An Overwiew on Machining of Engineering Polymers

[1]Siddharth Jeet, [2]Abhishek Barua and [3]Sasmita Kar

Abstract— Engineering polymers have good mechanical properties. Price and weight of synthetic polymer products are less as compared to metallic products. Therefore, plastic is replacing to metals in various applications. For instance, acrylonitrile butadiene styrene (ABS) is used to manufacture car bumpers, dashboard trim & Lego bricks, polycarbonate is used in motorcycle helmets & polyamides (nylons) are used for skis & ski boots. Typically, an engineering polymer is chosen for its range of enhanced physical properties. For e.g. polycarbonate is highly impact resistant & polyamides are highly resistant to abrasion. In these types of applications, designers & researchers are looking for synthetic or semi-synthetic polymers that can replace traditional engineering materials & metals. The advantage gained is the inherent 'Formability' (ease of manufacture) of engineering polymers as opposed to metals. Other properties exhibited by various grades of engineering polymers include high heat resistance, mechanical strength, rigidity, and chemical stability & flame retardency. Most of the engineering polymers are primarily produced by moulding process. For large scale production moulding process is preferred, whereas small scale production and requirement of surface quality, machining is preferred. Turning, drilling and milling these are the machining operations mostly carried out in polymer machining. Study carried out in the field of synthetic polymer machining is discussed in this paper.

Index Terms— Engineering Polymers, ABS, Poly-carbonate, Formability, Polymer machining, Moulding, Formability

1 Introduction

Polymers are organic materials having exemplary formability and mouldability. The term plastic is synonymously used for polymers. It can be classified depending upon the nature of the intermolecular bonding, polymers/plastics classified as thermoplastics and thermosets. Commonly, polymer products are manufactured by moulding processes like injection moulding, blow moulding, compression moulding, transfer moulding, etc. Plastic injection moulding is the process primarily used for manufacturing of large quantities of plastic/polymer products and suffers through the problems of warpage, poor weld lines, sink marks and poor surface finish. So, post processing or recycling is required in these cases. In majority of the cases, post processing is limited to removing burr, runners, flash etc. However, wherever dimensional accuracy and surface finish requirements cannot be fulfilled by moulded components, they are required to be finished by machining. Also quantity requirement of products does not justify investment in tooling, particularly moulds, plastic/polymer components become economical, if produced by machining. Dimensional accuracy and superior surface smoothness are desirable characteristics of polymer products in the applications of precision machinery, electronics and optics. To acquire these characteristics, plastic/polmer products need to undergo machining process. Higher form and shape accuracies may be achieved by the precision machining processes like turning, drilling, milling, etc. Machining also enables a high flexibility in the production of asymmetric polymer products. During turning process, measure of the technological quality such as surface roughness is influenced by cutting parameters. These cutting parameters are like cutting speed, feed rate, depth of cut, etc. For drilling process, thrust force and surface roughness of hole are considered as process and quality measure respectively. While performing milling operation, surface roughness and machining force can be affected by spindle speed, feed rate and helix angle. This paper discepts polymer/plastic machining, particularly, machining processes like turning, drilling, and milling. Fig. 1. Represents the machining of ABS component using CNC machine.

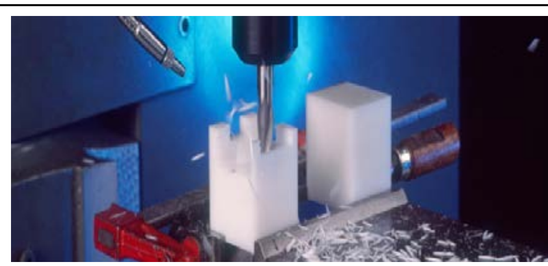

Fig. 1. CNC Machining of ABS Component

2 Literature Review

Polymers (plastics) are organic materials having long chain carbon molecules. Polymer molecule is formed by number of monomers. As per intermolecular bonding, plastics can be classified as thermoplastics and thermosets. Thermoplastics can be recycled by melting; hence it is widely used. Polyethylene (PE), polystyrene, polypropylene (PP), Polyvinylchloride (PVC), nylon (polyamide), Teflon is some examples of thermoplastic materials. Thermosets, before moulding, are in partially polymerized state. Cross linking of molecular chain takes place in polymerization process. After polymerization, if thermosets are heated, it does not melt. Epoxies (EP), Phenolic (PF), Polyurethane (PUR), unsaturated polyester are examples of thermosets. Generally,

