the help of oven and weighing machine. A digital oven (as shown in figure 3.4) has been used to drive out the moisture content from wood samples and have 0% moisture content. Maximum temperature of oven is 200°C.

Then specimens were kept in an oven at a temperature of 103 ± 2 °C for 24 hrs to remove its all moisture content. At 0% moisture content weight of each sample was measured.

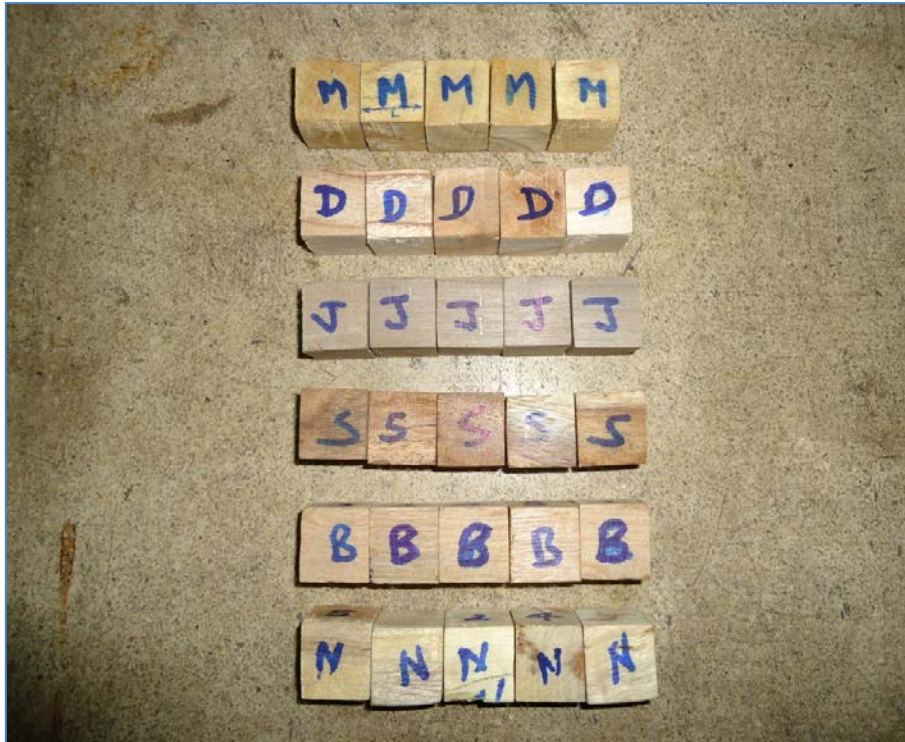


Figure 3.3: Samples of different wood species prepared for Density test

Oven-dry density was calculated using the following formula:

$$D_o = M_o / V_o \quad (\text{Eq: 3.1})$$

Where D_o , M_o and V_o are the oven dried density, weight and volume of samples respectively.



Figure 3.4: Sentwin core baking

3.3.3 Modulus of Rupture and Modulus of Elasticity

As per the IS: 1708:5-1986 measuring 20mm x 20mm x 300mm as shown in figure 3.5 and 3.6 were prepared and tested on Universal testing machine (HUNG Ta Instrument Go., Ltd Make) which is fully computerised machine with servo control and having capacity of 1000 kN.



Figure 3.5: Specimens of Babool, Sheesham and Neem wood Species prepared for MOR and MOE test

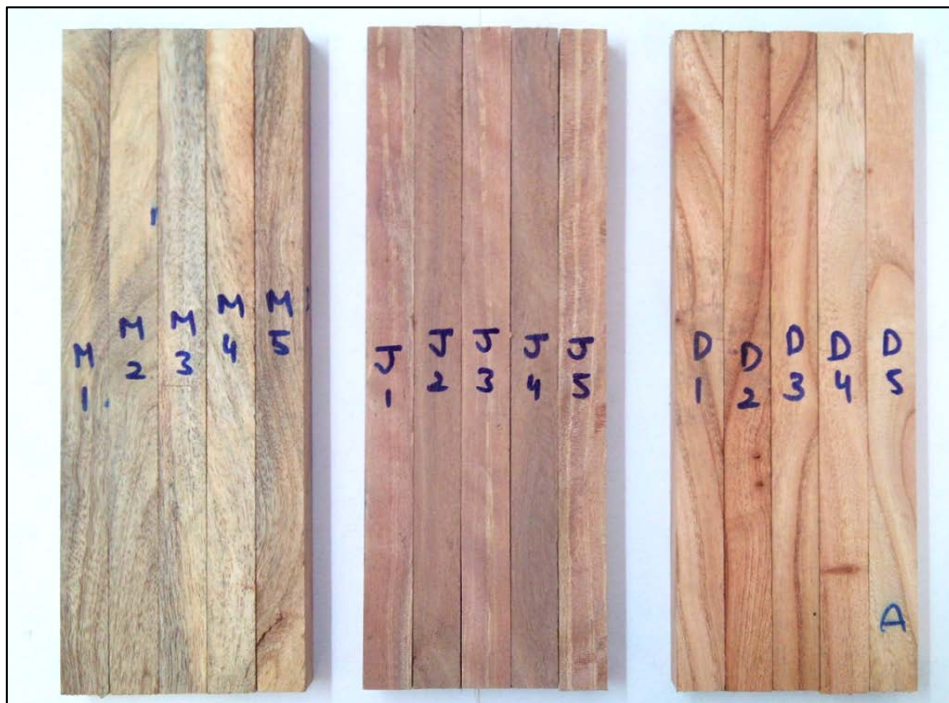


Figure 3.6: Specimens of Mango, Jamoha and Dake wood Species prepared for MOR and MOE test

The load was applied continuously through-out the test with a rate of 1.0 mm.min^{-1} . The wood specimen was placed in horizontally position and load was applied on the center of the

specimen. The load was calculated till the specimen broke. The following equations were used to determine values of Modulus of Rupture and Modulus of Elasticity:

$$M.O.R. = \frac{3Pl}{2bh^2} \quad (\text{Eq: 3.2})$$

$$M.O.E. = \frac{Pl^3}{4\Delta bh^3} \quad (\text{Eq: 3.3})$$

Where P = Load (N), l = Effective length (mm), b = Breadth of Specimen (mm), h = Depth of Specimen (mm), Δ = Deflection (mm).

3.3.4 Maximum Crushing Strength

Maximum crushing strength (MCS) is the ability to withstand axial load. For wood there are two types of crushing strength:

Maximum crushing strength parallel to the grain

Maximum crushing strength perpendicular to the grain

The test was performed according to standard IS: 1708:8-1986 for MCS parallel to the grain and IS: 1708:9-1986 for MCS perpendicular to the grain. The size of specimens (as shown in figure 3.9) for parallel to grain was 20mm x 20mm x 80mm and for perpendicular to grain was 20mm x 20mm x 100mm. Rate of loading for both was same that is 0.6 mm per minute.

A UTM (as shown in figure 3.7) as mentioned in 3.3.3 was used for this test as well. In this test specimen was placed vertically between movable and fixed head of machine (as shown in figure 3.8) and load was applied continuously at a load rate 0.6 mm per minute till the fracture occurred.



Figure 3.7: Universal testing machine HUNG Ta Instrument Go., Ltd.

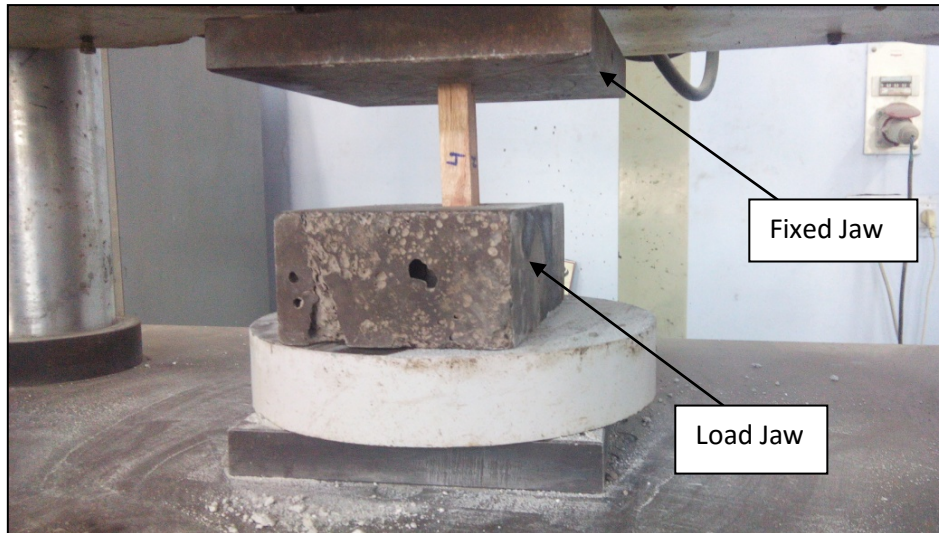


Figure 3.8: Specimen parallel to grain under load

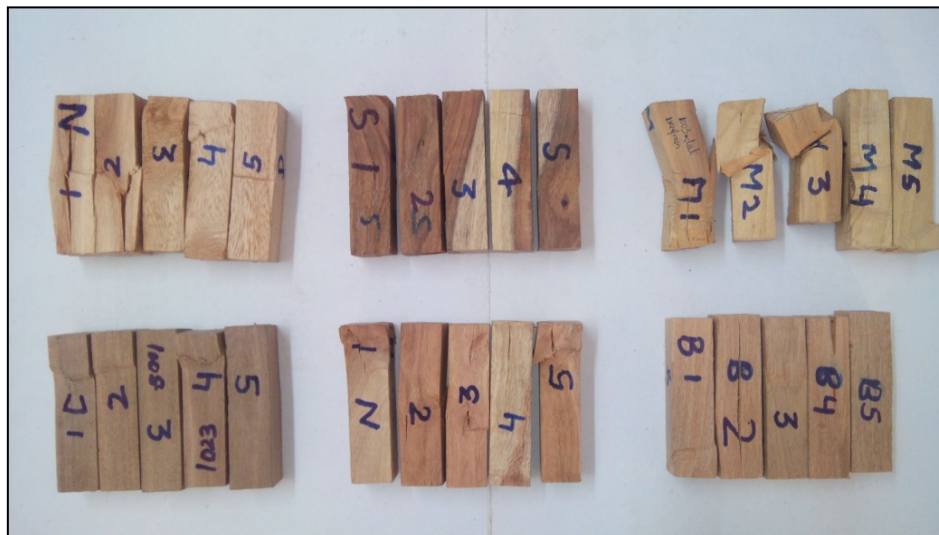


Figure 3.9: Specimens after crushing strength (Parallel to the grain) testing

The load was calculated and following equation was used to determine maximum crushing strength:

$$\sigma = \frac{P}{A} \quad (\text{Eq: 3.4})$$

Where **P** is Load (N) and **A** is Cross sectional area of specimen (mm²)

3.4 Grain Orientation of Wood for Machining

Wood grain is longitudinal arrangements of wood fibre. While milling on wood the effect of wood grain direction is important because interaction of the tool with the grains along different directions imposes varying cutting loads and also yields varying levels of surface finish. The following combinations of tool interaction with the wood grain along different

direction (as shown in figure 3.10) in milling operation have been considered in the present study.

