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Design and Synthesis of Polymer Composite Material for Tribological Applications

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***Abstract*—Polymer composite shows good tribological performance in engineering applications with low cost and ease in manufacturing. The improvement in material developments has carried out for improving mechanical properties without consideration of wear of polymer composites. Wear is main parameter which reduces the effective life of machine or its components. A wear resistance polymer composite material was synthesized containing three element compositions consisting of a matrix material, reinforcing material, friction and anti-wear material in particulate form. In this project different samples containing compositions of Polyaryletherketone (PAEK) as a matrix, alumina (Al_2O_3) and silicon carbide (SiC) as a reinforcing material and Polytetrafluoroethylene (PTFE) as anti-wear material are prepared according to ASTM standards. The aim is to design and synthesize new thermoplastic polymer composite material for improvement in tribological properties specially wear resistance of material, to investigate the new polymer composite material and to test it for wear and other mechanical properties. It will be a good replacement for an isotropic material and may for some of composite materials also if the developed composite gives challenging results and passes the entire mechanical test which will be undertaken during this study. Possible application areas: Gears, Bearings, Artificial human joint in medical field, Brake pad, Clutches, Tires, etc.**

Keywords: Polymer Composite; Wear resistance; Friction; ASTM

I. INTRODUCTION

In present days, polymers and their composites are widely considered as an important group of materials due to their excellent properties such as resistance to wear, self-lubrication, lower density, high strength, easy formability/ moldability, high capacity to absorb vibrations and shocks. There are a wide range of applications such as bearings, gears, brakes, conveyor aids, sprockets, valve guides, seals, pumps handling industrial fluids/slurries containing abrasives etc. in wear-related situations. Abrasive wear behavior is important due to sliding motion between counter-face and hard particles in tribological applications. The development of advanced materials for tribological purposes is becoming a pressing demand of manufacturing industries. Polymer-based composites have capability of operating for a long time in conditions of cryogenic and elevated temperatures without lubrication. Special fillers added in polymer composites gives advantage suitable for industrial applications. Generally, wear resistance and strength of materials on polymer base are increased by filling with organic and inorganic solid lubricants. Thermoplastic matrix composites are produced by injection molding for industrial components like gears, bearings etc. because of easy manufacturing. Nanocomposites can provide better performance in area of tribological applications. Moreover, nanocomposite molding is a new approach for wear resistant materials at low filler content. In the virgin form, only a few of the polymers would play an important role, composite and hybrid forms advantageous over metals and ceramics for tribological applications. Polymers in virgin, composite and hybrid forms have seen numerous research articles and publications in past 50 plus years in tribological phenomena.

Metals and alloys are traditionally used as a tribo-materials because they have excellent combination of mechanical, thermal, and tribological (in oil/grease lubricated conditions) properties. Polymers have poor heat dissipation rate at sliding interface causes low performance of tribo-properties with a rapid decay in their strength. This strength decay is because of restricted PV (pressure–velocity) values during operation. To avoid this problem, polymers with higher thermal stability and improved tribological properties would be essential in engineering research. Hence, special type of polymers like Polyaryl-ether-ketone family (PAEK) are preferred to develop more efficient performance in tribological field. In a composition of PEEK and PTFE, the lowest friction and wear was recorded at 85 weight % of PEEK and 15 weight % of PTFE. Hence it was decided to develop a composite consisting of materials like PAEK, alumina, silicon carbide and PTFE to improve wear resistance and processability of tribo-composites, since such investigations were not included yet. PAEK, PEEK, PEK, PBI etc. are high performance polymers used at high temperature applications for better performance. [1-3]