- *Siddharth Jeet, CAPGS, Biju Patnaik University of Technology, Odisha, India, E-mail: siddharthjeet7@gmail.com*
- *Abhishek Barua, CAPGS, Biju Patnaik University of Technology, Odisha, India, E-mail: rahulbarua69@gmail.com*
- *Sasmita Kar, CAPGS, Biju Patnaik University of Technology, Odisha, India, E-mail: sasmitakarom@gmail.com*

polymer and polymer composite materials are used in production of plastic components. Plastics like Nylon, Teflon, and Polypropylene have good mechanical properties. These polymer materials have increasing applications for specialty purposes where their toughness, rigidity, abrasion resistance and heat resistance are important. Therefore, it is widely used in the applications like gears, cams, bearings, bushes, valve seats, etc. On the other hand, polymer materials have few limitations over bimetals. Such as melting point of polymers is comparatively low, therefore applications of polymers in high working temperature are not favorable. Thermal expansion of polymers is ten times as that of metals, hence it is one of the constraint need to be consider in application. Polymers deformation occurs in plastic materials under heavy stresses. Some important properties of material are compared between polymers and metals in table 1.

TABLE 1
IMPORTANT MATERIAL PROPERTIES OF POLYMERS AND METALS

S.N	Property	Metals	Polymers
1	Density,g/cm3	2 to 22 (average 8)	1 to 2
2	Melting points	Low to high	Low
3	Hardness	Medium	Low
4	Machinability	Good	Good
5	Tensile strength, MPa	Up to 2500	Up to 140
6	Compressive Strength,MPa	Up to 2500	Up to 350
7	Young's modulus, GPa	15 to 400	0.001 to 10
8	Thermal expansion	Medium to high	Very high
9	Thermal conductivity	Medium to high	Very low
10	Electrical characteristics	Conductors	Insulators
12	Chemical resistance	Low to medium	Good
13	Stiffness	High	Low
14	Malleability	High	High

Polymer composites are mixture (blend) of two or more polymer materials having different characteristics. Composites are generally made by reinforcing fibers in original polymer. Reinforcement of fibers in polymers is done for better mechanical properties of material. These composites (like glass fiber reinforced polymer, carbon fiber reinforced polymer) are preferred in the field of automotive parts, modern underwater projectiles, parts of aircraft, etc. Important properties and applications of polymer materials are summarized in table 2.

TABLE 2
PROPERTIES AND APPLICATIONS OF DIFFERENT POLYMER MATERIALS

S.N	Material	% Elongation at break	Applications
1	Acrylonitrile butadiene Styrene(ABS)	8	Housing appliances, Safety helmets, interio of automotive
2	Acetal(POM)	40	Gears, bearings, plumbing parts, Automotive parts, electronic equipment
3	Nylon (Polyamide)	60	Bearings, gears, appliance housings, cams, bushes, valve seats
4	Polycarbonate(PC)	100	Electronic connectors, appliance housings, pen bodies, geometry instruments, lenses
5	Low density polyethylene(LDPE)	400	Squeezable bottles, packaging films
6	High density polyethylene(HDPE)	150	Storage and transport containers, packaging
7	Polymethyl methacrylate(PMMA)	2	Optical fibers, lenses, appliance panels, windshields, automotive taillight films
8	Polypropylene(PP)	150	Disposable syringes, automotive interior trims, utensils
9	Polystyrene(PS)	1.5	toys, food packaging, coffee cups, hangers
10	Polyvinyl chloride(PVC)	80	Cable insulation, pipelines, floor coverings, shoe soles
12	Epoxy(EP)	3	Encapsulation of electronic components, adhesives
13	Phenolic(PF)	0.8	Utensil handles, terminal boards, oven trims, electrical switch housings

