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WEAR AND MECHANICAL STRENGTH OF EPOXY FILLED BY ALUMINIUM OXIDE NANOPARTICLES

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ABSTRACT

This study proposes polymeric dies capable of producing aluminum sheets that will withstand wear and compressive stresses. The wear behavior and compressive strength of the proposed epoxy matrix composites filled by aluminum oxide (Al_2O_3) nanoparticles and paraffin oil is discussed in this study. Six reinforced dies were produced with different volume fractions containing aluminum oxide nanoparticles (0, 0.2, 0.4, 0.6, 0.8 and 1.0 %), then another set of dies were fabricated with the same volume fractions and 3.5 wt. % paraffin oil content. An optical microscope test was carried out to measure dimensional variation caused by wear. It was found that adding paraffin oil to epoxy filled by 0.2 wt. % aluminum oxide has reduced wear of the corners of dies.

KEYWORDS

Epoxy composites, polymeric dies, compression test, paraffin oil.

INTRODUCTION

Global market pressure requires faster product development and reduced time to market. Customer driven product customization, rapid product changes and continued demands for cost savings are forcing companies to look for new technologies and processes that can cope with low-volume products in a quicker and cheaper manner. Rapid prototyping (RP) technology was developed to solve these problems using an approach in which the shape of the physical part is generated by adding the material layer-by-layer. RP has the particular advantages of time saving and low cost, irrespective of the complexity of the shape, [1]. RP products are particularly effective in verifying design concept and the early stages of product development. This technology is considered to be a major breakthrough in production engineering because it helps provide a seamless process of computer based design and manufacture. However, many RP methods currently in use are unable to produce functional parts with good material properties and are generally cost prohibitive for making more than a handful of models. Even though the technology is improving and there is increasing use of RP for direct rapid manufacturing (RM). Rapid tooling (RT) is a tooling fabrication method, which is a natural extension of RP. Today, many products have quantity requirements insufficient to justify steel tooling. Also in the new product development cycle, there is often need of some intermediate tooling to produce a small quantity of prototypes or working samples for marketing, functional test, or production process design and evaluation purposes. In these cases, making cost effective tooling quickly for small batch production can become very important.

The presence of a small ceramic particles which are known to enhance the mechanical and tribological properties of polymers introduced into an epoxy resin was investigated, [2]. They discovered that the filler morphology, size, particle amount and the dispersion homogeneity influence extensively the composite's performance. In their study, various amounts of micro and nanoscale particles (calcium silicate $CaSiO_3$, 4 - 15 µm, alumina Al_2O_3, 13 nm) were systematically introduced into an epoxy polymer matrix for reinforcement purpose. The influence of these particles on the impact energy, flexural strength, dynamic mechanical thermal properties and block-on-ring wear behavior was investigated.

Small amounts of milled fibers enhance the wear resistance, with little changes in the process ability and in the allowed aluminum concentration in the resin matrix were show, [3]. Also, A tribological study of these materials was performed involving the neat resin, the aluminium filled resin and tri-phase composites composed by epoxy, aluminium particles and milled glass or carbon fibers. The study was focused on the role of the particles and fibers in the friction and wear at room temperature and at a typical plastic injection temperature of 160 °C.

A rapid and economical method for making tools with low volume production was developed, [1], where some particulate reinforced epoxy composites were investigated in their study. Metal, ceramic or mineral salt powders were used as filling particles and epoxy for the matrix. The mechanical and thermal properties of the above composites in different ratios of fillers were tested to verify the suitability for injection molds and the improvement of material characteristics. By analysis and comparison, a suitable composite, 20 wt. % alumina nanoparticles filled epoxy composite, was found to work best.

Polymeric composite was designed, [4], in order to operate under low friction and low wear against steel counterparts are described. A particular emphasis is focused on special filler (including nanoparticle) reinforced thermoplastics and thermosets. Especially, the influence of particle size and filler contents on the wear performance is summarized. In some of the cases, an integration of traditional fillers with inorganic nanoparticles is introduced and presents an optimal effect. Furthermore, some new steps towards the development of functionally graded tribo-materials are illustrated.

A technique using a rapid soft-tooling approach was investigated, [5], namely, aluminium filled epoxy resin tooling for injection mold preparations successfully explored. An aluminium filled epoxy resin mold is evaluated and the characteristics of the injection molded products are presented. Rapid prototyping (RP) is fast becoming a standard tool in today's product design and manufacturing environment. Significant benefits in terms of lead time and cost savings have been reported with the use of RP technology.

