Studies on Machinability and Mechanical Behaviour of Epoxy Based Polymer Matrix Composites

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Abstract: *Epoxy resins can be compounded to the desired levels of mechanical properties like toughness, modulus and machinability. Hence, they find a variety of applications in the areas of adhesives, composites, insulators, castings, foams and semi-conductor encapsulations. Among the casting applications, one area of great promise is in making of temporary tools especially for injection moulding of thermoplastics. For Rapid Tooling, casting of a epoxy resin is faster than machining of a metal. Thus, while developing a new plastic product, down time in stages like making a temporary mould for limited runs for making sample products can be saved using this method. The present work studies the machinability characteristics on a few combinations of epoxies with aluminium, Spheriglass and a silicone modifier (Amine Containing Silicone -ACS). Surface finish and resultant tool force were analyzed for various compositions.*

Keywords: *Particulate reinforced epoxy composites, Machinability, Rapid Tooling.*

1. Introduction

Epoxies have poor thermal conductivities. To improve this property, aluminium powder has been used as filler, especially for tooling applications. Aluminium may also improve machinability and a few other properties [1]. Adding aluminium powder to epoxies leads to sharp increase in viscosities which makes the resin difficult to cast. Now a days, solid glass microspheres (called Spheriglass) are also recommended for tooling applications as they improve compressive strength, reduce thermal expansion etc [4]. These improvements can be achieved without a sharp increase in viscosity (unlike aluminium powder). The surface finish of the mould reflects the ability to be used as a mould material. Hence the machinability test was carried out to study the effect of different inclusions in the epoxy on surface finish and resultant cutting tool force [2&3]. In this surface finish and resultant cutting tool force analysis the turning operation was performed in a lathe by varying the feed and speed at three levels and depth of cut at four levels. For each feed, speed and depth of cut the surface roughness (Ra in microns) value and resultant cutting tool force (in kgf) was measured by surf coder and lathe tool dynamometer respectively.

2. Experimental

2.1. Materials Used

DGEBA liquid epoxy resin (LY556) with epoxy equivalent around 170 and viscosity of 9000 cp (as given by supplier) at 25ºC was used as received from Huntsman advanced materials. Amine-containing poly dimethylsiloxane with molecular weight of 5000 was used as liquid rubber modifier as received from Resil chemicals Pvt Ltd, Bangalore, India. In each silicone chain, there is one amine group for every 7-8 Si-O links. The end groups are alkoxy. Triethylene tetramine (HY 951-curing agent) was used as received from Petro Araldite India Pvt, Ltd. Aluminium powder [DU-grade with grain size above 75µ of 3 %, below 45µ of 85 % and in-between 45µm to 75µm of remaining %] was obtained from MEPCO Ltd. Thirumangalam. Glass micro-spheres (A-grade) were received from Potter industries Inc., USA. The trade name for glass microspheres used in this study is Spheriglass of Potter Industries Inc, USA with a density of 2.5g/cm^3 and mean particle dia of 35 microns. The spheres are very strong, with crush strength in excess of about 200 MPa and Mohr's hardness 6.0-6.5. They have a coupling agent coating, compatible with epoxy resin.

2.2. Preparation of Liquid Rubber Modified Epoxy Matrix

Amine-containing poly dimethyl siloxane (ACS) was taken as liquid rubber modifier. 5-10 phr of ACS was taken along with epoxy resin and the mixture was heated at 50°C for 30 minutes with continuous stirring. Then the liquid rubber modified epoxy resin, which appears as a creamy white liquid, was allowed to cool at the room temperature. This can be cured in a way similar to the unmodified epoxy.