II. LITERATURE REVIEW

Recent studies have focused on the tribological behavior of nanocomposites by researchers, for example the wear of nanoparticle filled PA 66 composites. The experimentation was performed by means of a pin-on-disc machine with a variation in contact pressure (P) and sliding velocities (V). The addition of 5 vol% of TiO_2 nanoparticles in a 5 vol% graphite + 15 vol% short carbon fiber reinforced PA66 resulted in a reduction of the frictional coefficient and wear rate. The friction coefficient of the nanocomposite ranged between 0.2 to 0.4 depending on the PV (pressure and velocity) term. The friction coefficient ranged between 0.3 and 0.4 depending on the nanofiller content, whereas the friction coefficient of the PA6 was close to 0.5. By increasing the nanofiller content, the friction coefficient is decreased. A wide variety of materials like graphite powder, carbon nanotubes, tungsten disulphide powder, alumina nanoparticles, PTFE nanopowder available in micro and nano sized form are studied by researchers. During study they found that the friction coefficients are ranges from below 0.05 to above 0.06, whereas the wear rate varies from 10^{-4} to 10^{-7} mm^3/ (Nm). [7, 8]

The researchers found that the Ultra High Molecular Weight Polyethylene (UHMWPE) shows good option as a material for artificial human joints which is useful in medical field because of good wear resistance and excellent biocompatibility. A PEEK polymer gives low wear rate at high temperature but at the same time the value of frictional coefficient can be high (~0.3). Nowadays, formulation of wear resistant materials can be done with a use of popular PEEK polymer matrix in composites. Nylons perform as a wear resistant material with a low friction under tribological applications. Polytetrafluoroethylene (PTFE), normally shows very low friction coefficient and high wear rate compared with other thermoplastics. This behavior of PTFE is due to slippage of molecular bond structure in the crystalline form. PTFE acts as a good solid lubricant due to the property of low friction when it is used in composite form. Amorphous thermoplastics such as poly(styrene) and PMMA shows high coefficients of friction and high wear rates in engineering applications. In a medical application, an artificial hip joint was developed by using a carbon fabric reinforced polyetheretherketone (PEEK) composite. In past trials are taken out for replacement of the ultra-high molecular weight polyethylene cap (UHMW-PE) by a carbon fiber (CF) reinforced UHMW-PE material, but this trial was not successful. For tribological application in polymeric composites usage of natural fibers as reinforcement, research work has already been published on various types of polymer. The researchers had also found that the composite of maleic anhydride-grafted polypropylene (PP) and jute-polypropylene shows low wear rate. The reinforcement of sugarcane fiber in thermoset polymers affects the adhesive wear behaviour in tribological applications.

The relative motion between the two surfaces responsible for progressive removal of a material, this phenomenon is known as a wear. According to the classification, wear of a polymer against a hard counterface may be termed as abrasive, adhesive, interfacial, cohesive, chemical wear etc. The polymer wear rate is also depends on the type (amorphous, elastomer, and semicrystalline) of the polymer. The properties like as the tensile strength, elastic modulus and the percentage elongation at failure (toughness) varies drastically from one type of polymer to another.

Asbestos material has been the most widely used fiber in automotive friction material. The excellent tribological properties, thermal stability, miscibility, and low cost of asbestos are some of the reason due to which it is used traditionally. Asbestos causes increasing environmental and health consciousness; the replacement may necessitate the different non-asbestos friction materials with asbestos fibers as it can cause adverse respiratory conditions and lodge in the lungs. So the government announced a proposed ban on asbestos material. Hence there is need to modify alternative friction materials that can replace asbestos material. [3]

The design of a composite material is carried out according to requirement for the particular application. The wear resistance and the frictional coefficient are not material properties but they are system properties. The wear resistance and the frictional coefficient depend on the application in which the composite material has to perform. The materials must be designed for low wear and low friction for applications like gears or bearings, but in some applications like brake pads or clutches, a low wear with high frictional coefficient is required.