Wear behavior, of epoxy matrix composites filled with uniform sized sub-micron spherical silica particles, was investigated, [6]. Two distinct sizes of uniform sized silica particles (120 and 510 nm in diameter, respectively) were prepared in their laboratory and used as model fillers in the composite systems. The wear test results showed that the spherical silica particles could improve the wear resistance of the epoxy matrix even

though the content of the fillers was at a relatively low level (0.5 - 4.0 wt. %).It was found that the filler with smaller size seemed to be more effective in the improvement of the wear resistance of the composites.

Time and expense are two main important issues that are needed to manufacture sheet metal forming dies imprecision machinery industry, [7]. This study presents an alternative approach of producing sheet metal forming dies that is suitable for application in a new sheet metal component research and development phase. It was found that the sheet metal forming dies can be fabricated within 1 day. The sheet metal forming dies are strong enough to fulfill small batch production. In addition, the fabricated punch has better wear resistance compared to that fabricated directly by a 3D printing machine using acrylonitrile butadiene styrene plastics.

Rapid prototyping machine was used was designed, [8], to process a photo elastic resin to fabricate the pre-molds. Liquid particle filled epoxy resin was poured in the pre-mold and cured in an oven. Real autoclave process conditions were then applied to the mold several times to assess the geometrical stability and the accuracy of the produced parts, measured using a laser 3D scanner. The method is applicable to components of small to medium dimensions (max 500 mm).

The rapid prototyping and tooling (RP & T) techniques for developing punch & die for press metal forming die was evaluated, [9]. In this evaluation, one type of prototype tool called Quick tool has been manufactured and tested. This type of tool is being a stereo lithography Quick Cast pattern infiltrated with aluminum filled epoxy, as the material it is made of does not render much durability. Further, the developed tool has been evaluated in press metal forming of by producing components with 0.8 mm aluminum sheets.

A competitive environment forces product development phase to shorten increasingly in order to meet customers' changing demands was evaluated, [10]. In their paper, production of prototype sheet metal parts with polymer tooling was investigated in order to analyze dimensional conformance, cost and manufacturing time comparison with conventional method. Production of a fender is selected as a case study for polymer tooling.

The failure mechanism of the rapid prototyped tools was investigated, [11], as a fundamental step for effective tool life estimation, the microstructure and the mechanical properties of the polymer composite tooling material were characterized. A finite element model of 90° V-die bending process was developed, and the effects of process parameters on stress distribution in punch and die were investigated through simulation. The simulation results were verified through experiments using instrumented, laboratory-scale punch and die sets.

Result dealing with tribological and tool design aspects for the use of polymeric materials in sheet metal forming was investigated, [12]. Friction and wear of sheets with different surface topologies have been investigated. A newest method for measuring polymer/sheet wear is presented. A coupled simulation model for the production of a test geometry aimed specifically at the investigation of die deformations and loads is

presented. Three kinds of epoxy-based composite mold inserts fabrication methods are proposed, [13]. A simple and cost-effective method for fabricating epoxy-based composite mold inserts of propeller using rapid prototyping and rapid tooling technique is demonstrated. This method can be employed in the intermediate tooling to produce a small quantity of working samples by plastic injection molding at the first development stage for a new product.

Epoxy-based composites molds were developed, [14], to inject functional polymer prototypes and pre-series. The molds developed are composed by an epoxy resin and aluminum particles, which were added to improve the thermal conductivity of the tool, which is an essential parameter for plastic injection molding. However, this procedure also lowers the mechanical properties of the tool. To overcome this problem, fibers were added to the composite. The quality of the glass and carbon fiber/resin interface was evaluated by the determination of the interfacial shear strength based on Kelly Tyson's model, in order to tailor the composite for RT applications.

Tri-phase materials were produced, [15], composed by an epoxy resin, aluminum particles and milled fibers, with mechanical and thermal performances better than the single materials, increasing the competitiveness of the epoxy rapid tooling processes. Charpy impact tests were employed to obtain a qualitative indication of the composites toughness. The aluminum filled resins and the tri-phase composites (composed by epoxy, aluminum particles and milled glass or carbon fibers), and to consequently tailor the composites mechanical properties for rapid tooling applications.