2.3. Preparation of Aluminum and Spheriglass-Filled Epoxy and Modified Epoxy Matrix

The weighed amount of glass micro-spheres was added to epoxy system and stirred for 15 min. The weighed amount of aluminium was added to the glass micro-spheres /epoxy system and stirred for 15 min. This tri-phase material was cured using triethylene tetramine at room temperature. The resultant material was cured at 100ºC for 3 hrs in aluminium moulds. The same procedure was carried out for ACS modified epoxy matrix. Various weight ratios (in gram) of aluminium and glass micro-spheres filled epoxy matrix and modified epoxy matrix were analyzed. The compositions of various specimens are given in Table 1.

TABLE 1: Various Compositions of Prepared Specimens.

S No	Mix Grade	ACS (Vol. %)	DU grade Aluminium powder (Vol. %)	Spheriglass (Vol. %)
1	P	0	0	0
2	C	0	26	14
3	D	0	22.5	24.5
4	H	3	25	13.5
5	I	5.5	21.5	23
6	J	2.5	22	24

3. Results and Discussion

3.1 Mechanical Properties of the Composites Containing Aluminium, Spheriglass and Acs

The mechanical properties of various samples are given in Tables II and III.

TABLE II: Mechanical Properties of the Aluminum Filled and Modified Epoxy Resin Composites

S. No	Notation Used	Tensile Strength (MPa)	Tensile Modulus (GPa)	Impact Strength (J/m)	Compositions		
					ACS (vol. %)	Al. powder (vol. %)	Solid glass spheres (vol. %)
1	P	48± 2.5	1.5± 0.2	34± 2.5	0	0	0
2	i	43± 2	1.3± 0.15	35± 3	5	0	0
3	ii	45± 1.5	1.5± 0.2	39± 2	9.5	0	0
4	A	27± 2	2± 0.25	51± 1.5	0	30	0
5	B	29.5± 2	2± 0.25	65± 3	0	0	31.5
6	C	20.2± 2.5	1.2± 0.2	65± 3	0	26	14
7	D	17.2± 2	1.7± 0.2	63± 2	0	22.5	24.5
8	E	27.5± 1.5	1.1± 0.15	58± 3	3.5	28.8	0
9	F	28.3± 2	0.83± 0.1	63± 2	6.8	27.8	0
10	G	32± 2.5	1.2± 0.2	68± 3	6.6	0	29.5
11	H	28.4± 2	1.1± 0.25	70± 3	3	25	13.5
12	I	26.3± 1.5	1.5± 0.25	70± 2	5.5	21.5	23
13	J	24.6± 2	1.1± 0.2	67± 2.5	2.5	22	24

TABLE III: Mechanical Properties of the Aluminium Filled and Modified Epoxy Resin Composites

S. No	Notation Used	Flexural Strength (MPa)	Flexural Modulus (GPa)	Compressive Strength (MPa)	Compressive Modulus (GPa)	Compositions		
						ACS (vol. %)	Al. powder (vol. %)	Solid glass spheres (vol. %)
1	P	97± 2	3.8± 0.2	46.25± 2	1.18± 0.21	0	0	0
2	i	82.8± 1.5	2.6± 0.15	47± 2	1.2± 0.15	5	0	0
3	ii	93± 2	2.6± 0.2	47.5± 2.5	1.3± 0.2	9.5	0	0
4	A	51.5± 2	5.7± 0.2	76.8± 2	1.53± 0.2	0	30	0
5	B	59± 2.5	6± 0.25	88.09± 2	2.75± 0.22	0	0	31.5
6	C	37± 2	6± 0.15	83.8± 2	1.75± 0.25	0	26	14
7	D	38.0± 2	6± 0.25	96.2± 2.4	2.00± 0.2	0	22.5	24.5
8	E	53± 2.5	5.3± 0.23	78.6± 1.7	1.6± 0.2	3.5	28.8	0
9	F	54± 2.5	4.1± 0.2	79.8± 2	1.55± 0.2	6.8	27.8	0
10	G	60.0± 2	4.6± 0.21	90.3± 2.5	2.2± 0.23	6.6	0	29.5
11	H	40.6± 1.5	4.6± 0.2	90± 2.3	2.5± 0.2	3	25	13.5
12	I	42± 2	3.4± 0.2	98.5± 2	2.25± 0.2	5.5	21.5	23
13	J	40.0± 2	3.1± 0.2	97.2± 2	2.1± 0.2	2.5	22	24