III. OBJECTIVES

1. The objective is to synthesize a thermoplastic polymer composite that will decrease the wear of material.

2. To investigate the new thermoplastic polymer composite material and to test for wear and other mechanical properties.

IV. METHODOLOGY

- Literature survey
- Design of polymer composite
- Synthesis of polymer composite
- Testing methods in tribology of polymeric composites
- Comparison between existing tribological materials and new polymer composite material

V. EXPERIMENTAL

1. Development of composites

The samples are prepared to reduce wear of material, by using fillers/ solid lubricants or their combinations in varying amounts. Table no. I shows the detailed composition of composites of Poly-aryl-ether-ketone (G-PAEK^{TM} 1200P) (supplied by Gharda Chemicals Ltd., Mumbai) as a matrix, alumina (Al_2O_3) and Silicon carbide (SiC) as a reinforcing material and Poly-tetra-fluoro-ethylene (PTFE) as an anti-wear material for this study. 14 variations of different compositions with 3 each samples are prepared. The average results of sample 1 and 1-L, 2 and 2-L, 3 and 3-L, 4 and 4-L, 5 and 5-L, 2 and 1-SiC, 3 and 2-Sic, 4 and 3-SiC, 5 and 4-SiC are compared. Also the trend for samples 1 to 5, 1-L to 5-L,1-SiC to 4-SiC are noted.

TABLE.IA COMPOSITIONS OF MATERIALS

Sr. No.	Polyaryletherketone [PAEK] (% IN WEIGHT)	Alumina [Al_2O_3] (% IN WEIGHT)
1.	100	0
2.	95	5
3.	90	10
4.	85	15
5.	80	20

TABLE.IB COMPOSITIONS OF MATERIALS

Sr. No.	[PAEK] / [PTFE] (% IN WEIGHT)	Alumina [Al_2O_3] (% IN WEIGHT)
1-L.	95/5	0
2-L.	90/5	5
3-L.	85/5	10
4-L.	80/5	15
5-L.	75/5	20

TABLE.IC COMPOSITIONS OF MATERIALS

Sr. No.	Polyaryletherketone [PAEK] (% IN WEIGHT)	Silicon Carbide [SiC] (% IN WEIGHT)
1-SiC.	95	5
2-SiC.	90	10
3-SiC.	85	15
4-SiC.	80	20

Poly-aryl-ether-ketone (PAEK) as a matrix, alumina (Al_2O_3) and silicon carbide (SiC) as a reinforcing material and anti-wear material PTFE (Polytetrafluoroethylene) composites are prepared by taking powders and the dry blending is done using a mixer. After mixing the mixtures were put into the main feeder of the twin screw extruder. The alumina and PTFE powders are used in sub micrometer dimensions and SiC powders are used in micrometer dimensions. The extrusion compounding temperatures are in the range of 375-395 ˚C. The output i. e. melt compounded material of the twin screw extruder had given to the strand pelletizer in which the granules of melt compounded material are made and these granules were kept in oven at 150˚C for 2 hours for drying. Then the granules are fed into the injection molding machine at 375-390 ˚C to produce the test specimens.

The flowchart of design of tribo-materials for low wear as shown below:

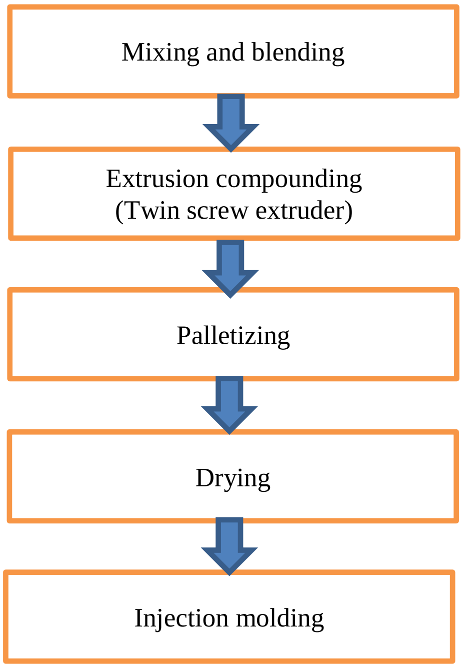

Fig. 1. General procedure followed for developing anti-wear polymer composite specimens

2. Experimental testing

A. Tensile testing
B. Wear testing
C. Hardness testing

A. Tensile testing

Samples are prepared according to ASTM D638 (type-V) for tensile testing as shown in figure no.2. These samples are tested on universal testing machine (UTM) and finally the results are recorded. The testing is done at 25 ˚C and 50% relative humidity.