1. Cut along the fibre (With tool axis aligned normal to fibre)
2. Cut across the fibre (With tool axis aligned normal to fibre)
3. 45° Inclined cut across the fibre (With tool axis aligned normal to fibre)
4. Cut across the fibre (With tool axis aligned parallel to fibre)
5. Plunge (When tool axis aligned normal to fibre)
6. Plunge (When tool axis aligned parallel to fibre)

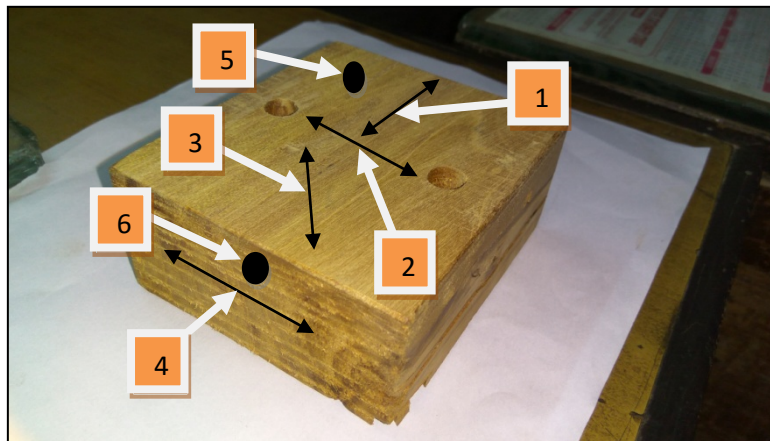


Figure 3.10: Slot milling different direction

The following table 3.1 shows the codes which are assigned to different cutting direction. These codes are used for further discussion in next chapters.

Table 3.1 Codes assigned to different cutting direction:

| S.No. | Code | Cutting direction |
|-------|-------|-----------------------------------|
| 1. | 90-0 | Cut along the fibre |
| 2. | 0-90 | Cut across the fibre |
| 3. | 0-45 | 45° Inclined cut across the fibre |
| 4. | 90-90 | Axial cut |

3.5 Machine Setup for Milling

Machine setup consists of a CNC wood router, a Kistler make Dynamometer and details of the set up are as under:

3.5.1 Three-Axis Wood Router

For machining a 3-axis wood router as shown in figure 3.11 with X,Y,Z axis was used. Each axis had motors attached with its each axis for movement.

On wood router table a dynamometer (as shown in figure 3.11) was attached to measure cutting forces encountered during in the machining. The machining parameters include feed rate, depth of cut and spindle rpm. The router was connected to a laptop for tool positioning movement commands via a controller. Rated spindle rpm of the router was 35000 rpm. High rpm is generally employed in order to avoid the local burning of wood.



Figure 3.11: 3-Axis CNC wood router

3.5.2 Dynamometer

Dynamometer (KISTLER LTD.) has been used to measure the cutting forces during the operation. Dynamometer has a piezoelectric sensor which senses the forces acting on the work piece attached to dynamometer. There are two types of dynamometer available (i) Stationary dynamometer (ii) Rotating dynamometer. Depending upon nature of machining suitable dynamometer is selected. Stationary is used where the work piece is stationary like milling and rotating is generally used in lathe machine where work piece is rotating. It is attached with an amplifier to the computer to measure the forces. In the present study stationary dynamometer was used in the machining.

The main purpose of knowing forces in machining are listed as below:

1. Machining process analysing
2. Determine the material machinability
3. Tool wear analysis
4. Optimize the machining process
5. Compare the machining process with others

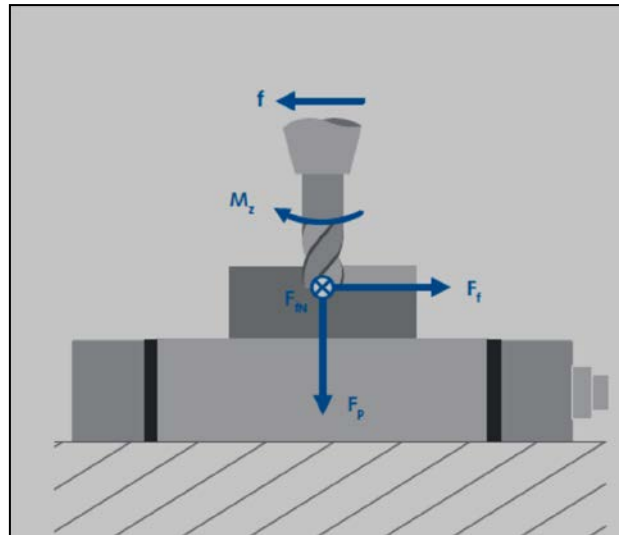


Figure 3.12: Direction of forces in milling [33]

Where F_f is feed force, F_{fn} is feed normal force, F_p is Passive force, M_z is Spindle moment respectively.

3.6 Cutting Tool

A high carbide steel flat end mill cutter tool with four cutting edges as shown in figure 3.13 has been employed in this study.



Figure 3.13: Flat end mill cutter

3.7 Machining Parameters

As discussed earlier, wood carving using a milling CNC router has mainly three parameters viz.: feed rate, depth of cut and spindle rpm. Objective of this study is to explore the interaction these parameters with respect to the cutting forces and the resultant surface finish for a variety of class II wood species. Table 3.2 shows the values of these three parameters that have been used for machining of various wood species in this study:

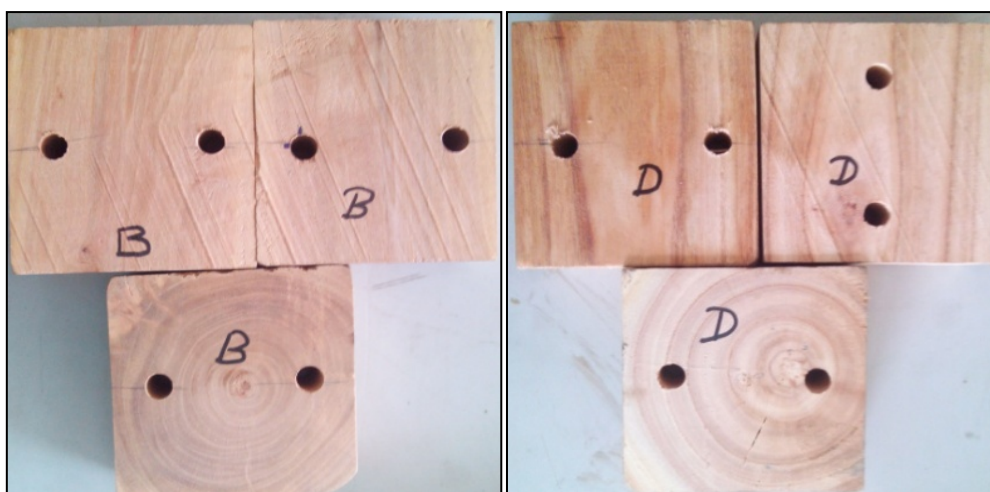
Table 3.2: Parameters for machining of wood species

| Type of operation | FEED RATE (mm/min) | DEPTH OF CUT (mm) | SPINDLE SPEED (rpm) |
|-------------------|--------------------|-------------------|---------------------|
| CUT | 200 | 5 | 33000 |
| PLUNGE | 200 | 10 | 33000 |

The parameters were same for every wood species cut and surface roughness of cutting slot was measured after milling.

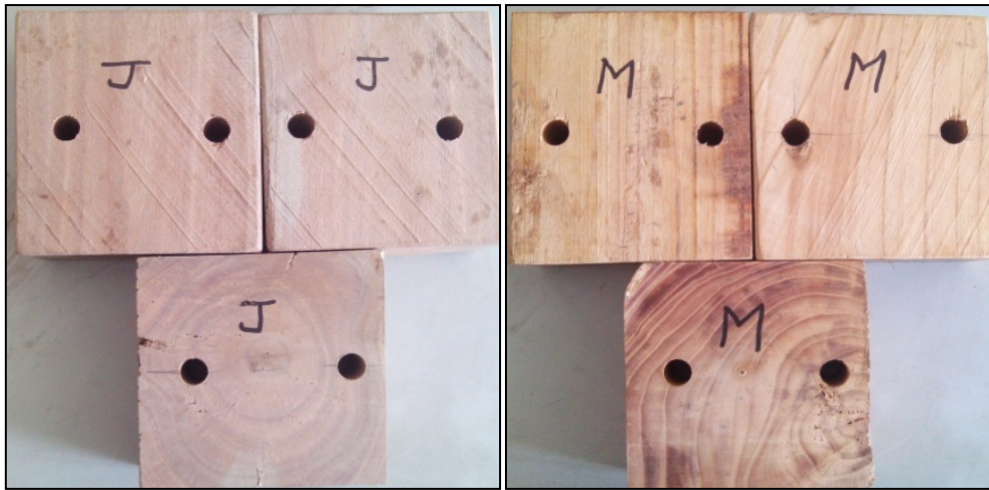
3.8 Specimens for Machining

The specimens were mounted on the dynamometer table with the help of bolts. So the specimens had pre drilled holes to receive the bolts to fix the specimen on top of dynamometer. Dynamometer readings were found be sensitive with respective to the position of the work piece on top table. So all the work specimen sized to fit within the top surface of the dynamometer. A figure 3.14 shows specimen of different wood species measuring was 95mm x 95mm x 45mm. Even during the machining of different specimens, it was assured that tool position and tool travel remains unaltered with respect to the dynamometer in order to avoid spurious data collection.



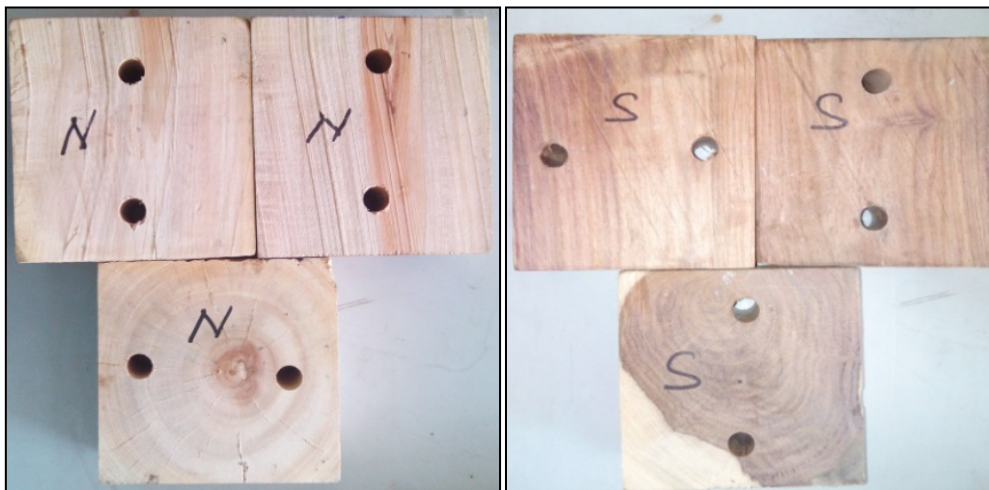
(a) Babool

(b) Dake



(c) Jamoha

(d) Mango



(e) Neem

(f) Sheesham

Figure 3.14: Specimens of different wood species for machining

3.9 Procedure of Cut and Plunge

The figure 3.15 shows different machining trials capturing different interactions of the tool and wood grains. Figure 3.15 a, b, c and d show the slot milling operations in which the tool axis is kept normal to the wood grains while the tool travel is along, across and oblique to the wood grains respectively. Similarly figure 3.15 a, also shows a tool plunge operation in which tool axis as well the tool travel is oriented normal to the wood grains leading to plunging of the tool in to the wood for each of these trials dedicated. Tool paths were generated using the relevant G & M codes. The one by one different slot cut was performed on different wood species. Their forces were measured and recorded in computer using software Dynoware.