Some of the factors considered for selecting the compositions based on the mechanical properties analysis, are as follows:

The specimen should have higher compressive strength.

i) Compositions should contain some amount solid glass spheres with it, so that the viscosity of the mixture may not be more in order to ease the mixing difficulties of all the ingredients, and for easy processing. (As per the product literature from Potters Industries Inc, USA)

ii) Also the selected system should have the maximum aluminium content in order to have better thermal conductivity (Simon Konzelmann et al 2008).

iii) Better impact strength.

Considering the above mentioned factors the mechanical properties analysis was carried out as follows:

3.1.1 Compressive Strength

From Table III, when comparing the compressive strength the various specimens, it was found that specimens B, D, G, H, I and J have more than 85 MPa. Simon Konzelmann et al (2008) found that for high thermal conductivity, the maximum quantity of aluminium must be required. For specimens I and J it was found that the compressive strength was nearly 100% more than the compressive strength of pure epoxy. The literature from Potters Industries shows that the solid glass spheres will maintain the viscosity of the system without increasing. So, the solid glass spheres is also required in the system, for an easy processing of the mixture and pouring it inside the mould cavity for making the product.

When specimen B is considered, it does not have any aluminium content in it. So , it is not considered for further analysis. Specimen D has both aluminium and solid glass spheres, and hence, the compressive modulus will be more for this specimen; so, specimen D is considered for further analysis. Even though Specimen G has good compression strength it does not have aluminium in it, so this specimen is also not considered further. Specimens H, I and J have both solid glass spheres and aluminium in them, and the compressive strength and modulus values are more for these specimens; so, specimens H, I and J are considered for further study. Finally from the compressive properties analysis, the selected specimens are D, H, I and J.

3.1.2 Flexural Strength

From Table II, when comparing the flexural properties of the various specimens, the following observations were obtained. All the specimens have a flexural strength of more than 35 MPa, but if the flexural modulus also considered, specimens i and ii are omitted from further study. Also, pure epoxy is not considered. Specimen A does not have solid glass spheres, and specimen B does not have aluminium in it; so, specimens A and B are not considered for further study. But specimens C and D have both aluminium and solid glass spheres, so they may be expected to have good thermal conductivity, which is the key property required for mould application; so, specimens C and D are considered for further analysis.

Specimens E and F do not have solid glass spheres, so these two specimens are not considered. Specimen G also does not have aluminium in it; so, this specimen is also not considered further. Specimens H, I and J have both aluminium and solid glass spheres in them; also, these specimens have good flexural properties. So, from the flexural strength analysis, it is concluded that specimens C, D, H, I and J may be considered for further study.

3.1.3 Tensile Strength

From Table II, it was concluded that specimens C, D, H, I and J have both aluminium and solid glass spheres in them, and these specimens have good tensile properties also; so, it is decided to study specimens C, D, H, I and J, further. Finally based on mechanical properties analysis (compressive, flexural and tensile strength), specimens C, D, H, I and J are considered and machinability parameters were studied for those specimens.

3.2 Surface Roughness and Resultant Tool Force Analysis

For various depth of cut, feed and speed conditions the values of surface roughness (Ra) and Resultant tool force (F) was noted.