Polymer products can be manufactured by moulding processes like injection moulding, blow moulding, compression moulding, transfer moulding, etc. Out of which, injection moulding contributes 70-80 % of production of polmer components [2-3]. Products manufactured by injection moulding suffers through problems like warpage, poor weld lines, sink marks and poor surface finish which affects closer tolerances and accurate dimensions. Therefore, post processing or recycling is required in these cases [2-6]. Requirement of small quantities plastic products are not preferably produced by moulding process. As cost of making mould, process setting time and wastage of material through runners, testing experimentation material wastage do not justify cost of product. Therefore, production of small quantities of products are primarily done by machining process [9]. Turning and drilling operations are mainly carried out in machining of polymers. Special tools (like carbide or diamond tools) are preferred to prevent localized melting, smearing, or cleaving in coarse fragments. It helps in machining of plastics and reinforced plastics at higher rates with acceptable surface finish [4]. During machining, quality surface characteristics are being affected by process parameters like cutting speed, feed rate, depth of cut, etc. [3-4, 7-19]. Whereas, along with surface characteristics, high dimensional accuracy is important in the field of precision machinery, electronics and optics. Where precision machining is preferred [7-8, 11]. Study carried out by researchers on machining of plastics is discussed here:

[1] Kobayashi studied ultra precision machining on polymethyl methacrylate (PMMA). It is found that the surface roughness decreases as the feeding rate decreases. Optical grade surface roughness can be obtained for PMMA by machining method. Author advocates machining of plastics for achieving high dimensional accuracy and good surface finish.

Whereas, while studying turning on PMMA, [2] Jagtap observed that spindle speed is most significant parameter. When the spindle speed is less then surface flatness is better. Diamond tool is used by the researchers in turning on PMMA. [3]Keresztes studied machinability of polymers such as PA 6 (Mg), PA 6 (Na), POM C (Polyoximethylene), HD 1000 (UHMWPE). It is found that PA 6 (Mg) is toughest material in the view of cutting force and the cutting resistance. Cutting force decreases substantially by increasing feed rate and depth of cut. With increase in feed rate and depth of cut, amount of decrease in cutting force for remaining polymers are stated in descending order: PA 6 (Na), POM C, HD 1000.

[4] Salles studied effects of machining on surface quality of Ultra High Molecular Weight Polyethylene (UHMWPE). It is found that as higher the feed rate then higher the surface roughness. Cutting speed doesn't affect much on surface roughness.

[5] Pawade studied effects of machining on surface flatness of Nylon and Polypropylene (PP) during precision turning. For lower values of surface flatness, surface quality is considered as better. It is found that, for both polymers, feed rate is an effective parameter in precision turning for both polymers. With increase in feed, cutting speed and depth of cut, there is increase in surface flatness. Larger degree insert clearance angle gives better surface quality than the smaller degree insert clearance angle.

[6] Lazarevic found out, during turning on polyamide 6 (PA 6), that as feed rate is less then surface roughness is less. Also at lower level of depth of cut and tool nose radius, surface roughness is less. Whereas the influence of cutting speed is negligible. It is suggested that cutting speed can be set at the highest level to obtain higher material removal rate.

[7] Silva studied machinability of polyamide 66 (PA66) with and without glass fiber reinforcing during precision turning. It is found that surface roughness of the reinforced polyamide is insensitive with respect to changes in the feed rate and for the polyamide, surface roughness increases with feed rate.

[8] Mehdi found out that, during turning, content of nano calcium carbonate in polyamide 6 decreases the cutting forces, but it doesn't have any effect on surface roughness. As feed rate increases both cutting force and surface roughness increase. Cutting force is maximum for lower cutting speed.

[9] Kini studied finish turning of ±300 filament wound glass fiber reinforced polymers (GFRP) pipes using carbide insert. Surface roughness is inversely proportional to feed rate and cutting speed. For lower tool nose radius, the depth of cut and feed rate, the material removal rate is small.

[10] Gupta observed, while turning on GFRP, that factors which have great influence on surface roughness and material removal rate are depth of cut followed by feed rate.