Fig. 2. Tensile testing specimen

B. Wear testing

Tribo-studies will be done using pin on disk machine. Its experimental diagram is shown in Figure no. 4. A pin of dimensions 20 mm in length, 10mm in width and 3.2mm in thickness was manufactured for wear testing as shown in figure no.3. The load is applied on the pin by using the load lever of the machine. The various types (i.e. metal, cast iron, titanium, aluminum, stainless steel, etc.) of counterface can be used depending on the nature of the test.

Fig. 3. Wear testing specimen

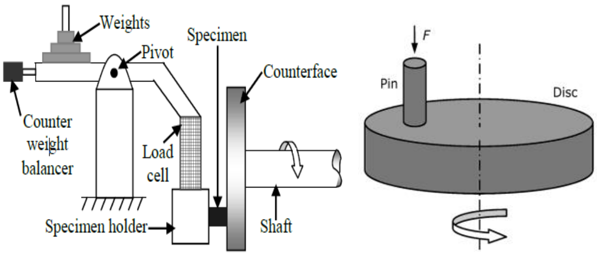

Fig. 4. Schematic view of a pin on disk tribo test machine

Wear rate and coefficient of friction (μ) will be sequentially recorded on the computer with the help of the software. Specific wear rate will be calculated as follows:

$$K_0 = \frac{\Delta m}{(\rho LD)} \quad (m^3/Nm) \qquad (1)$$

where Δm (kg) is the loss in weight of the pin, ρ (kg/ m^3) is density, L (N) is the load and D (m) is the sliding distance.

C. Hardness testing

Micro hardness test is carried out by using Vicker's Micro hardness tester and hardness values are recorded. The specimen used in this testing is in flat shape. The hardness value (HV) number is measured by the F/A ratio, where F (kgf) is the force applied to the diamond and A is the surface area of the resulting indentation in mm^2.

$$A = \frac{d^2}{(2\sin(136^\circ/2))} \qquad (2)$$

$$A \approx \frac{d^2}{(1.8544)} \qquad (3)$$

where d (mm) is the average length of the diagonal impressed by the indenter. Hence

$$HV = \frac{F}{A} \approx \frac{1.8544F}{d^2} \qquad (4)$$

VI. RESULTS AND DISCUSSION

1. Physical properties of composites

Analytical Calculations for density ($\rho_{composite}$) by using rule of mixture:

$$\rho_{composite} = \frac{(((100\times1.30)+(0\times4.0)))}{100} \qquad (5)$$

$$= 1.30 \text{ gm/cc}$$

Similarly calculations are done for all samples as shown in following table no. II.

TABLE.II CALCULATIONS FOR DENSITY OF COMPOSITE MATERIAL SAMPLES

Sr. No.	**$\rho_{composite}$ gm/cc**	**Sr. No.**	**$\rho_{composite}$ gm/cc**	**Sr. No.**	**$\rho_{composite}$ gm/cc**
1.	1.30	1-L.	1.345	1-SiC.	1.395
2.	1.435	2-L.	1.48	2-SiC.	1.491
3.	1.57	3-L.	1.615	3-SiC.	1.586
4.	1.705	4-L.	1.75	4-SiC.	1.682
5.	1.84	5-L.	1.885		

As seen from table no.II density of the composites samples increases gradually with addition of weight % of Al_2O_3 in PAEK. In addition of weight % of PTFE, the sample 1 and 1-L, 2 and 2-L, 3 and 3-L, 4 and 4-L, 5 and 5-L are compared. After comparing it is found that the value of density of the composites increases. In further addition of weight % of SiC, the sample 2 and 1-SiC, 3 and 2-Sic, 4 and 3-SiC, 5 and 4-SiC are compared. After comparing it is found that the value of density of the SiC composites is less for all combinations.