The present study proposes polymeric dies consisting of epoxy matrix filled by aluminum oxide (Al_2O_3) nanoparticles and paraffin oil. Wear and compressive strength of the proposed are discussed.

EXPERIMENTAL

Materials

Epoxy resin is one of the most important thermosetting resins used in several engineering applications. A commercially available epoxy resin denominated Jotafloor SF Primer, was used in the current work as the base resin for all of the nanocomposites studied, and it is converted to solid state by adding a hardener. The weight ratio of hardener to epoxy was 1:2. The mechanical and physical properties of epoxy are shown in Table 1, according to supplier information.

Table 1 Epoxy mechanical and physical properties.

Property	**Value**
Density	**(1.11 ± 0.02) gm/cm3**
Compressive Strength	**(500-1000 kg/cm2)**
Resistance to Bending	**(200-400 kg/cm2)**
Components Mixture Weight Percentage	**(Epoxy (A): hardener (B)) A: B = 2:1**
Initial Curing Time	**(8 hr.)**
Final Curing Time	**(24 hr.)**
Completely Hardening Time	**(7 days)**

Aluminum oxide is a chemical compound of aluminum and oxygen with the chemical formula Al_2O_3, Table 2. It is commonly called alumina. Al_2O_3 is significant in its use to produce aluminum metal, as abrasive owing to its hardness, and as a refractory material owing to its high melting point. Being fairly chemically inert and white, aluminum oxide is favored filler for plastics. Aluminum oxide is a common ingredient in sunscreen.

Mineral oil, also known as liquid paraffin, is a very highly refined mineral oil used in a variety of industries ranging from food production to pharmaceuticals, cosmetics and engineering.

Table 2 Aluminum oxide nanoparticles physical properties.

PROPERTY	VALUE
Chemical formula	Al_2O_3
Molar mass	101.96 $g.mol^{-1}$
Appearance	white solid
Odor	odorless
Density	3.987 g/cm^3
Melting point	2,072 ˚C

Die and Punch Fabrication

A 3D printer was used to produce an accurate die and punch, which were used for samples production. The design of punch and die were investigated using solid works software. The design considerations and tolerances were made to ensure a feasible succeed sheet drawing operation. Guide ways were added in die to ensure the alignment between punch and die to prevent localized wear at a specific corner. A clearance angle was investigated at the exit of the die to facilitate the removal process of the drawn rectangular cup. Also, a central hole was provided at the top head to eject the tested punch.

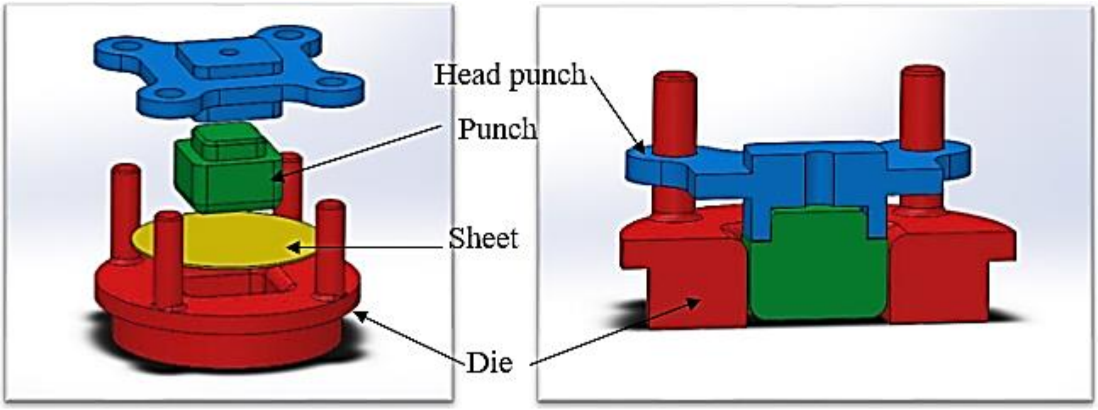


Fig. 1 The process 3D-setup for deep drawing process.