[11] Whereas Kumar observed machining on unidirectional GFRP is different from the metals. Plastic deformation, bending rupture and shearing are observed during the machining of these composites. The machinability of composites depends on the flexibility, orientation and toughness of the fibers used in the composite materials. Cutting speed is inversely proportional to surface roughness. Surface roughness increases with increase in feed rate and depth of cut.

[12] Hussain studied machinability of glass fiber reinforced polymer (GFRP) materials during turning. It is found that surface roughness increases with increase in feed rate, whereas it decreases with increase in cutting speed and orientation angle. Depth of cut has very little effect on surface roughness. Cutting forces are highly influenced by feed, followed by cutting speed and fiber orientation angle. While drilling on plastics, surface quality affects by process parameters such as drilling speed, feed rate and drill diameter, etc.

[13] Quadrini studied drilling on glass fiber reinforced polyamide. It is found that the dependence of the thrust on the drilling process parameters is significantly affected by the chip formation mechanism. If chip is discontinuous, thrust increases with drilling speed and decreases with feed rate.

[14] Krishnaraj studied high speed drilling of carbon fiber reinforced plastic (CFRP) by using carbide tool. It is observed that thrust force increases with increase in feed rate. Whereas thrust force decreases with increase in spindle speed. Circularity decreases with an increase in spindle speed, while it remains almost constant for increase in feeds. Hole size is influenced by feed rate.

[15] Ramirez monitored tool wear and surface quality during drilling of CFRP by using cemented carbide tool. It is observed that abrasion is main wear mechanism during drilling of CFRP, wear has a direct impact on the final surface topography of the hole. There is poor surface roughness of the hole due to localization of uncut fibers.

[16] Li studied surface quality while drillingon CFRP composites by using diamond coated carbide tools. Surface roughness is lowered with increase in feed rate. Tool wear is occurred and it affects on hole surface quality. Surface defects in the form of grooves or cavities are generally observed at higher degree plies irrespective of cutting parameters and tool condition. Machining parameters considered during milling of plastics are: spindle speed, feed rate, helix angle and fiber orientation angle.

[17] Jenarthanan observed in his study that end mills with small helix angles develop the greatest machining force, lowest surface roughness and delamination factor. Surface roughness, machining force and delamination factor increases with increase in fiber orientation angle and feed rate, and decreases with increase in cutting speed. It is suggested that lower fiber

orientation angle, lower helix angle, moderate spindle speed and lower feed rate are the ideal machining conditions for machining of GFRP composite. Generally, optical polymer components are widely used for bioengineering applications. [18] Grabchenko studied precision cutting (milling) of optical polymer by using diamond tool. Diamond tool can be used in high speed cutting. High speed helps to keep temperature of surface layer under control. High temperature leads to thermal destruction of polymer. It is found that surface roughness is minimum at very high cutting speed. Lower feed rate gives less shear sections, which increases life of optical product. Now days, unconventional machining methods like laser cutting are being used in machining of plastics.

[19] Tamrin tells laser cutting has the advantages over conventional machining process in terms of reduced heat affected zone, improved cut quality, speed of cutting process. Due to non-contact type cutting process, it does not produce any unwanted mechanical stresses. Laser cutting enables precision cutting of very thin materials also. While studying on PMMA, polycarbonate (PC) and polypropylene (PP). It is found that the laser power has dominant effect on heat affected zone (HAZ) as compared to the cutting speed and air pressure. Also low laser power and high cutting speed are required during laser cutting of thermoplastics.