2. Mechanical properties of composites

2.1 Tensile testing

The average testing results of tensile testing samples are as follows:

TABLE.III TENSILE TESTING RESULTS

Sr. No.	Tensile strength MPa	Max. Load KN	Breaking Load KN	Breaking % Strain %	Tensile Modulus MPa
1.	105.36	1.2942	1.1397	10.69	3054
2.	101.66	1.1106	1.0273	10.25	3065
3.	98.180	1.0720	0.8847	8.06	3010
4.	98.390	1.0745	1.0625	6.947	3358
5.	99.295	1.0840	0.9342	6.673	3521
1-L.	101.05	1.1035	1.0500	16.71	2924
2-L.	96.820	1.0576	1.0195	10.15	2543
3-L.	95.245	1.0405	0.8203	9.4905	2962
4-L.	91.825	1.0025	0.9923	8.084	3093
5-L.	90.130	0.9842	0.91355	7.549	2930
1-SiC.	94.580	1.0330	0.9578	8.524	2976
2-SiC.	94.155	1.0281	0.8773	5.9015	3287
3-SiC.	97.18	1.0615	1.0410	6.383	3445
4-SiC.	92.32	1.008	0.9715	6.231	3277

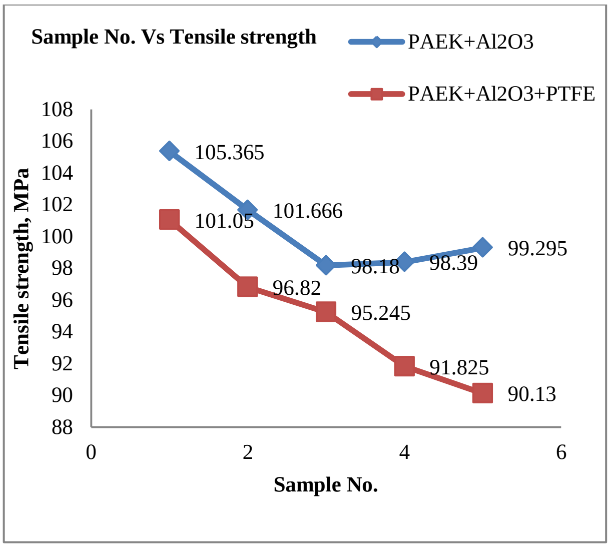

Fig. 5. Comparison results for Tensile Strength

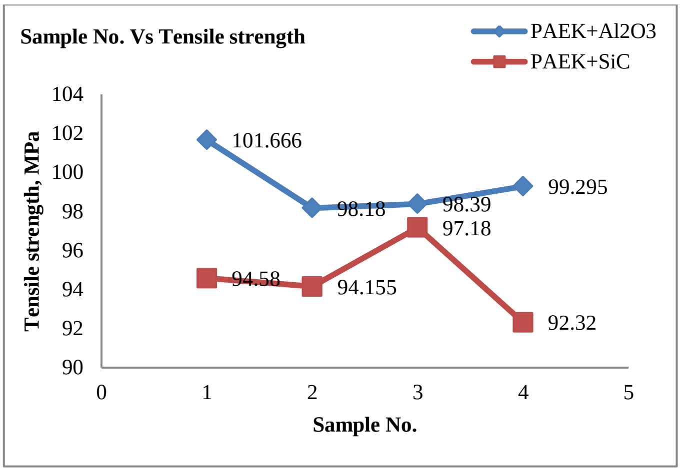

Fig.6. Comparison results for Tensile Strength

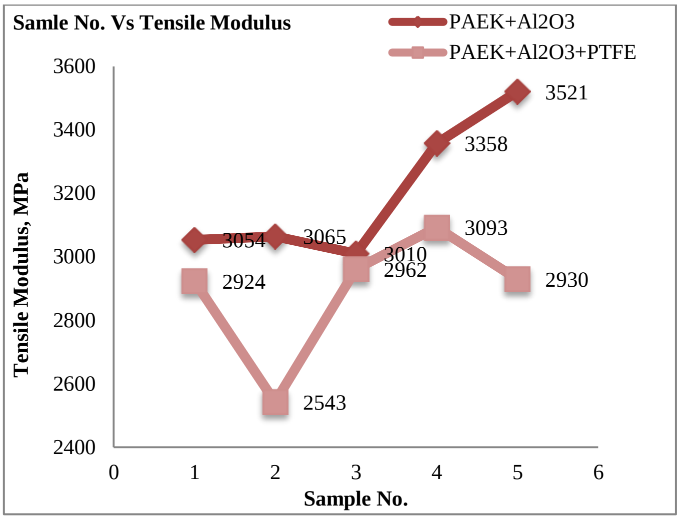

Fig.7. Comparison results for Tensile Modulus

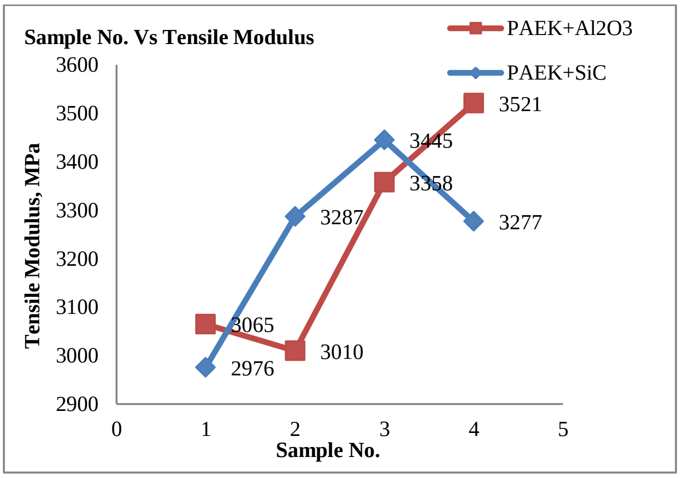

Fig. 8. Comparison results for Tensile Modulus

As seen table no.III, from fig.5 and 7, if the weight % of Al_2O_3 increases up to 10% the tensile strength decreases, beyond 10% it increases. However, breaking % strain decreases gradually as weight % of Al_2O_3 increases