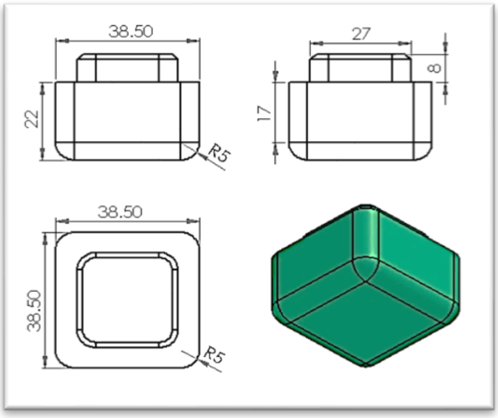


Fig. 2 Punch dimensions (mm)

For producing the composite punch, a layer from wax was added above 3D printed punch to form a cavity mold, as shown in Fig. 3. A trimming tool was used to remove the excess wax and formed the required mold.

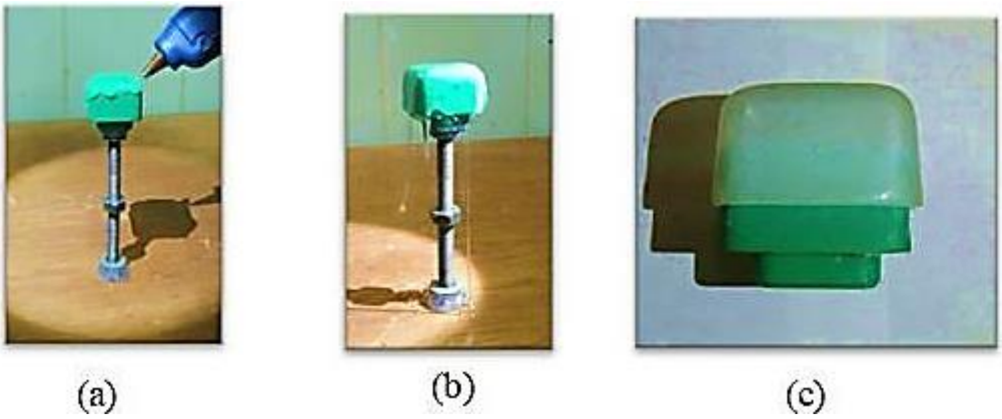


Fig.3 Mold making procedure: (a) Pouring melon wax over the punch. (b) Solidified wax. (c) Trimmed and finished mold.

The epoxy resin was mixed mechanically with Al_2O_3 very well. The oil was added and mixed with epoxy/ Al_2O_3 mixture, finally the hardener was added to the mixture at a resin-to-hardener weight ratio of 2:1.The Al_2O_3/Epoxy/oil mixture was mechanically stirred at 350 rpm, for 15 min using (STANHOPE-SETA) stirrer, to form a homogeneous suspension. The mixture was transferred to the mold cavity, Fig. 4.

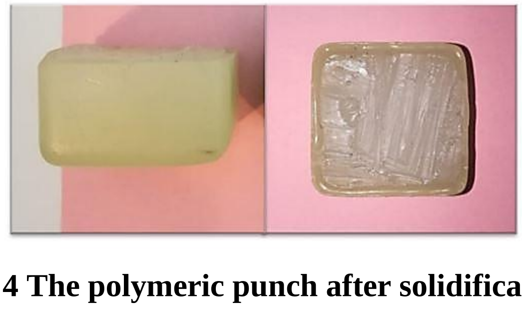


Fig. 4 The polymeric punch after solidification.

Polypropylene pipe was used as a mold for producing the compression test specimens. Its diameter was 16mm with 24mm height.

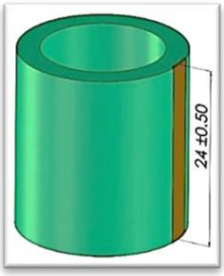


Fig. 5 Dimensions of the die

The tests were carried out on the hydraulic press shown in Fig. 6. Its capacity was 100 KN (10 Ton). It is used to supply enough pressure over the punch head, which will cause the sheet to be drawn. The effect of Al_2O_3 and olive oil on the punch corners wear was investigated after deep drawing process for sheet of aluminum foil. The sheet thickness was 0.4 mm. The aluminum foil work piece, called a blank, is placed over the die opening, as shown in Fig. 6. A blank holder, that surrounds the punch, applies pressure to the entire surface of the blank, (except the area under the punch), holding the blank flat against the die and acts as a guide for the punch movement during forming process to adjust and alignment the punch motion towards the die.