4 Machining of Engineering Polymers: An Emerging Trend

Polymer materials have exquisite mechanical properties. Polymer materials have lower price and weight. Consequently, polymer is replacing metals in many applications. Mostly polymer processing can be done by moulding process. Moulding processes are like injection moulding, blow moulding, compression moulding, transfer moulding, etc. For manufacturing of large quantity polymer products, moulding is preferred. For requirement of small quantities polymer products, moulding process is not preferred, because cost of making mould, process setting time and wastage of material do not justify cost of product. Hence, machining of plastics can be adopted in this case. Machining methods primarily used are like turning, drilling and milling. In the production of polymer products like gears, cams, bearings, bushes, valve seats, these machining methods can be used. Whereas in the production of precision machinery, electronics and optics, there is a desideratum of high dimensional accuracy and good surface finish. Where precision machining is preferred. Today, employment of non-conventional machining processes like laser cutting is also used for precision cutting. During turning operation, cutting speed, feed rate and depth of cut show maximum influence on quality measure such as surface roughness. Machinability differs for different types of plastics/polymers. For example, feed rate, for PA66, excalates surface roughness, whereas it is indifferent to reinforced PA66. Cutting speed affects surface roughness of PMMA, but it is insensitive to PA 6. This different nature of polymer proposes need of investigation on machining on each synthetic polymer material separately. During turning on PMMA, diamond tool is used by the researchers, it is observed that when the spindle speed is less then surface flatness is better. During turning on UHMWPE, feed rate is directly proportional to surface roughness. Cutting speed doesn’t affect much on surface roughness. Generally, during turning on GFRP, cutting speed is inversely proportional to surface roughness, whereas directly proportional to feed rate. But in case of turning on pipes of composite GFRP, feed rate is inversely proportional surface roughness. During drilling on plastics, surface quality affects by process parameters such as drilling speed, feed rate and drill diameter, etc. During drilling of glass fiber reinforced polyamide, chip formation mechanism affects part quality. If chip is discontinuous, thrust decreases with feed rate and increases with drilling speed. Whereas in case of CFRP, thrust force decreases with increase in spindle speed and increases with increase in feed rate. These results show that along with drilling parameters, chip formation has the same importance in drilling operation. During milling on synthetic polymers, mainly following machining parameters are considered: spindle speed, feed rate, helix angle and fiber orientation angle. It is observed that small helix angles develop the greatest machining force and lowest surface roughness. During unconventional machining, methods like laser cutting are being used in machining of polymers. It has advantages in operation like reduced heat affected zone, improved cut quality, speed of cutting process. Also it does not produce any unwanted mechanical stresses. Requirements of dimensional accuracy, good surface finish and flexibility in shape of products are challenge for moulding processes. Moulding processes have few limitations in overcoming these types of challenges. Production of small quantities of plastic/polymer components by moulding process does not justify cost of component. Therefore, polymer machining is needed to overcome these types of challenges. Fig. 2. shows the finished Polocarbonate components.

Fig. 2. Machined Polycarbonate Components

4 Conclusion

Mechanical properties (like toughness, rigidity, abrasion resistance and heat resistance) of some polymers are like metals. So, these types of polymers can replace metals. Also price and weight of polymer products are less as compared to metallic products. For achieving high dimensional accuracy and desired surface roughness of plastic components, plastic machining is preferred. Generally polymer machining has processes like turning, drilling, milling and unconventional methods like laser cutting, etc. Study of machining on polymer shows, machining nature of all polymers is not same. Hence effects of machining parameters need to be studied for different plastic material separately. In the field of machining, many investigations are carried out on various metallic materials and metal alloys. Literature on machining of metals and alloys are widely available. Very few investigations are carried out on polymer machining. Hence, literature in this area is comparatively less. Therefore, polymer machining needs to study very widely.

REFERENCES

[1] Kobayashi, Hirakawa, ―Ultra precision machining of Plastics. Part 1. Polymethyl Methacrylate‖, Polymer-Plastic technology and engineering (1984), Vol. 22, No. 1, pp. 15-25.

[2] Patton, ―Plastics technology: Theory, Design, Manufacture‖, Reston publishing company, Mumbai, 1986.

[3] Brydson, ―Plastics materials‖, Butterworth scientific, London, 5th edition, 1989.

[4] ASM international Handbook, ―Material selection and design‖, Volume 20, 1997

[5] Crawford, ―Plastic engineering‖, Butterworth Heinemann, 3rd edition, 1998.

[6] Grabchenko, Verezub, Laverynenko, Horvath, Mamalis, ―Precision cutting of optical polymer components for bioengineering applications‖, Journal of Materials Processing Technology (2000), Vol. 97, pp. 126-131.

[7] Salles, Goncalves, ―Effects of machining parameters on surface quality of the ultra high molecular weight polyethylene (UHMWPE) ‖, Conamet/SAM-SIMPOSIO Materia (2002).