and tensile modulus increases as weight % of Al_2O_3 increases. In addition of weight % of PTFE, the sample 1 and 1-L, 2 and 2-L, 3 and 3-L, 4 and 4-L, 5 and 5-L are compared. After comparing it is found that tensile strength and tensile modulus decreases but breaking % strain increases in addition of weight % of Al_2O_3 and PTFE in PAEK.

From fig.6 and 8 in addition of weight % of SiC, the sample 2 and 1-SiC, 3 and 2-Sic, 4 and 3-SiC, 5 and 4-SiC are compared. After comparing it is found that tensile strength and breaking % strain decreases in addition of weight % of SiC in PAEK. However, tensile modulus decreases up to the addition of 5 weight % of SiC then increases up to 15 weight % of SiC and further addition of weight % SiC it decreases.

2.2 Hardness testing

Vickers Microhardness testing is done as per ASTM E-384 standard. Three readings are taken for each sample and the results are shown below.

TABLE.IV VICKERS MICROHARDNESS TESTING RESULTS

Sr. No.	Reading 1	Reading 2	Reading 3	Average
1.	31.9	32.2	32.5	32.2
2.	31.1	31.7	31.7	31.5
3.	32.2	31.9	31.9	32.0
4.	31.9	31.4	31.4	31.6
5.	32.7	33.1	32.7	32.8
1-L.	28.3	28.5	28.5	28.5
2-L.	30.2	30.4	30.4	30.3
3-L.	30.9	31.1	31.1	31.0
4-L.	31.9	31.9	32.2	32.0
5-L.	31.7	31.9	32.2	31.9
1-SiC.	32.2	31.7	32.2	32.0
2-SiC.	31.4	30.9	31.4	31.2
3-SiC.	32.5	32.2	31.9	32.2
4-SiC.	31.7	31.1	30.9	31.2