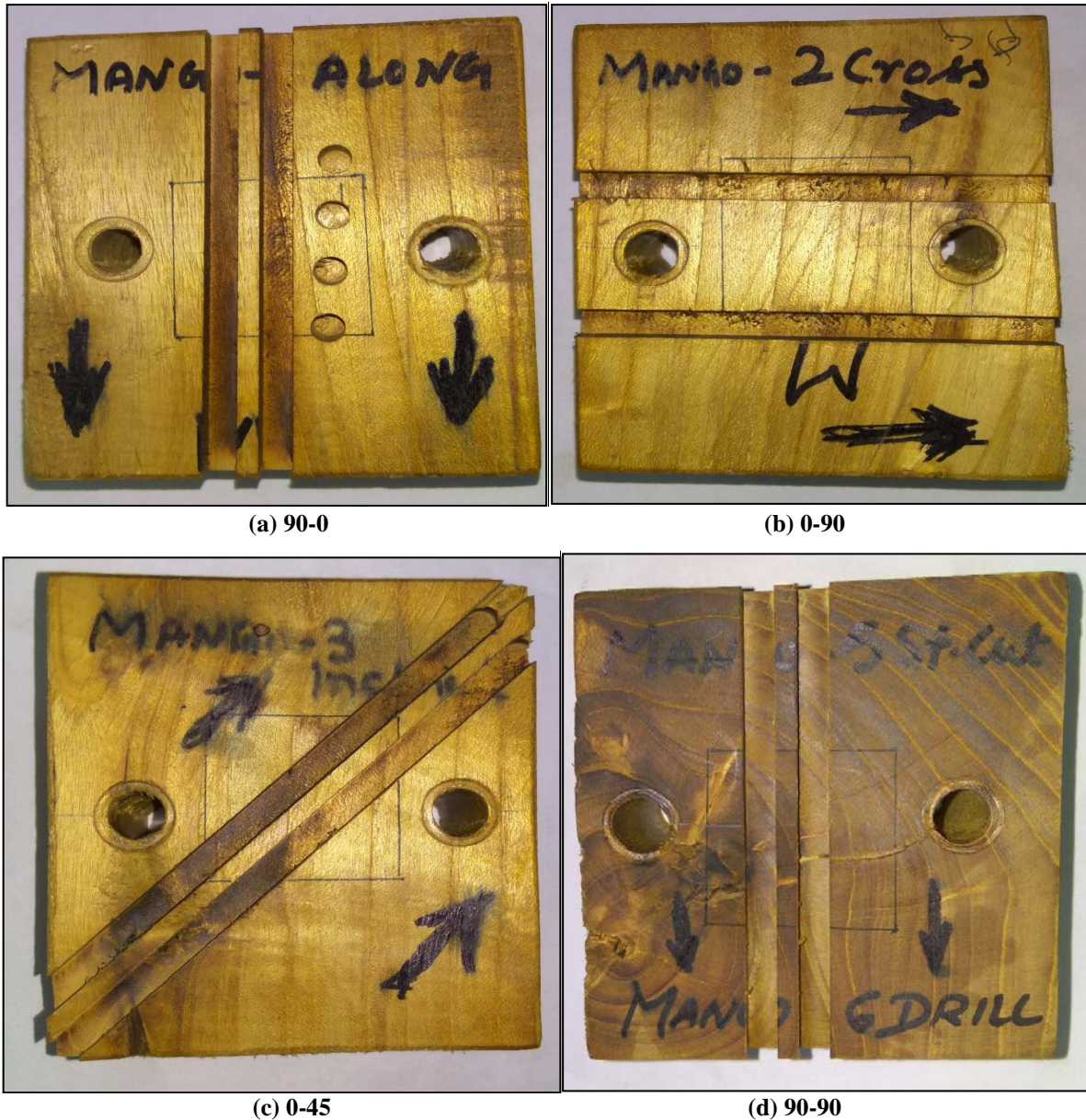


Figure 3.15: Machining trials showing different interactions of tool and wood grain (for mango wood)

3.10 Surface Roughness

It is quantified by the deviations in the way of the normal vector of an actual surface from its ideal appearance. If these deviations are huge, the surface is uneven; if they are little, the surface is even. Roughness is usually considered to be the high-frequency, short-wavelength part of a measured surface. On the other hand, in practice it is often compulsory to know both the amplitude and frequency to make sure that a surface is fine for a purpose. Roughness plays a key role in determining how an actual object will interact with its surrounding environment. Rough surfaces frequently wear more quickly and offer higher friction coefficients than smooth surfaces.

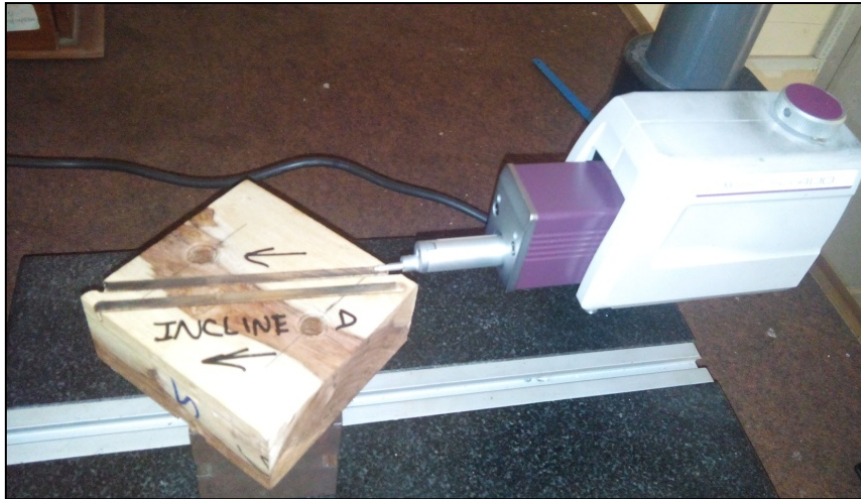


Figure 3.16: Surface roughness testing on wood sample

Surface roughness of the machined surface generating by slotting operation was measured by Mitutoyo surface roughness tester Model SJ-400. It has trace length of 8mm. It operates on a contact stylus method in which a tip called stylus moves on surface of the specimen whose surface roughness has to be measured. Each wood species had four different direction slot cut which already discussed earlier. Two readings were taken for each slot cut from different places and after averaged value for slot milled.

The results of different mechanical properties, cutting forces produced in slot milling of different directions and surface roughness of different slots milled have been analyzed in next chapter results and discussion.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results obtained for mechanical properties of various wood species, measured operating parameters and the corresponding machining responses vis-avis different wood varieties. The aim of work is to correlate the mechanical properties of various wood species selected with the machinability parameters which have been considered in this case machining forces and then try to correlate the effect of mechanical properties of various wood species and machining cutting forces with surface finish. Since wood is an anisotropic material, an attempt has been made consider six different directions for cutting which are pictorially shown in chapter 3. For all this direction, machine the material along the direction, across the direction, inclined the direction and axial the directions as well as an attempt is tried to figure out the effect of magnitude of forces in plunge. The standard procedures to find forces and surface finish have been already explained in chapter 3 and the results of different mechanical properties of wood species selected, cutting forces and surface finish thus obtained has been presented in this chapter in various sections:

4.1 Experimental Plan

In experimental plan first of all mechanical properties of wood species selected was determined as per standards and procedure discussed in chapter 3 section 3.3. The averaged values of each mechanical properties are considered in this chapter for analysis and compiled data of mechanical properties can be seen in Annexure A for hardness, Annexure B for density, Annexure C for modulus of rupture, Annexure D for modulus of elasticity, Annexure E for maximum crushing strength (Parallel to grain), Annexure F for maximum crushing strength (Perpendicular to grain). Subsequently the different wood species specimens were machined in different configurations like slot milling in along, across, inclined, axial to the grains and plunge (drilling) in along and axial directions of wood species as per procedure discussed in chapter 3 section 3.5 and using different machining parameters like feed rate and depth of cut. Stationary dynamometer was mounted on CNC router for measuring and recording cutting forces during different machining event. Dynoware is software which was used for measuring forces through dynamometer and convert data into excel file. As wood is an anisotropic material so two slots were milled on each specimen (as shown in figure 3.15 a,b,c,d) during slot milling, Similarly four plunge cuts were carried out (as shown in figure 3.15 a) on each specimen during plunge cut operation. One by one each slot was milled in different selected directions of wood species and recorded the forces. Mitutoyo model SJ-400

surface roughness tester which work on contact stylus method was used to measure the surface roughness of each slot milled.

4.2 Forces Produced In Slot Milling

The forces produced during slot milling and drilling operations in various directions of wood species are shown. Different iterations of forces and averaged forces for different directions are shown and by considering averaged values various graphs are plotted to analysis the forces.

Table 4.1: Forces produced during slot milling in different direction

| Wood species | 90-0 | | | Plunge on 90-0 | | | | | 0-90 | | | 0-45 | | | 90-90 | | | Plunge on 90-90 | | | | |
|--------------|-------------|-------------|---------|----------------|-------------|-------------|-------------|---------|-------------|-------------|---------|-------------|-------------|---------|-------------|-------------|---------|-----------------|-------------|-------------|-------------|---------|
| | Iteration 1 | Iteration 2 | Average | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Average | Iteration 1 | Iteration 2 | Average | Iteration 1 | Iteration 2 | Average | Iteration 1 | Iteration 2 | Average | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Average |
| Babool | 11.2190 | 10.4071 | 10.8130 | 8.3471 | 7.1665 | 7.9939 | 8.1546 | 7.9155 | 8.0890 | 12.2256 | 10.1573 | 10.3931 | 13.6431 | 12.0181 | 8.6888 | 7.7856 | 8.2372 | 7.2688 | 7.5616 | 6.9642 | 8.0831 | 7.4694 |
| Dake | 12.8904 | 13.1354 | 13.0129 | 4.3085 | 4.3415 | 3.9425 | 4.4000 | 4.2481 | 8.0985 | 17.9388 | 13.0186 | 11.0673 | 14.6988 | 12.8831 | 5.4493 | 8.7810 | 7.1152 | 5.4126 | 5.7353 | 4.7500 | 5.6630 | 5.3902 |
| Jamoha | 13.0226 | 10.9758 | 11.9992 | 5.5000 | 5.3363 | 6.1406 | 5.1175 | 5.5236 | 14.0561 | 14.1834 | 14.1197 | 14.1780 | 9.3387 | 11.7584 | 6.8506 | 7.0075 | 6.9290 | 6.9808 | 5.9654 | 7.7240 | 6.5329 | 6.8008 |
| Mango | 11.5078 | 10.2118 | 10.8598 | 8.6953 | 5.7197 | 5.6134 | 7.5554 | 6.8959 | 11.3569 | 11.3619 | 11.3594 | 11.0826 | 10.4356 | 10.7591 | 8.4383 | 11.1476 | 9.7930 | 7.1712 | 6.4959 | 8.4858 | 9.6093 | 7.9406 |
| Neem | 14.7621 | 14.4222 | 14.5922 | 7.4801 | 7.4268 | 6.7214 | 6.6286 | 7.0642 | 9.0091 | 11.4122 | 10.2106 | 10.0973 | 9.3487 | 9.7230 | 6.8193 | 7.1546 | 6.9869 | 8.5437 | 9.5848 | 9.0822 | 9.7945 | 9.2513 |
| Sheesham | 14.0154 | 13.4112 | 13.7133 | 7.0926 | 6.5418 | 6.9937 | 5.8638 | 6.6230 | 6.7396 | 10.3364 | 8.5380 | 16.0128 | 15.0562 | 15.5345 | 7.4086 | 8.8328 | 8.1207 | 6.8095 | 7.0787 | 4.7858 | 9.6254 | 7.0749 |