[8] Quadrini, Squeo, Tagliaferri, ― Machining of glass fiber reinforced polyamide‖, Express Polymer Letters (2007), Vol. 1, No. 12, pp. 810-816.

[9] Cheng, Feng, Tan, Wei, ―Optimization of injection mould based on fuzzy mouldability evaluation‖, Journal of materials processing technology (2008), No. 208, pp. 222-228.

[10] Silva, Davim, Festas, Abrao, ―Machinability study on precision turning of PA66 polyamide with and without glass fiber reinforcing‖, Materials and Design (2009), Vol. 30, pp. 228–234.

[11] Kini, Chincholkar, ―Effect of machining parameters on surface roughness and material removal rate in finish turning of ±300 glass fiber reinforced polymer pipes‖, Materials and Design (2009), Vol. 31, pp. 3590-3598.

[12] Mathivanan, Nouby, Vidhya, ―Minimization of sink mark defects in injection moulding process –Taguchi approach, ―International Journal of Engineering, Science and Technology (2010), Vol. 2, No. 2, pp. 13-22.

[13] Keresztes, Kalacska, Zsidai, Dobrocsi, ―Machinability of engineering polymers‖, Sustainable Construction and Design (2011), pp. 106-114.

[14] Hussain, Pandurangadu, Kumar, ― Machinability of glass fiber reinforced plastic (GFRP) composite materials‖, International Journal of Engineering, Science Science and Technology (2011), Vol. 3, No. 4, pp. 103-118.

[15] Pawade, Jagtap, Balasubramaniam, ―Some Investigations on Surface characteristics in Precision Turning of Nylon and Polypropylene‖, International Journal of electronics, Communication & Soft Computing Science & Engineering (2012), pp. 236-240.

[16] Lazarevic, Madic, Jankovic, ―Surface roughness minimization of polyamide PA-6 turning by Taguchi method‖, Journal of Production engineering (2012), Vol.15, No.1, pp. 29-32.

[17] Kumar, Meenu, Satsangi, ―Experimental investigation and optimization in turning of UD-GFRP composite material by regression analysis using PCD tool‖, International Journal of Advanced Engineering Technology (2012), Vol. 3, No. 3, pp. 32-38.

[18] Krishnaraj, Prabukarthi, Ramanathan, Elanghovan, Kumar, Zitoune, Davim, ―Optimization of machining parameters at high speed drilling of carbon fiber reinforced plastic (CFRP) laminates‖, Composites: Part B (2012), Vol. 43, pp. 1791-1799.

[19] Mehdi, Zinati, Razfar, ―Experimental and Modeling Study of the Turning Process of PA 6/Nano Calcium Carbonate Composite‖, Journal of Composites (2013), Article No. 970954.

[20] Gupta, Kumar, ―Multi-objective optimization of cutting parameters in turning using grey relational analysis‖, International Journal of Industrial Engineering Computations (2013), Vol. 4, pp. 547–558

[21] Jenarthanan, Jeyapaul, ―Optimisation of machining parameters on milling of GFRP composites by desirability function analysis using Taguchi method‖, International Journal of Engineering, Science and Technology (2013), Vol. 5, No. 4, pp. 23-36.

[22] Jagtap, Pawade, ―Experimental Investigation on the Influence of Cutting Parameters on Surface Quality obtained in SPDT of PMMA‖, International Journal of Advanced Design and Manufacturing Technology (2014), Vol. 7, No. 2, pp. 53-58.

[23] Ramirez, Poulachon, Rossi, Saoubi, ―Tool wear monitoring and hole surface quality during CFRP drilling‖, Procedia CIRP Conference on Surface Integrity (2014), Vol. 13, pp. 163-168

[24] Li, Soo, Aspinwall, Pearson, Leahy, ―Influence of lay-up configuration and feed rate on surface integrity when drilling carbon fibre reinforced plastic (CFRP) composites‖, Procedia CIRP Conference on Surface Integrity (2014), Vol. 13, pp. 339-404.

[25] Tamrin, Nukman, Choudhury, Shirley, ―Multiple-objective optimization in precision laser cutting of different thermoplastics‖, Optics and Lasers in Engineering (2015), Vol. 67, pp. 57-65