TABLE IV: Surface Roughness and Resultant Tool Force Values for DOC: 0.25mm

Speed	Feed	C		D		H		I		J		P	
		Ra	F	Ra	F	Ra	F	Ra	F	Ra	F	Ra	F
4.712	0.065	8	2.5	9	1.7	8	2.2	8	1.4	6	2.2	8	3.2
4.712	0.305	25	3.7	27	3.7	22	1.7	23	5.8	17	6.7	21	7
4.712	0.5	31	2.5	35	3.7	32	1.7	40	1.4	39	2.5	40	3.3
7.383	0.065	14	4.1	8	2.5	7	1	9	2.2	6	1.7	11	1.7
7.383	0.305	19	5.4	25	4.4	28	2.5	17	2.5	16	1.7	23	3.7
7.383	0.5	36	2.5	28	1.7	37	2.2	40	2.2	43	1.4	42	2.5
11.167	0.065	12	3	8	3	9	1.4	8	2.2	9	1.4	10	2.5
11.167	0.305	24	2.5	30	3	29	1.4	23	2	15	1	23	1.4
11.167	0.5	27	2.5	32	2.5	38	1.7	32	1.4	40	1.4	40	2.8

Where, speed in m/min

Feed in mm/rev

R_a (Surface roughness) in micrometer

F (Resultant tool force) in kgf.

TABLE V: Anova Result for specimen C:

	Speed	feed	doc	Ra	F
Speed	1				
feed	0	1			
doc	0	0	1		
Ra	0.008733	0.935807	0.081648	1	
F	-0.18424	0.2204	0.589047	0.19966	1

From the Table 4, it observed that the effect of feed on surface roughness is more significant and the effect of depth of cut on resultant tool force was also found significant (value more than 0.45) for the specimen C. So the discussion may be restricted to the effect of feed on surface roughness and the effect of depth of cut on resultant tool force. From the Table 4, surface roughness value found to be 6µm for the specimen J in the machining condition of speed 4.712 m/min, feed 0.065 mm/rev and depth of cut of 0.25 mm. This R_a value of 6µm is lesser than the surface roughness value of all other specimens in the above mentioned machining conditions. Similarly the resultant tool force of 1.41kgf is obtained for the specimen I which is lesser than the value obtained for all other specimens.

In general for all the machining conditions the lesser R_a value and lesser resultant tool force obtained for the specimens either H or I or J. This is also shown in the figure. The similar observations were obtained for all the depth of cut conditions shown in table 4, 6 and 8.

TABLE VI: Surface Roughness and Resultant Tool Force Values for DOC: 0.5mm

Speed	Feed	C		D		H		I		J		P	
		R_a	F	R_a	F	R_a	F	R_a	F	R_a	F	R_a	F
4.712	0.065	9	3	10	4.4	8	1.4	6	1.4	11	1.4	10	3.3
4.712	0.305	27	5.1	31	4.6	29	3	32	2.5	29	2.5	25	3.7
4.712	0.5	49	3.7	40	5.8	35	1.7	43	1.7	30	2.5	31	4.7
7.383	0.065	13	4.4	9	2.5	9	1	10	1.7	8	1.7	11	3.5
7.383	0.305	31	5.8	29	5.8	29	2.5	28	2.5	29	3.3	22	3.7
7.383	0.5	45	4.2	34	4.2	38	2.3	35	2.5	33	2.5	33	3.3
11.167	0.065	10	2.5	9	2.5	14	1	10	2.8	10	2.2	10	2.5
11.167	0.305	31	3.3	29	2.5	30	2.5	25	2.5	27	1.7	23	2.5
11.167	0.5	42	3.7	43	4.2	38	3.3	31	2.5	35	2.5	33	3.7

TABLE VII: Anova Result for Specimen D

	Speed	feed	doc	Ra	F
Speed	1				
feed	0	1			
doc	0	0	1		
Ra	0.011055	0.960989	0.036093	1	
F	-0.01683	0.40828	0.596227	0.432964	1

From the Table VII, it observed that the effect of feed on surface roughness is more significant and the effect of depth of cut on resultant tool force was also found significant (value more than 0.45) for the specimen D