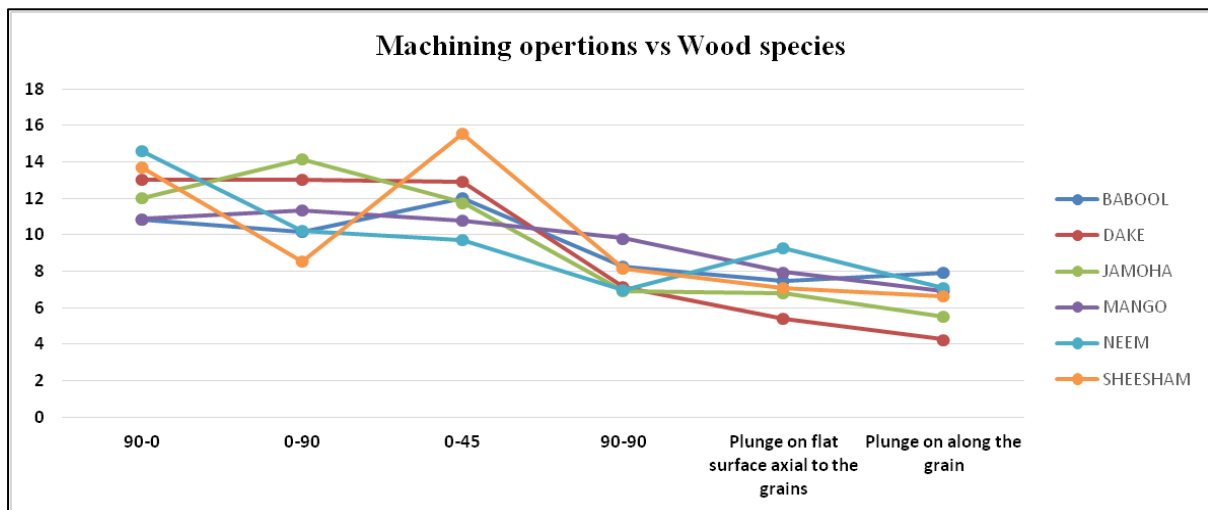


Figure 4.1: Trends of different cutting directions with cutting forces

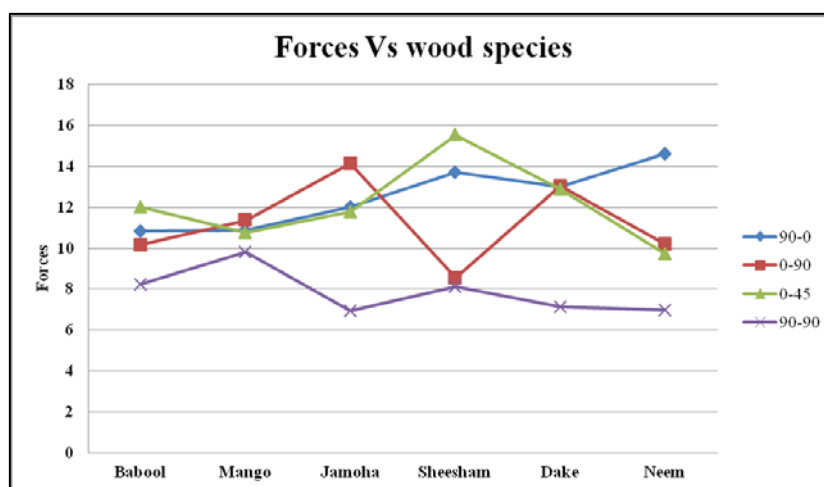


Figure 4.2: Forces in different wood species

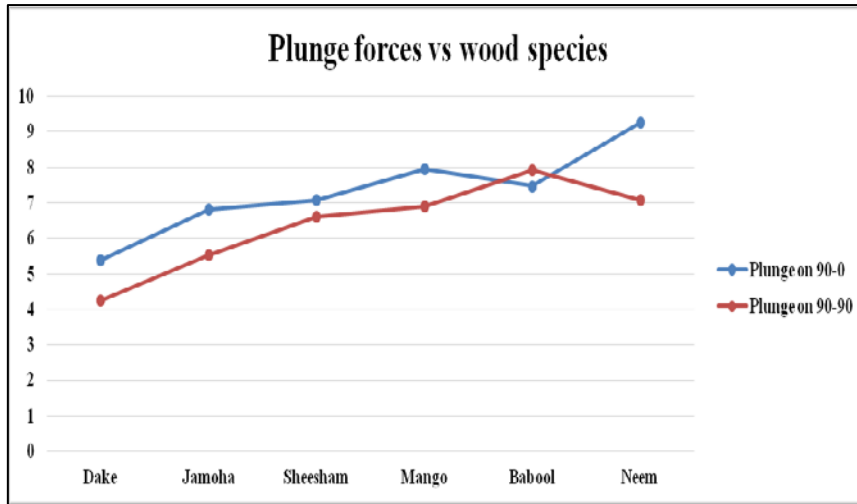


Figure 4.3: Plunge forces in different wood species

In Figure: 4.1 trends are shown of different cutting directions for different wood species. From graph it can be seen that force trends is continuously decreasing. Maximum forces are occurred in 90-0 direction slot milling and minimum forces are occurred in 90-90 direction slot milling. From figure 4.3 it is observed that during 90-90 direction drilling less force is occurred than 90-0 drilling except babool.

4.3 Surface Roughness of Various Wood Species

Surface roughness of slots milled in various directions is shown in tabular form. Surface roughness has three parameters Roughness average (Ra), Mean roughness depth (Rz) and Root mean square average (Rq). These three parameters are measured with Mitutoyo SJ-400 surface roughness tester. Two iterations for each slot were noted and after averaged to get final value.

Table 4.2: Surface roughness for various wood species in different slot milling direction

| Cutting Direction | Wood Species | Neem | | | Babool | | | Sheesham | | | Jamoha | | | Dake | | | Mango | | |
|-------------------|---------------------------|-------------|--------------|-------------|-------------|--------------|-------------|-------------|--------------|-------------|-------------|--------------|-------------|-------------|--------------|-------------|-------------|--------------|--------------|
| | | Ra | Rz | Rq | Ra | Rz | Rq | Ra | Rz | Rq | Ra | Rz | Rq | Ra | Rz | Rq | Ra | Rz | Rq |
| 90-0 | Iteration 1 | 2.11 | 13.10 | 2.67 | 2.08 | 14.90 | 2.74 | 2.89 | 14.60 | 3.62 | 2.48 | 15.50 | 3.16 | 1.78 | 9.60 | 2.18 | 2.24 | 14.60 | 2.81 |
| | Iteration 2 | 3.20 | 17.90 | 4.11 | 2.30 | 14.10 | 2.87 | 3.21 | 17.00 | 4.05 | 2.40 | 13.65 | 2.97 | 3.01 | 20.25 | 4.00 | 2.26 | 13.50 | 2.78 |
| | Mean of Iteration 1 and 2 | 2.66 | 15.50 | 3.39 | 2.19 | 14.50 | 2.81 | 3.05 | 15.80 | 3.84 | 2.44 | 14.58 | 3.06 | 2.39 | 14.93 | 3.09 | 2.25 | 14.05 | 2.80 |
| 0-90 | Iteration 1 | 4.04 | 21.45 | 4.68 | 3.97 | 23.20 | 4.87 | 6.51 | 39.60 | 8.53 | 5.33 | 31.90 | 6.68 | 3.70 | 20.25 | 4.52 | 10.61 | 57.80 | 13.89 |
| | Iteration 2 | 3.50 | 22.95 | 4.64 | 4.22 | 26.10 | 5.38 | 4.15 | 27.05 | 5.50 | 4.91 | 30.00 | 6.06 | 4.05 | 25.05 | 5.27 | 4.49 | 26.30 | 5.74 |
| | Mean of Iteration 1 and 2 | 3.77 | 22.20 | 4.66 | 4.10 | 24.65 | 5.13 | 5.33 | 33.33 | 7.01 | 5.12 | 30.95 | 6.37 | 3.87 | 22.65 | 4.89 | 7.55 | 42.05 | 9.82 |
| 0-45 | Iteration 1 | 4.71 | 23.00 | 5.83 | 3.86 | 21.40 | 4.77 | 3.36 | 20.62 | 5.12 | 5.55 | 29.50 | 6.78 | 6.11 | 31.95 | 7.69 | 10.50 | 53.30 | 13.00 |
| | Iteration 2 | 4.01 | 19.60 | 4.74 | 5.88 | 30.50 | 7.38 | 6.65 | 40.50 | 8.44 | 5.75 | 33.85 | 7.29 | 8.64 | 44.65 | 10.82 | 7.51 | 42.70 | 9.61 |
| | Mean of Iteration 1 and 2 | 4.36 | 21.30 | 5.28 | 4.87 | 25.95 | 6.08 | 5.00 | 30.56 | 6.78 | 5.65 | 31.68 | 7.04 | 7.37 | 38.30 | 9.25 | 9.01 | 48.00 | 11.31 |
| 90-90 | Iteration 1 | 2.55 | 15.50 | 3.29 | 2.59 | 16.40 | 3.40 | 2.05 | 15.60 | 2.92 | 2.40 | 14.85 | 3.05 | 3.00 | 21.45 | 3.59 | 2.01 | 16.00 | 2.87 |
| | Iteration 2 | 2.38 | 13.50 | 2.96 | 3.50 | 23.80 | 4.79 | 2.57 | 19.40 | 3.70 | 4.11 | 26.60 | 5.56 | 4.86 | 35.20 | 6.75 | 2.04 | 13.00 | 2.58 |
| | Mean of Iteration 1 and 2 | 2.46 | 14.50 | 3.12 | 3.05 | 20.10 | 4.10 | 2.31 | 17.50 | 3.31 | 3.26 | 20.73 | 4.31 | 3.93 | 28.33 | 5.17 | 2.03 | 14.50 | 2.73 |