Fig. 6 (a) Hydraulic Press, (b) Sheet Drawing Process.

Punch wear measurement

For developing epoxy composites to be used as fast and cheap dies. A die and punch for deep drawing forming process was fabricated from Epoxy/ Al_2O_3/Oil composite. The presence of Al_2O_3 led to enhancing the compressive strength, and the addition of olive oil for developing the tribological properties of die and punch. Deformation of specimens dimensions due to wear caused by the relative motion between punch (specimen) and the drawn sheet, is measured by means of magnification microscope, by which allowing for zooming in into the worn corners and measure there flatten radius, as shown in Fig. 7.

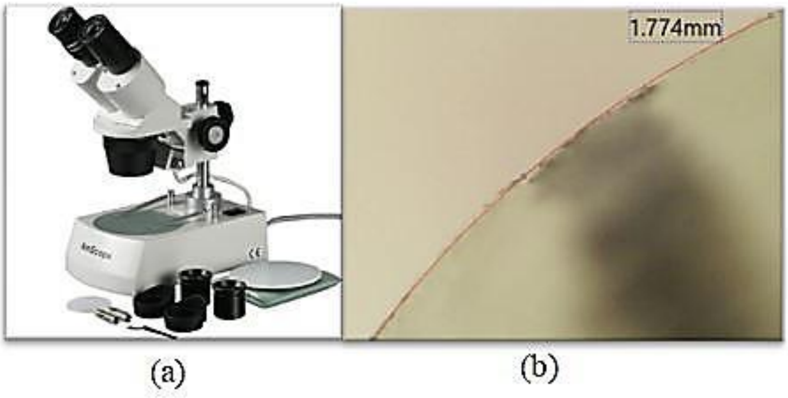


Fig. 7 (a) Microscopes. (b) Photomicrograph used to calculate the deformed radius.

All compression specimens were tested on a computer-controlled servo-hydraulic universal testing machine, its capacity was 30 tons, as shown in Fig.8

Fig. 8 Universal Testing Machine for compression test.

RESULTS AND DISCUSSION

Compression Test Results

Mechanical properties for (epoxy/ Al_2O_3) composites

The influence of Al_2O_3 concentrations on the mechanical performance of epoxy composites is shown in Fig. 9. By analyzing the figure, it is clear to observe that, the compressive strength affected by adding Al_2O_3. This may be attributed to its very high modulus. Al_2O_3 also known as stiffest materials with high strength and modulus, therefore, the incorporation of this filler in epoxy is possible to improve mechanical properties of composites. It is observed that, epoxy composites with 1.0 wt. % Al_2O_3 give the highest modulus of elasticity.

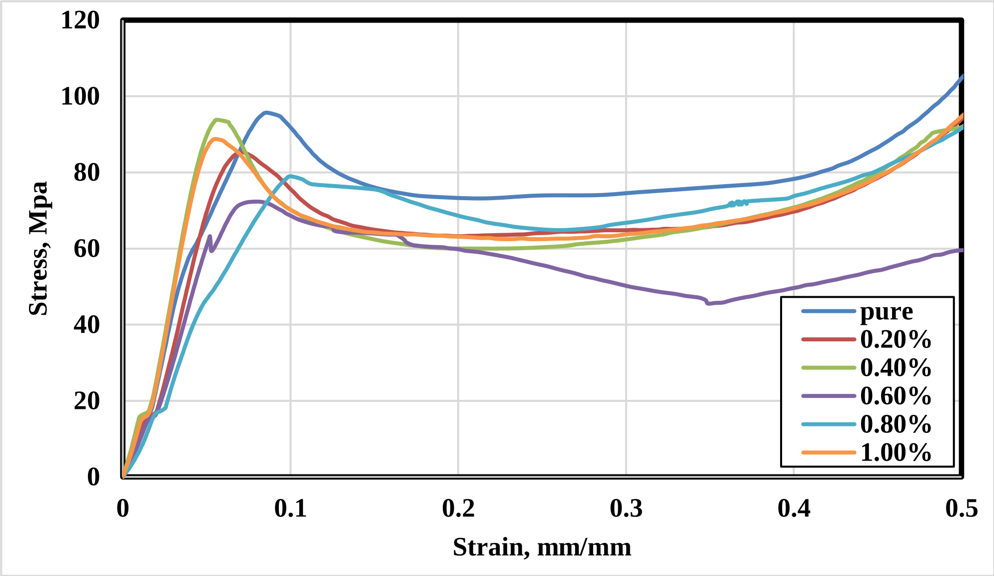


Fig. 9 Stress – Strain diagram for (epoxy/Al_2O_3) composites.