TABLE VIII: Surface roughness and resultant tool force values for DOC: 0.75mm

Speed	Feed	C		D		H		I		J		P	
		Ra	F	Ra	F	Ra	F	Ra	F	Ra	F	Ra	F
4.712	0.065	10	4.1	10	3	10	2.5	9	3.3	8	3.3	10	3.5
4.712	0.305	28	6.8	29	3.7	25	4.1	23	3	25	3.3	24	3.7
4.712	0.5	43	5.2	42	7	40	3.6	35	3	33	2.2	45	6
7.383	0.065	15	4.4	11	3	10	2.5	9	1.7	9	1.7	10	3
7.383	0.305	33	4.2	22	4.6	26	3	25	2.5	24	2.5	22	4.4
7.383	0.5	41	5.2	40	6.4	35	2.5	36	2.5	33	3.2	45	4.6
11.167	0.065	11	3.5	9	3.7	9	3	8	1.7	10	2.2	10	6.4
11.167	0.305	32	4.6	30	5.9	31	2.5	25	2.5	28	1.7	25	1.4
11.167	0.5	42	5.9	41	6.4	40	3.5	35	3.7	30	3.3	33	4.6

TABLE IX: Anova Result for Specimen H

	Speed	feed	doc	Ra	F
Speed	1				
feed	0	1			
doc	0	0	1		
Ra	0.104705	0.949673	-0.11128	1	
F	-0.18461	0.249571	0.443792	0.140261	1

From the Table IX, it observed that the effect of feed on surface roughness is more significant (value more than 0.45) for the specimen H

TABLE X: Surface Roughness and Resultant Tool Force Values for DOC: 1 mm

Speed	Feed	C		D		H		I		J		P	
		Ra	F	Ra	F	Ra	F	Ra	F	Ra	F	Ra	F
4.712	0.065	10	4.4	7	3.7	6	1.7	10	2.5	11	2.5	9	4.4
4.712	0.305	21	14	20	9.5	16	11	15	8.7	20	5.1	19	17
4.712	0.5	42	7.7	43	5.9	30	3.3	31	3.3	31	3.2	40	7.3
7.383	0.065	10	4.6	9	4.7	10	2.5	10	4.1	10	2.5	10	6.2
7.383	0.305	30	3.3	24	5.5	16	2.8	23	3	17	2.2	22	3
7.383	0.5	34	7.4	38	5.2	38	3.3	38	3.6	36	4.1	39	4.2
11.167	0.065	9	5.2	9	3	7	1.7	10	2.5	7	2.5	12	6.5
11.167	0.305	27	5.5	24	11	18	2.5	21	3.7	15	4.4	22	3
11.167	0.5	41	8.6	40	7.8	35	4.1	35	4.4	33	4.2	36	5.8

Table XI: Anova result for specimen I

	Speed	feed	doc	Ra	F
Speed	1				
feed	0	1			
doc	0	0	1		
Ra	-0.039	0.957803	-0.03884	1	
F	-0.14136	0.13184	0.437826	0.010318	1

Table XII: Anova result for specimen J

	Speed	feed	doc	Ra	F
Speed	1				
feed	0	1			
doc	0	0	1		
Ra	-0.00454	0.933556	-0.0494	1	
F	-0.24165	0.2352	0.37515	0.110285	1

Table XIII: Anova Result for Specimen P

	Speed	feed	doc	Ra	F
Speed	1				
feed	0	1			
doc	0	0	1		
Ra	-0.0178	0.962842	-0.00105	1	
F	-0.32372	0.082349	0.339674	0.01801	1

The anova result for all the specimens (Table V, VII, IX, XI, XII and XII) shows that the feed is having more influence on surface roughness and also depth of cut is having more influence on resultant tool force.

4. Conclusions

In the machinability studies, ACS addition was found to reduce the surface roughness after machining and also reduced the tool force, this leading to better machinability. This may be due to migration of silicone leads to lubricating action in between cutting tool and specimen.

Over all, the studies indicate that epoxies can be modified by aluminium, spheriglass and ACS for making temporary moulds for limited number of runs. This can help in reducing the lead time for developing plastic products.

5. References

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