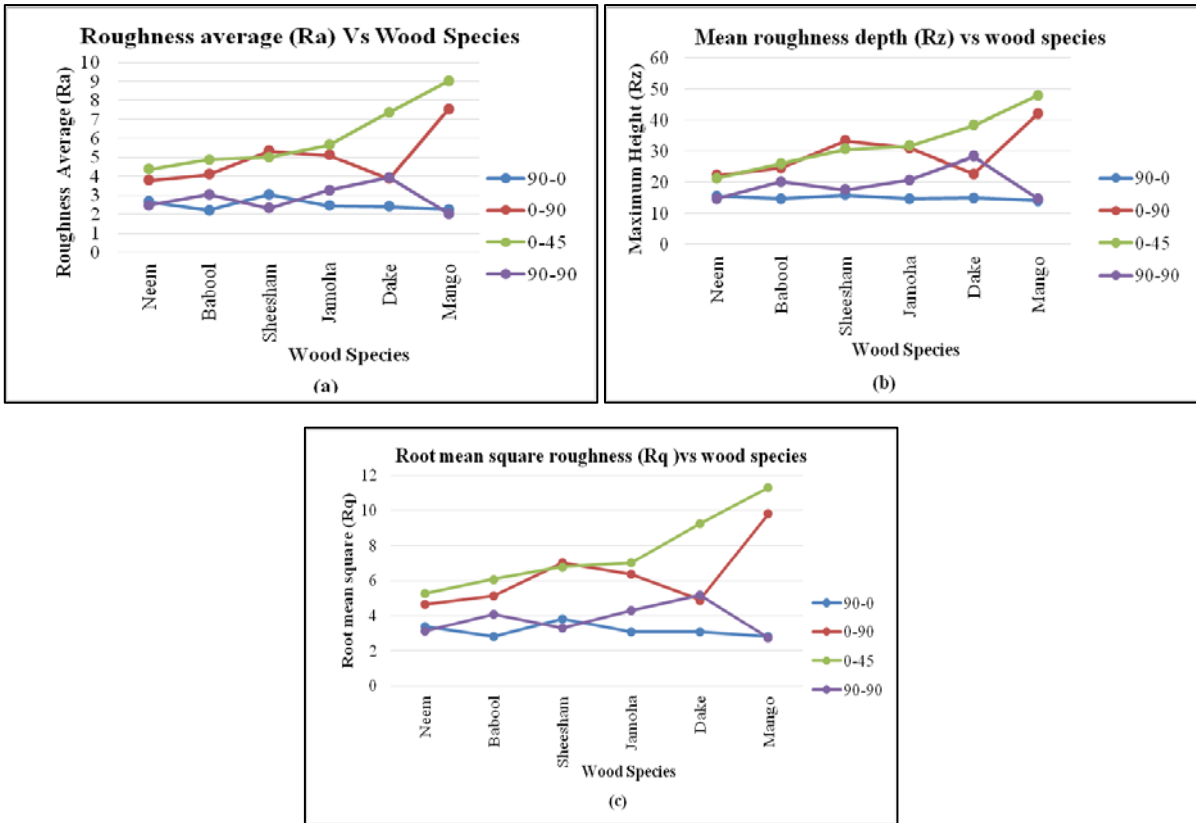


Figure 4.4: Comparison of (a) Ra, (b) Rz and (c) Rq values for different directions of six wood species

In figure 4.4 (a.,b,c) show comparison of Surface roughness parameter Ra, Rz and Rq with respect to different wood species and different wood grain direction slot milling. It is observed that these wood species have same trend and also it is shown that surface finish is better in slot milling direction 90-0 and 90-90 for wood species. 0-45 slot milling direction is increasing in all the surface roughness parameters. So it is preferable that for better surface finish slot milling should be done on along the grain or axial to the grain of wood species.

In figure 4.5 (a,b,c,d,e,f) individual graphs were plotted for each wood species having values of Ra, Rz and Rq. Graphs show that Rz values are way higher than Ra and Rq values. By comparing in terms of Rz values the result of mango is highest in 0-45 and Neem is lowest in 90-90 slot cutting direction. In slot cutting direction 0-90 and 0-45 Rz values are almost highest in all wood species except Dake. 90-0 and 90-90 both direction has minimum Ra values in all wood species. Ra ,Rz and Rq have same trends and Ra is roughness average which is a main parameter to analyze a surface so this is a reason for choosing only Ra for analysing different slot milled surface in section 4.4.

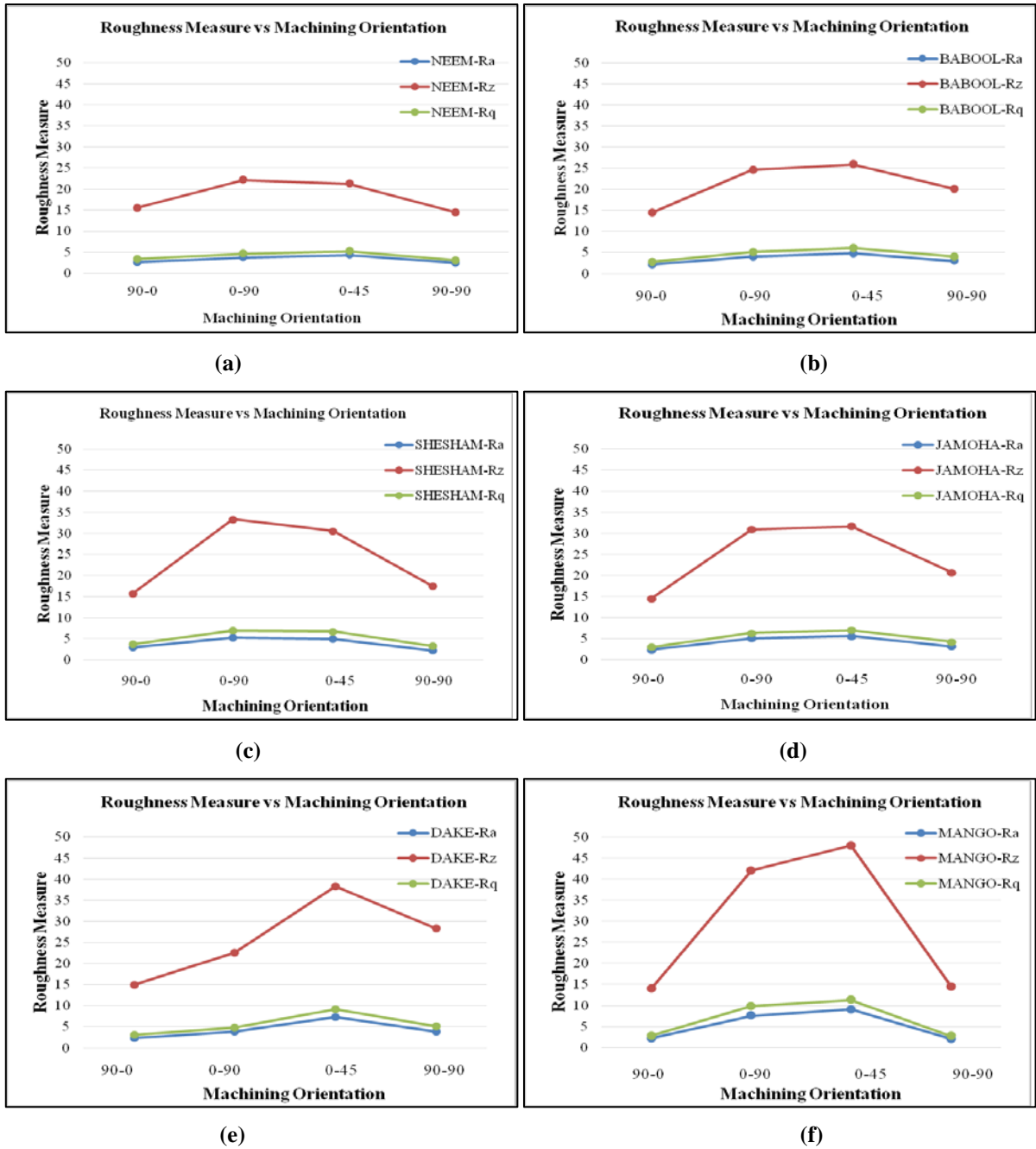


Figure 4.5: Surface roughness average (Ra), Mean roughness depth (Rz) and Root mean square (Rq) for (a) Neem (b) Babool, (c) Sheesham, (d) Jamoha, (e) Dake and (f) Mango

Table 4.3: Averaged values of surface roughness for various wood species

| Cutting Direction | Wood Species | Sr No. | Babool | | | Dake | | | Jamoha | | | Mango | | | Neem | | |
|-------------------|---------------------------|--------|--------|-------|------|------|-------|------|--------|-------|------|-------|-------|-------|------|-------|------|
| | | | Ra | Rz | Rq | Ra | Rz | Rq | Ra | Rz | Rq | Ra | Rz | Rq | Ra | Rz | Rq |
| 90-0 | Mean of Iteration 1 and 2 | 1 | 2.19 | 14.50 | 2.81 | 2.39 | 14.93 | 3.09 | 2.44 | 14.58 | 3.06 | 2.25 | 14.05 | 2.80 | 2.66 | 15.50 | 3.39 |
| 0-90 | Mean of Iteration 1 and 2 | 2 | 4.10 | 24.65 | 5.13 | 3.87 | 22.65 | 4.89 | 5.12 | 30.95 | 6.37 | 7.55 | 42.05 | 9.82 | 3.77 | 22.20 | 4.66 |
| 0-45 | Mean of Iteration 1 and 2 | 3 | 4.87 | 25.95 | 6.08 | 7.37 | 38.30 | 9.25 | 5.65 | 31.68 | 7.04 | 9.01 | 48.00 | 11.31 | 4.36 | 21.30 | 5.28 |
| 90-90 | Mean of Iteration 1 and 2 | 4 | 3.05 | 20.10 | 4.10 | 3.93 | 28.33 | 5.17 | 3.26 | 20.73 | 4.31 | 2.03 | 14.50 | 2.73 | 2.46 | 14.50 | 3.12 |

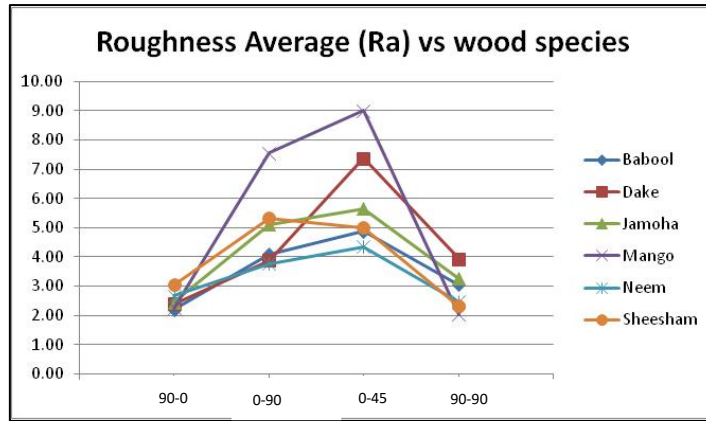


Figure 4.6: Surface roughness of different direction slot milled for various wood species

In figure 4.6 trends shows for surface roughness of various wood species in different directions. It is observed that trends is same for every wood species and 90-0, 90-90 direction gives better surface finish so in slot milling these directions are best for good surface finish.