For more illustration of data shown in Fig. 9, yield points have been considered as an indicator to the mechanical strength of test specimens as shown in Fig. 10. As illustrated, epoxy composites with 0.4 wt. % Al_2O_3 give the highest yield strength.

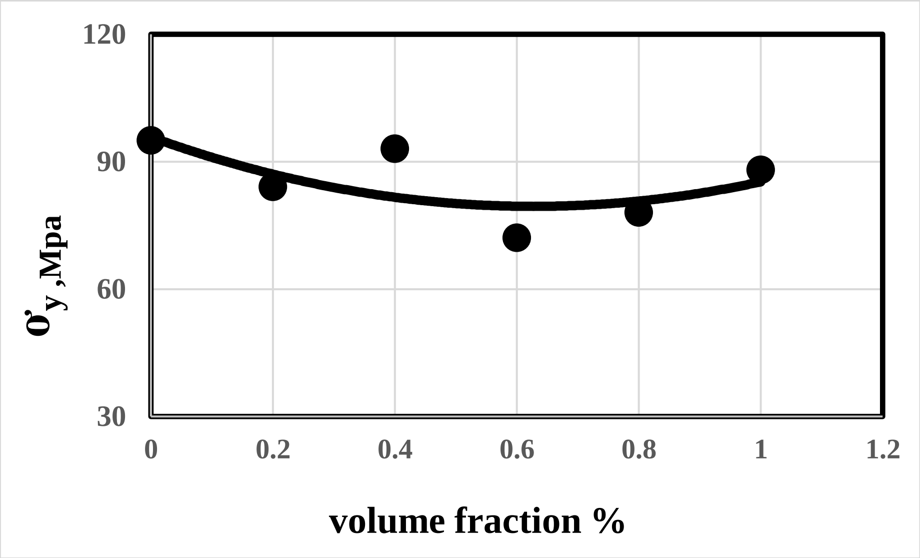


Fig. 10 Relationship between volume fraction and yield strength.

A slight decrease is located at 0.2 % followed by an increase in yield point for 0.4 % wt. % Al_2O_3. Then another drop associated with 0.6% specimen followed by higher yield values in both 0.8 % and 1 % nanoparticles content. By examining the whole curve behavior, an overall slight decrease in yield strength can be observed.

Epoxy / aluminum oxide composites filled by Paraffin oil

Figure 11 shows the stress - strain relationship of epoxy/ Al_2O_3 composites filled by paraffin oil. It is clear that, the Al_2O_3 improve on the mechanical properties of epoxy composites. This may be referred to a good distribution of Al_2O_3 in the matrix and its

unique mechanical properties. The Al_2O_3 dispersion into the epoxy composite makes the micro-cracks propagation more difficult, allowing an increase in compressive strength. As it can be noticed, there is a slight decrease in strength due to the addition of oil. This may be regarded to the oil effect on decreasing the bounding force between epoxy chains. The relationship between volume fraction and yield strength is shown in Fig. 12.