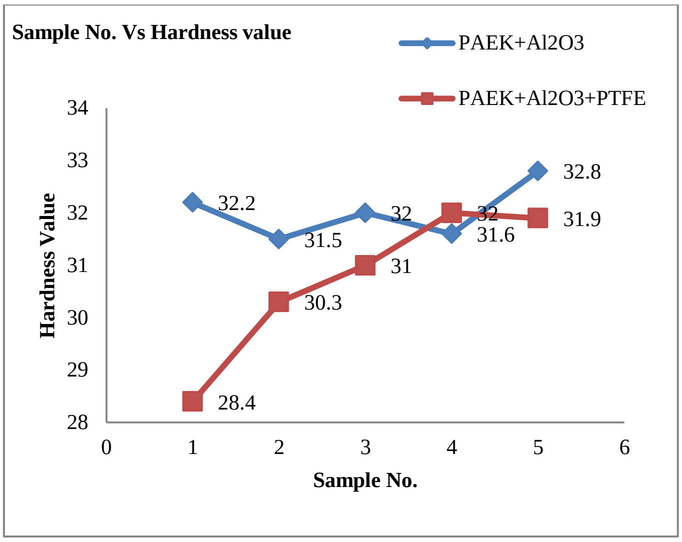

Fig. 9. Comparison results for Hardness Testing

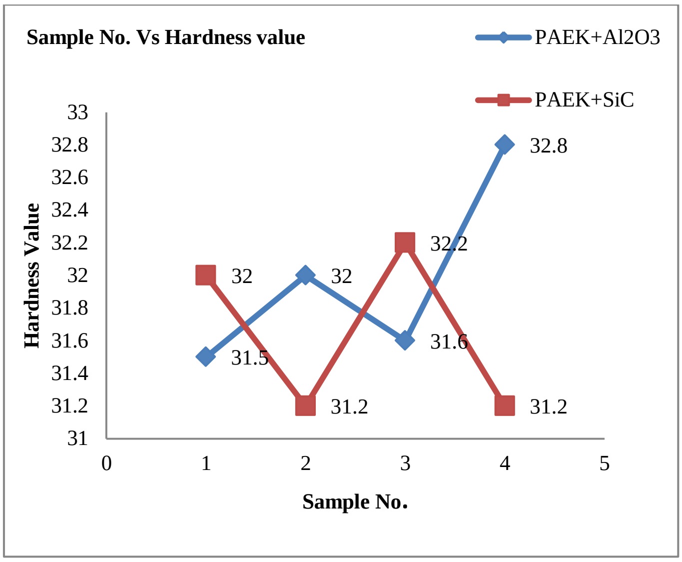

Fig.10. Comparison results for Hardness Testing

From fig. 9, as % of Al_2O_3 increases the hardness value varies slightly but in case of Al_2O_3 and PTFE as % increases the hardness value increases gradually. The hardness value of PAEK+Al_2O_3 is greater than PAEK+Al_2O_3 +PTFE at all combinations except at 15%. From fig.10, as % of SiC increases the hardness value varies slightly.

VII. CONCLUSION

- From comparison between PAEK+Al_2O_3 and PAEK+Al_2O_3+PTFE: tensile modulus, tensile strength decreases but breaking % strain increases on addition of PTFE in all compositions.
- From comparison between PAEK+Al_2O_3 and PAEK+SiC: tensile strength and breaking % strain decreases on addition of SiC but tensile modulus decreases up to 10 wt.% beyond that it increases.
- Hardness value decreases on addition PTFE except at 15 wt% of Al_2O_3.
- From the analytical calculation the physical property i.e. density of polymer composite testing specimens increases on addition of PTFE in PAEK+Al_2O_3 combination but from comparison between PAEK+ Al_2O_3 and PAEK+SiC density decreases on addition of SiC.

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