4.4 Mechanical Properties Correlation

Table 4.4 Averaged values for mechanical properties, surface roughness and different wood species

| Wood species | Hardness (HRB) | | Maximum crushing strength Parallel to grain (Mpa) (P2) | Maximum crushing strength Perpendicular to grain (Mpa) (P2') | Modulus of rupture (Mpa) (P3) | Modulus of elasticity (Mpa) (P4) | Density (Kg/m ³) (P5) | 90-0 | | 0-90 | | 0-45 | | 90-90 | | Plunge cutting force on the 90-0 | Plunge cutting force on 90-90 |
|--------------|----------------------|------------------------|--|--|-------------------------------|----------------------------------|-----------------------------------|-----------|-----------|-----------|---------|------|-----------|-------|--------|----------------------------------|-------------------------------|
| | Along the grain (P1) | Across the grain (P1') | | | | | | R1 | F1 | R2 | F2 | R3 | F3 | R4 | F4 | F5 | F6 |
| | R _a (μm) | Force (N) | R _a (μm) | Force (N) | R _a (μm) | Force (N) | R _a (μm) | Force (N) | Force (N) | Force (N) | | | | | | | |
| Mango | 55 | 54 | 43.5074 | 8.0364 | 40.2881 | 5742.5117 | 580.1136 | 2.25 | 10.8598 | 7.55 | 11.3594 | 9.01 | 10.759098 | 2.03 | 9.7930 | 6.8959 | 7.9406 |
| Sheesham | 49.4 | 41.8 | 39.2992 | 8.9064 | 84.3994 | 6824.1811 | 656.1369 | 3.05 | 13.7133 | 5.33 | 8.5380 | 5.00 | 15.534472 | 2.31 | 8.1207 | 6.6230 | 7.0749 |
| Neem | 45.6 | 50.2 | 27.6282 | 5.3190 | 48.5792 | 2810.1535 | 604.3313 | 2.66 | 14.5922 | 3.77 | 10.2106 | 4.36 | 9.72298 | 2.46 | 6.9869 | 7.0642 | 9.2513 |
| Babool | 43.6 | 49.8 | 36.9796 | 12.6125 | 78.1785 | 8530.3912 | 609.7452 | 2.19 | 10.8130 | 4.10 | 10.1573 | 4.87 | 12.018094 | 3.05 | 8.2372 | 7.9155 | 7.4694 |
| Jamoha | 59.6 | 53.4 | 34.5156 | 7.2663 | 43.8979 | 4312.0866 | 658.9171 | 2.44 | 11.9992 | 5.12 | 14.1197 | 5.65 | 11.758353 | 3.26 | 6.9290 | 5.5236 | 6.8008 |
| Dake | 51.6 | 46.4 | 24.1877 | 5.9715 | 34.0974 | 4528.2572 | 509.7641 | 2.39 | 13.0129 | 3.87 | 13.0186 | 7.37 | 12.883087 | 3.93 | 7.1152 | 4.2481 | 5.3902 |

| | R1 | F1 | R2 | F2 | R3 | F3 | R4 | F4 | F5 | F6 |
|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| P1 | -0.11 | -0.25 | 0.55 | 0.73 | 0.54 | 0.00 | 0.11 | 0.02 | -0.57 | -0.38 |
| P1' | -0.73 | -0.55 | 0.36 | 0.55 | 0.35 | -0.83 | -0.09 | 0.19 | 0.16 | 0.34 |
| P2 | -0.03 | -0.59 | 0.82 | -0.35 | 0.26 | 0.17 | -0.70 | 0.83 | 0.57 | 0.25 |
| P2' | -0.27 | -0.65 | 0.09 | -0.39 | -0.18 | 0.30 | -0.11 | 0.46 | 0.62 | -0.02 |
| P3 | 0.44 | 0.01 | -0.12 | -0.78 | -0.60 | 0.58 | -0.32 | 0.17 | 0.62 | 0.15 |
| P4 | -0.16 | -0.60 | 0.18 | -0.44 | -0.03 | 0.49 | -0.11 | 0.55 | 0.48 | -0.19 |
| P5 | 0.45 | 0.04 | 0.16 | -0.28 | -0.57 | 0.21 | -0.45 | -0.04 | 0.46 | 0.36 |
| CORRELATION VALUES LESS THAN -0.5 (NEGATIVE CORRELATION) | | | | | | | | | | |
| CORRELATION VALUES MORE THAN 0.5 (POSITIVE CORRELATION) | | | | | | | | | | |

Figure 4.7: Correlation matrix

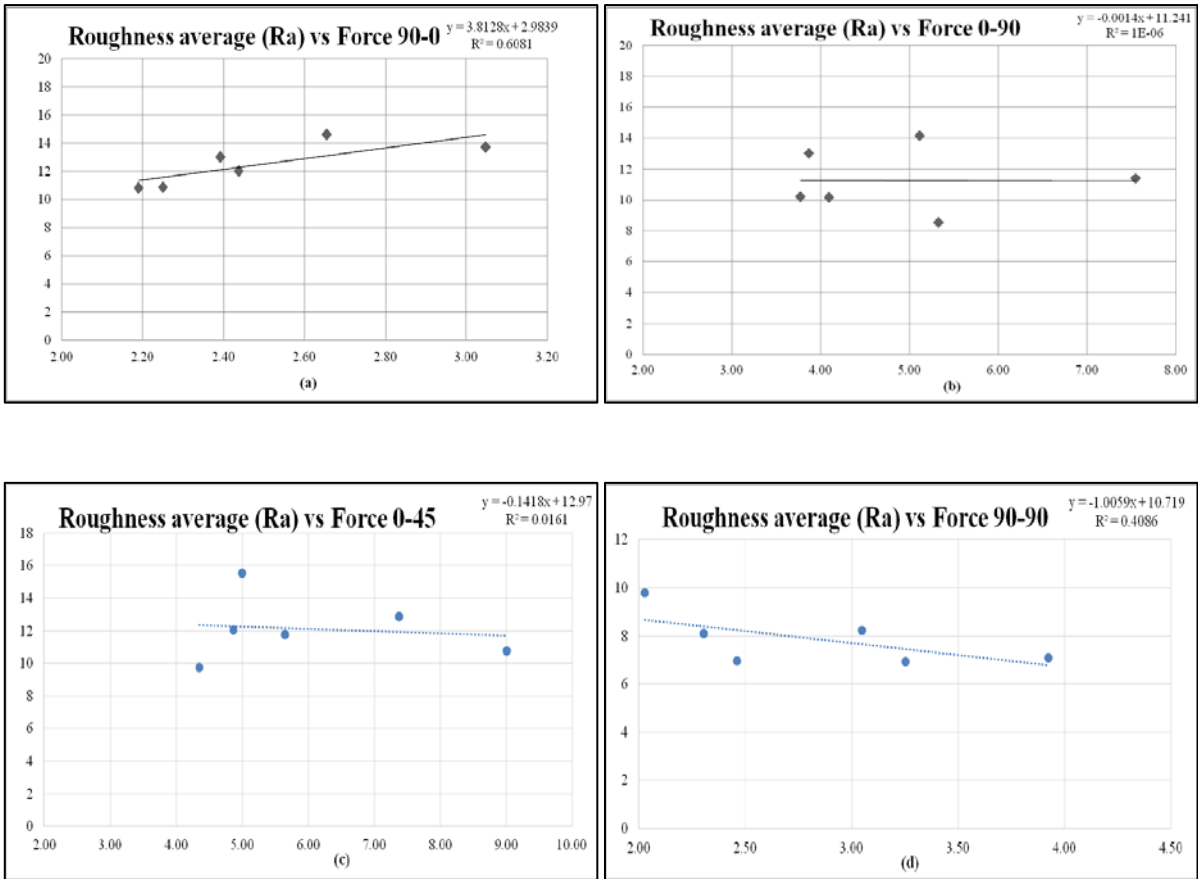


Figure 4.8: (a) Surface roughness vs. force in direction 90-0, (b) Surface roughness vs. force in direction 0-90, (c) Surface roughness vs. force in direction 0-45, (d) Surface roughness vs. force in direction 90-90

To determine mechanical properties according to different standards five samples of each wood species were taken to neglect the anisotropic properties found in wood species. In table 4.4 averaged results of various mechanical properties of six different wood species are shown in table form. Detailed of each mechanical properties can be found in Annexure A, B, C, D, E and F. After mechanical properties surface roughness of each slot milled in different directions and their forces are also shown in same figure. Plunge (drilling) forces in 90-0 and 90-90 directions are also shown for selected wood species. Then a correlation matrix is formed which shows mechanical properties correlation with surface roughness and machining forces in different directions.

In correlation matrix mechanical properties denoted as P, Surface roughness as R and machining forces as F. It is observed from correlation matrix that maximum correlation is found between Maximum crushing strength (Parallel to grain) and Surface roughness in 0-90 (Across the grain) that is 0.82 and with forces in 90-90 (Axial to the grain) that is 0.83. Hardness has a good correlation with surface roughness in direction of 0-90 and 0-45 that is 0.55 and 0.54 respectively.

Figure: 4.8 (a) to Figure: 4.8 (d) shows linear regression of different direction slot milled surface roughness between their forces. The maximum linear regression coefficient ($R^2 = 0.60$) was found between surface roughness and forces in 90-0 direction. In section 4.3 it was found that minimum forces and good surface finish is in 90-90 direction so for further analyses surface roughness (R_a) and forces only in 90-90 direction is considered. In further analyses regression coefficient is found between mechanical properties with surface roughness and forces in 90-90 direction.

4.5 Analysis of Mechanical Properties Viz A Viz Cutting Forces and Surface Finish for 90-90 Slot Milling Direction

Table 4.5: Regression coefficient of mechanical properties with surface roughness and forces in 90-90 direction

| Wood species | 90-90 | | Hardness (HRB) | | Maximum crushing strength Parallel to grain (Mpa) | Maximum crushing strength Perpendicular to grain (Mpa) | Modulus of rupture (Mpa) | Modulus of elasticity (Mpa) | Density (Kg/m^3) |
|--|-------------------------|-----------|-----------------|------------------|---|--|--------------------------|-----------------------------|-----------------------------|
| | R_a (μm) | Force (N) | Along the grain | Across the grain | | | | | |
| Mango | 2.03 | 9.7930 | 55 | 54 | 43.5074 | 8.0364 | 40.2881 | 5742.5117 | 580.1136 |
| Sheesham | 2.31 | 8.1207 | 49.4 | 41.8 | 39.2992 | 8.9064 | 84.3994 | 6824.1811 | 656.1369 |
| Neem | 2.46 | 6.9869 | 45.6 | 50.2 | 27.6282 | 5.3190 | 48.5792 | 2810.1535 | 604.3313 |
| Babool | 3.05 | 8.2372 | 43.6 | 49.8 | 36.9796 | 12.6125 | 78.1785 | 8530.3912 | 609.7452 |
| Jamoha | 3.26 | 6.9290 | 59.6 | 53.4 | 34.5156 | 7.2663 | 43.8979 | 4312.0866 | 658.9171 |
| Dake | 3.93 | 7.1152 | 51.6 | 46.4 | 24.1877 | 5.9715 | 34.0974 | 4528.2572 | 509.7641 |
| Regression coefficient (R^2) of R_a value with other individual mechanical properties and forces | | 0.41 | 0.01 | 0.008 | 0.49 | 0.01 | 0.10 | 0.01 | 0.20 |
| Regression coefficient (R^2) of forces with other individual mechanical properties | | | 0.0006 | 0.037 | 0.68 | 0.20 | 0.02 | 0.29 | 0.001 |

Regression coefficient for different mechanical properties with surface roughness and forces in 90-90 direction is shown in Table 4.5. It observed that maximum regression coefficient is found in surface roughness with maximum crushing strength (Parallel to grain) that is $R^2 = 0.49$, with density $R^2 = 0.20$ and with modulus of rupture $R^2 = 0.10$.

4.6 Summary

The correlation and regression coefficient was found in this chapter. From results it was observed that better surface finish is found in 90-0 and 90-90 direction slot milling of various wood species. Maximum correlation was found in 90-0 direction surface roughness with maximum crushing strength (parallel to grain). 90-0 direction slot milling produced maximum cutting forces than other directions of wood grains. In case of plunge (drilling) 90-90 direction cutting forces is less than 90-0 direction cutting forces.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE OF WORK

5.1 Conclusion for Present Work

In the present work correlation was found between mechanical properties with machining forces in different directions and surface finish of slot milled for selected wood species. The regression coefficient was also found between mechanical properties with forces and surface roughness in 90-90 direction. The conclusion of present work is as follows:

- (1) Maximum crushing strength (Parallel to grain) has maximum correlation with surface roughness in 90-0 direction of wood species.
- (2) Maximum regression coefficient was found in maximum crushing strength (Parallel to grain).
- (3) Maximum forces are produced while slot milling in 90-0 direction and minimum forces are produced while slot milling in 90-90 direction of wood species.
- (4) Forces produced in case of plunge (drilling) in 90-0 direction are more than 90-90 direction.
- (5) Better surface finish was found in the 90-0 and 90-90 slot milling directions than 0-90 and 0-45 of wood species so it is preferable to milled on 90-0 and 90-90 directions to achieve better surface finish.

5.2 Future Scope of Work

The present work has been focused on correlation of mechanical properties with machining and surface finish of wood species. The more work can be carried out for expansions of the present work are listed below:

- (1) Correlation can be extend for more wood species (Local or International) with adding new parameters.
- (2) From results of different wood species it is beneficial for industries which deal with ornamental carving or machining.
- (3) Regression equation can be formulated with the available result of mechanical properties, forces and surface finish.

ANNEXURE A

HARDNESS OF DIFFERENT WOOD SPECIES

In this ANNEXURE values of Hardness for different wood species selected are shown in tabular form which was determined as per standards and procedures discussed in chapter 3 section 3.3.1. Five samples of each wood species were prepared as per standard IS: 1708-10:1986. The test was performed on Rockwell hardness tester. One reading for each sample was taken. Their values of each sample and final averaged values are shown below:

Table A1: Hardness of different wood species

| S.No. | Dake | | Sheesham | | Mango | | Neem | | Jamoha | | Babool | |
|----------------|-----------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|------------------|
| | Along the grain | Across the grain | Along the grain | Across the grain | Along the grain | Across the grain | Along the grain | Across the grain | Along the grain | Across the grain | Along the grain | Across the grain |
| 1. | 51 | 48 | 54 | 42 | 55 | 53 | 47 | 52 | 59 | 55 | 43 | 49 |
| 2. | 52 | 47 | 46 | 40 | 56 | 54 | 44 | 47 | 58 | 50 | 45 | 52 |
| 3. | 50 | 46 | 47 | 42 | 54 | 52 | 47 | 53 | 60 | 55 | 42 | 48 |
| 4. | 53 | 46 | 48 | 43 | 52 | 55 | 44 | 50 | 61 | 51 | 46 | 51 |
| 5. | 52 | 45 | 52 | 42 | 58 | 56 | 46 | 49 | 60 | 56 | 42 | 49 |
| Average | 51.6 | 46.4 | 49.4 | 41.8 | 55 | 54 | 45.6 | 50.2 | 59.6 | 53.4 | 43.6 | 49.8 |

ANNEXURE B

DENSITY OF DIFFERENT WOOD SPECIES

In this ANNEXURE B values of density for various wood species are shown in tabular form which was determined as per standards and procedures discussed in chapter 3 section 3.3.2. Five samples of each wood species were prepared as per standard ASTM D-143. The equipments used for this measurement include digital Vernier calliper for samples size measurement, Oven for drying the wood specimen and weighing machine for samples weight measurement. The readings for each sample and final averaged value for different wood species are shown below:

Table B1: Density of different wood species

| Wood species | Sample Number | Length (m) | Breadth (m) | Height (m) | Volume (m ³) | Weight (kg) | Density (kg/m ³) |
|-----------------|---------------|------------|-------------|------------|--------------------------|-------------|------------------------------|
| Babool | Sample 1 | 0.02025 | 0.02022 | 0.02038 | 0.00000834635387 | 0.0050 | 599.06 |
| | Sample 2 | 0.02039 | 0.02045 | 0.02034 | 0.00000848378392 | 0.0051 | 601.14 |
| | Sample 3 | 0.02038 | 0.02030 | 0.02034 | 0.00000841410849 | 0.0053 | 629.89 |
| | Sample 4 | 0.02039 | 0.02037 | 0.02043 | 0.00000848715032 | 0.0051 | 600.90 |
| | Sample 5 | 0.02026 | 0.02041 | 0.02036 | 0.00000841815482 | 0.0052 | 617.71 |
| | | | | | Average | | 609.74 |
| Jamoha | Sample 1 | 0.02032 | 0.01988 | 0.02044 | 0.00000825860049 | 0.0055 | 665.97 |
| | Sample 2 | 0.02047 | 0.01986 | 0.02017 | 0.00000819900541 | 0.0053 | 646.41 |
| | Sample 3 | 0.02020 | 0.01995 | 0.02028 | 0.00000817184439 | 0.0054 | 660.80 |
| | Sample 4 | 0.02012 | 0.02027 | 0.01964 | 0.00000801147113 | 0.0053 | 661.55 |
| | Sample 5 | 0.02039 | 0.01985 | 0.02023 | 0.00000818384913 | 0.0054 | 659.83 |
| | | | | | Average | | 658.91 |
| Mango | Sample 1 | 0.02027 | 0.02041 | 0.01963 | 0.00000812195715 | 0.0046 | 566.36 |
| | Sample 2 | 0.02026 | 0.02026 | 0.01960 | 0.00000804437076 | 0.0044 | 546.96 |
| | Sample 3 | 0.01980 | 0.02028 | 0.02024 | 0.00000812805364 | 0.0047 | 578.24 |
| | Sample 4 | 0.02033 | 0.02016 | 0.01977 | 0.00000810523984 | 0.0049 | 604.54 |
| | Sample 5 | 0.02046 | 0.01985 | 0.02037 | 0.00000827206175 | 0.0050 | 604.44 |
| | | | | | Average | | 580.11 |
| Dake | Sample 1 | 0.02043 | 0.02033 | 0.02028 | 0.00000842147448 | 0.0046 | 546.22 |
| | Sample 2 | 0.02020 | 0.02024 | 0.02029 | 0.00000829634361 | 0.0039 | 470.08 |
| | Sample 3 | 0.02034 | 0.02038 | 0.02002 | 0.00000830379453 | 0.0043 | 517.83 |
| | Sample 4 | 0.02027 | 0.02034 | 0.02015 | 0.00000830850609 | 0.004 | 481.43 |
| | Sample 5 | 0.02035 | 0.02041 | 0.02033 | 0.00000843895835 | 0.0045 | 533.24 |
| | | | | | Average | | 509.76 |
| Sheesham | Sample 1 | 0.02034 | 0.02038 | 0.02019 | 0.00000837099501 | 0.0058 | 692.86 |
| | Sample 2 | 0.02023 | 0.01990 | 0.02031 | 0.00000817393362 | 0.0053 | 648.40 |
| | Sample 3 | 0.02026 | 0.02028 | 0.01970 | 0.00000809264276 | 0.0052 | 642.55 |
| | Sample 4 | 0.02044 | 0.02033 | 0.01999 | 0.00000830840161 | 0.0055 | 661.98 |
| | Sample 5 | 0.02028 | 0.01987 | 0.02033 | 0.00000819060272 | 0.0052 | 634.87 |
| | | | | | Average | | 656.13 |
| Neem | Sample 1 | 0.02027 | 0.01997 | 0.02034 | 0.00000823430091 | 0.0054 | 655.79 |
| | Sample 2 | 0.02031 | 0.02028 | 0.02015 | 0.00000829623481 | 0.0051 | 614.73 |
| | Sample 3 | 0.02040 | 0.02042 | 0.02033 | 0.00000847049093 | 0.0048 | 566.67 |
| | Sample 4 | 0.02044 | 0.02030 | 0.02017 | 0.00000836751298 | 0.0052 | 621.45 |
| | Sample 5 | 0.02028 | 0.02025 | 0.02033 | 0.00000834810089 | 0.0047 | 563.00 |
| | | | | | Average | | 604.33 |

ANNEXURE C

MODULUS OF RUPTURE OF VARIOUS WOOD SPECIES

In this ANNEXURE C values of modulus of rupture for various wood species are shown in tabular form which was determined as per standards and procedures discussed in chapter 3 section 3.3.3. Six samples of each wood species were prepared as per standard IS: 1708:5-1986.

Table C1: Modulus of rupture of different wood species

| Wood Species | Sample number | Load (N) | Effective length (mm) | Breadth (mm) | Height (mm) | Modulus of Rupture (MPa) |
|--------------|----------------|----------|-----------------------|--------------|-------------|--------------------------|
| Sheesham | Sample 1 | 2200 | 280 | 20.38 | 20.41 | 108.83 |
| | Sample 2 | 1435 | 280 | 20.37 | 20.25 | 72.15 |
| | Sample 3 | 1670 | 280 | 20.21 | 20.42 | 83.23 |
| | Sample 4 | 1240 | 280 | 20.38 | 20.34 | 61.76 |
| | Sample 5 | 1530 | 280 | 20.24 | 20.25 | 77.42 |
| | Sample 6 | 2100 | 280 | 20.46 | 20.46 | 102.97 |
| | Average | | | | | |
| Mango | Sample 1 | 1145 | 280 | 20.40 | 20.45 | 56.36 |
| | Sample 2 | 665 | 280 | 20.40 | 20.39 | 32.93 |
| | Sample 3 | 765 | 280 | 20.22 | 20.42 | 38.10 |
| | Sample 4 | 285 | 280 | 20.44 | 20.34 | 14.15 |
| | Sample 5 | 955 | 280 | 20.42 | 20.37 | 47.33 |
| | Sample 6 | 1050 | 280 | 20.04 | 20.41 | 52.82 |
| | Average | | | | | |
| Babool | Sample 1 | 1335 | 280 | 20.43 | 20.22 | 67.13 |
| | Sample 2 | 1280 | 280 | 20.39 | 20.43 | 63.17 |
| | Sample 3 | 2100 | 280 | 20.33 | 20.05 | 107.92 |
| | Sample 4 | 1435 | 280 | 20.39 | 20.42 | 70.89 |
| | Sample 5 | 1465 | 280 | 20.40 | 20.41 | 72.41 |
| | Sample 6 | 1720 | 280 | 20.06 | 20.28 | 87.56 |
| | Average | | | | | |
| Jamoha | Sample 1 | 570 | 280 | 20.41 | 20.38 | 28.24 |
| | Sample 2 | 1240 | 280 | 20.09 | 20.33 | 62.72 |
| | Sample 3 | 935 | 280 | 20.39 | 20.39 | 46.32 |
| | Sample 4 | 1145 | 280 | 20.24 | 19.95 | 59.70 |
| | Sample 5 | 380 | 280 | 20.44 | 20.35 | 18.85 |
| | Sample 6 | 955 | 280 | 20.43 | 20.32 | 47.55 |
| | Average | | | | | |
| Neem | Sample 1 | 380 | 280 | 20.17 | 20.23 | 19.33 |
| | Sample 2 | 1145 | 280 | 20.41 | 20.40 | 56.62 |
| | Sample 3 | 955 | 280 | 20.33 | 20.40 | 47.41 |
| | Sample 4 | 570 | 280 | 20.45 | 20.34 | 28.30 |
| | Sample 5 | 1241 | 280 | 20.41 | 20.33 | 61.79 |
| | Sample 6 | 955 | 280 | 20.03 | 20.26 | 48.79 |
| | Average | | | | | |
| Dake | Sample 1 | 860 | 280 | 20.41 | 20.40 | 42.53 |
| | Sample 2 | 665 | 280 | 20.05 | 20.11 | 34.45 |
| | Sample 3 | 1050 | 280 | 20.07 | 20.11 | 54.33 |
| | Sample 4 | 789 | 280 | 20.39 | 20.32 | 39.36 |
| | Sample 5 | 285 | 280 | 20.45 | 20.21 | 14.33 |
| | Sample 6 | 395 | 280 | 20.39 | 20.38 | 19.59 |
| | Average | | | | | |

ANNEXURE D

MODULUS OF ELASTICITY OF DIFFERENT WOOD SPECIES

In this ANNEXURE D values of modulus of rupture for various wood species are shown in tabular form which was determined as per standards and procedures discussed in chapter 3 section 3.3.3. Six samples of each wood species were prepared as per standard IS: 1708:5-1986.

Table D1: Modulus of elasticity of different wood species

| Wood Species | Sample Number | Load (N) | Deflection (mm) | Effective length (mm) | Breadth (mm) | Height (mm) | Modulus of Elasticity (MPa) |
|--------------|----------------|----------|-----------------|-----------------------|--------------|-------------|-----------------------------|
| Sheesham | Sample 1 | 2200 | 12.3 | 280 | 20.38 | 20.41 | 5664.98 |
| | Sample 2 | 1435 | 5.7 | 280 | 20.37 | 20.25 | 8168.18 |
| | Sample 3 | 1670 | 6.7 | 280 | 20.21 | 20.42 | 7949.18 |
| | Sample 4 | 1240 | 6.1 | 280 | 20.38 | 20.34 | 6505.02 |
| | Sample 5 | 1530 | 7.1 | 280 | 20.24 | 20.25 | 7036.58 |
| | Sample 6 | 2100 | 11.7 | 280 | 20.46 | 20.46 | 5621.15 |
| | Average | | | | | | |
| Mango | Sample 1 | 1145 | 7.6 | 280 | 20.40 | 20.45 | 4739.10 |
| | Sample 2 | 665 | 3.0 | 280 | 20.40 | 20.39 | 7034.49 |
| | Sample 3 | 765 | 4.3 | 280 | 20.22 | 20.42 | 5670.99 |
| | Sample 4 | 285 | 1.3 | 280 | 20.44 | 20.34 | 6994.91 |
| | Sample 5 | 955 | 5.4 | 280 | 20.42 | 20.37 | 5623.35 |
| | Sample 6 | 1050 | 7.7 | 280 | 20.04 | 20.41 | 4392.24 |
| | Average | | | | | | |
| Babool | Sample 1 | 1335 | 4.9 | 280 | 20.43 | 20.22 | 8852.94 |
| | Sample 2 | 1280 | 4.2 | 280 | 20.39 | 20.43 | 9619.50 |
| | Sample 3 | 2100 | 8.4 | 280 | 20.33 | 20.05 | 8372.86 |
| | Sample 4 | 1435 | 5.7 | 280 | 20.39 | 20.42 | 7958.05 |
| | Sample 5 | 1465 | 6.8 | 280 | 20.40 | 20.41 | 6816.85 |
| | Sample 6 | 1720 | 5.9 | 280 | 20.06 | 20.28 | 9562.15 |
| | Average | | | | | | |
| Jamoha | Sample 1 | 570 | 4.5 | 280 | 20.41 | 20.38 | 4023.66 |
| | Sample 2 | 1240 | 12.9 | 280 | 20.09 | 20.33 | 3125.03 |
| | Sample 3 | 935 | 8.7 | 280 | 20.39 | 20.39 | 3412.22 |
| | Sample 4 | 1145 | 13.00 | 280 | 20.24 | 19.95 | 3007.72 |
| | Sample 5 | 380 | 1.7 | 280 | 20.44 | 20.35 | 7121.55 |
| | Sample 6 | 955 | 5.9 | 280 | 20.43 | 20.32 | 5182.34 |
| | Average | | | | | | |
| Neem | Sample 1 | 380 | 4.6 | 280 | 20.17 | 20.23 | 2714.85 |
| | Sample 2 | 1145 | 11.5 | 280 | 20.41 | 20.40 | 3153.47 |
| | Sample 3 | 955 | 12.6 | 280 | 20.33 | 20.40 | 2410.01 |
| | Sample 4 | 570 | 10.8 | 280 | 20.45 | 20.34 | 1683.14 |
| | Sample 5 | 1241 | 15.00 | 280 | 20.41 | 20.33 | 2647.52 |
| | Sample 6 | 955 | 7.4 | 280 | 20.03 | 20.26 | 4251.93 |
| | Average | | | | | | |
| Dake | Sample 1 | 860 | 4.9 | 280 | 20.41 | 20.40 | 5558.82 |
| | Sample 2 | 665 | 3.00 | 280 | 20.05 | 20.11 | 7460.43 |
| | Sample 3 | 1050 | 8.00 | 280 | 20.07 | 20.11 | 4412.96 |
| | Sample 4 | 789 | 5.00 | 280 | 20.39 | 20.32 | 5062.12 |
| | Sample 5 | 285 | 4.1 | 280 | 20.45 | 20.21 | 2259.87 |
| | Sample 6 | 395 | 5.2 | 280 | 20.39 | 20.38 | 2415.34 |
| | Average | | | | | | |

ANNEXURE E

MAXIMUM CRUSHING STRENGTH (PARALLEL TO GRAIN) OF DIFFERENT WOOD SPECIES

In this ANNEXURE E values of maximum crushing strength (parallel to grain) of different wood species for various wood species are shown in tabular form which was determined as per standards and procedures discussed in chapter 3 section 3.3.4. Five samples of each wood species were prepared as per standard IS: 1708:8-1986.

Table E1: MCS (Parallel to grain) of different wood species

| Wood species | Sample Number | Load (N) | Breadth (mm) | Height (mm) | Maximum Crushing strength (MPa) |
|-----------------|----------------|----------|--------------|-------------|---------------------------------|
| Babool | Sample 1 | 12820 | 20.34 | 20.39 | 30.91 |
| | Sample 2 | 15975 | 20.38 | 20.44 | 38.34 |
| | Sample 3 | 12530 | 20.24 | 20.15 | 30.72 |
| | Sample 4 | 13775 | 20.42 | 20.10 | 33.56 |
| | Sample 5 | 21235 | 20.38 | 20.29 | 51.35 |
| | Average | | | | |
| Sheesham | Sample 1 | 15305 | 20.39 | 20.02 | 37.49 |
| | Sample 2 | 17985 | 20.18 | 20.40 | 43.69 |
| | Sample 3 | 18465 | 20.34 | 20.31 | 44.70 |
| | Sample 4 | 11190 | 20.29 | 20.44 | 26.98 |
| | Sample 5 | 17795 | 20.37 | 20.02 | 43.64 |
| | Average | | | | |
| Dake | Sample 1 | 5640 | 20.38 | 20.34 | 13.61 |
| | Sample 2 | 6310 | 20.31 | 20.28 | 15.32 |
| | Sample 3 | 11670 | 20.34 | 20.12 | 28.52 |
| | Sample 4 | 9660 | 20.30 | 20.35 | 23.38 |
| | Sample 5 | 16165 | 19.94 | 20.21 | 40.11 |
| | Average | | | | |
| Jamoha | Sample 1 | 16165 | 20.29 | 20.39 | 39.07 |
| | Sample 2 | 13680 | 20.40 | 20.32 | 33.00 |
| | Sample 3 | 15975 | 20.02 | 20.34 | 39.23 |
| | Sample 4 | 9085 | 20.36 | 20.41 | 21.86 |
| | Sample 5 | 15690 | 20.24 | 19.67 | 39.41 |
| | Average | | | | |
| Mango | Sample 1 | 19230 | 20.29 | 20.37 | 46.52 |
| | Sample 2 | 19705 | 20.42 | 19.96 | 48.34 |
| | Sample 3 | 21810 | 20.40 | 20.22 | 52.87 |
| | Sample 4 | 15400 | 20.11 | 20.45 | 37.44 |
| | Sample 5 | 13105 | 20.30 | 19.96 | 32.34 |
| | Average | | | | |
| Neem | Sample 1 | 11000 | 19.91 | 20.29 | 27.22 |
| | Sample 2 | 15305 | 20.23 | 20.25 | 37.36 |
| | Sample 3 | 7175 | 19.86 | 20.43 | 17.68 |
| | Sample 4 | 13490 | 20.23 | 19.97 | 33.39 |
| | Sample 5 | 9180 | 20.19 | 20.23 | 22.47 |
| | Average | | | | |

ANNEXURE F

MAXIMUM CRUSHING STRENGTH (PERPENDICULAR TO GRAIN) OF DIFFERENT WOOD SPECIES

In this ANNEXURE F values of maximum crushing strength (Perpendicular to grain) of different wood species for various wood species are shown in tabular form which was determined as per standards and procedures discussed in chapter 3 section 3.3.4. Five samples of each wood species were prepared as per standard IS: 1708:9-1986.

Table F1: MCS (Perpendicular to grain) of different wood species

| Wood species | Sample Number | Load (N) | Breadth (mm) | Height (mm) | Maximum Crushing strength (MPa) |
|--------------|----------------|----------|--------------|-------------|---------------------------------|
| Babool | Sample 1 | 3920 | 20.09 | 20.35 | 9.58 |
| | Sample 2 | 6980 | 20.48 | 20.27 | 16.81 |
| | Sample 3 | 3155 | 20.42 | 20.12 | 7.67 |
| | Sample 4 | 5835 | 20.40 | 19.96 | 14.33 |
| | Sample 5 | 6025 | 20.46 | 20.10 | 14.65 |
| | Average | | | | |
| Sheesham | Sample 1 | 2580 | 20.25 | 20.29 | 6.27 |
| | Sample 2 | 4110 | 20.35 | 20.41 | 9.89 |
| | Sample 3 | 4205 | 20.41 | 20.40 | 10.09 |
| | Sample 4 | 3155 | 20.44 | 20.32 | 7.59 |
| | Sample 5 | 4400 | 20.19 | 20.44 | 10.66 |
| | Average | | | | |
| Dake | Sample 1 | 2963 | 20.36 | 20.35 | 7.15 |
| | Sample 2 | 1720 | 20.17 | 20.38 | 4.18 |
| | Sample 3 | 2580 | 20.36 | 20.21 | 6.27 |
| | Sample 4 | 2675 | 20.36 | 20.40 | 6.44 |
| | Sample 5 | 2390 | 20.37 | 20.19 | 5.81 |
| | Average | | | | |
| Jamoha | Sample 1 | 2485 | 20.37 | 20.06 | 6.08 |
| | Sample 2 | 2965 | 20.32 | 20.03 | 7.28 |
| | Sample 3 | 3440 | 20.25 | 20.14 | 8.43 |
| | Sample 4 | 3345 | 20.28 | 20.02 | 8.23 |
| | Sample 5 | 2580 | 20.36 | 20.14 | 6.29 |
| | Average | | | | |
| Mango | Sample 1 | 2965 | 20.46 | 20.28 | 7.14 |
| | Sample 2 | 3825 | 20.41 | 20.37 | 9.20 |
| | Sample 3 | 3440 | 20.43 | 20.27 | 8.30 |
| | Sample 4 | 4015 | 20.35 | 20.29 | 9.72 |
| | Sample 5 | 2390 | 20.35 | 20.23 | 5.80 |
| | Average | | | | |
| Neem | Sample 1 | 2485 | 20.42 | 20.28 | 6.00 |
| | Sample 2 | 1720 | 20.40 | 20.24 | 4.16 |
| | Sample 3 | 2295 | 20.33 | 20.36 | 5.54 |
| | Sample 4 | 1815 | 20.43 | 20.33 | 4.37 |
| | Sample 5 | 2675 | 20.38 | 20.15 | 6.51 |
| | Average | | | | |

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