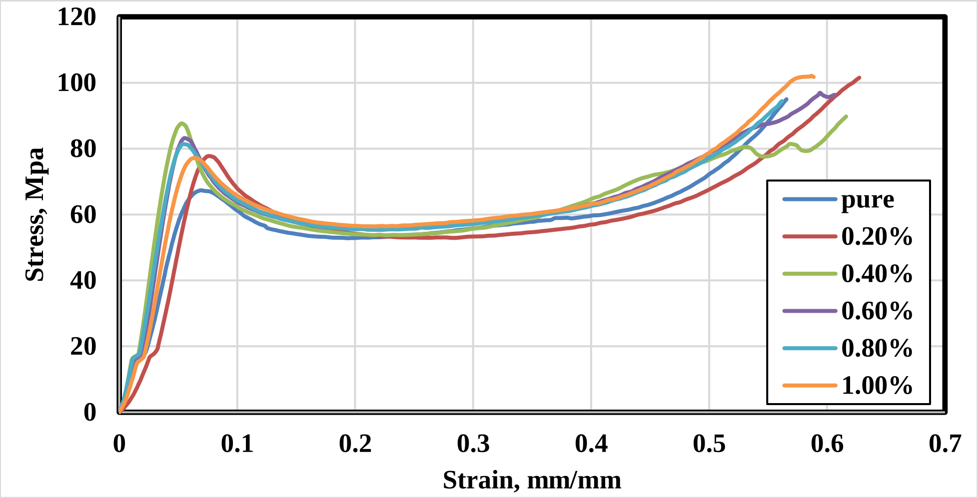


Fig. 11 stress – strain diagram for (epoxy/Al_2O_3/ Paraffin 3.5 %) composites

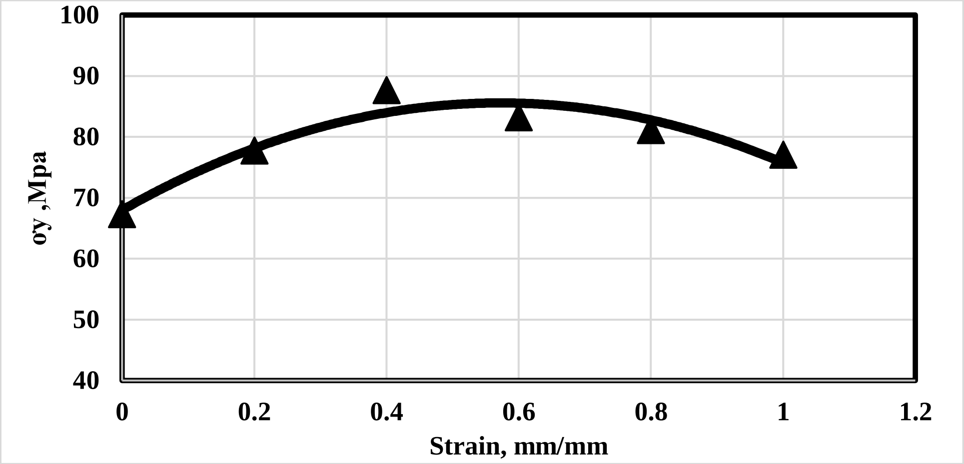


Fig. 12 Relationship between volume fraction and yield strength in the presence of paraffin oil.

Wear results of the tested composites

The values of punch wear in (mm) are shown in Fig. 13. The results implied that using Al_2O_3 for reinforcing epoxy resin have a drastic decrease in wear loss. This decrease in wear is attributed to, the increase of wear resistance of composites because of Al_2O_3. The large surface area of Al_2O_3 can increase the contact area with epoxy matrix and maximize the stress transfer from epoxy to the Al_2O_3. It was demonstrated that, the

improved composite mechanical and tribological performance can be achieved by combining the advantages of the Al_2O_3 and oils.

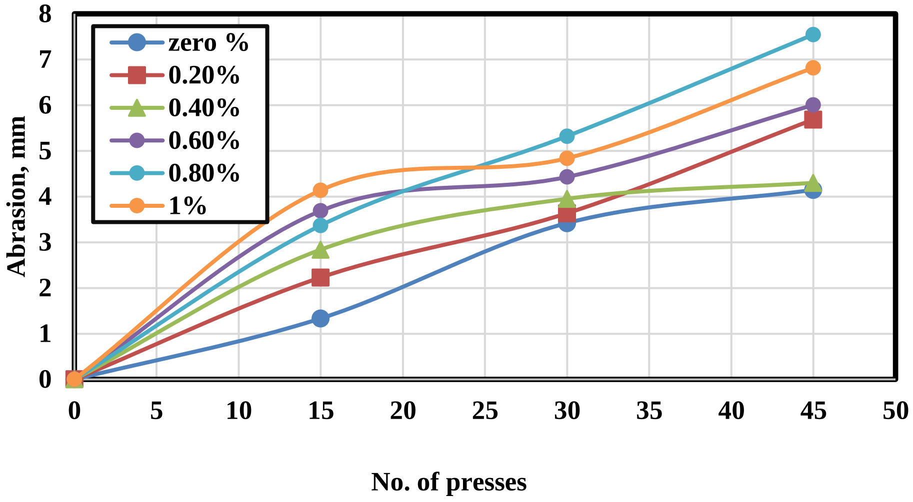


Fig. 13 Wear of punch corner vs. number of presses.

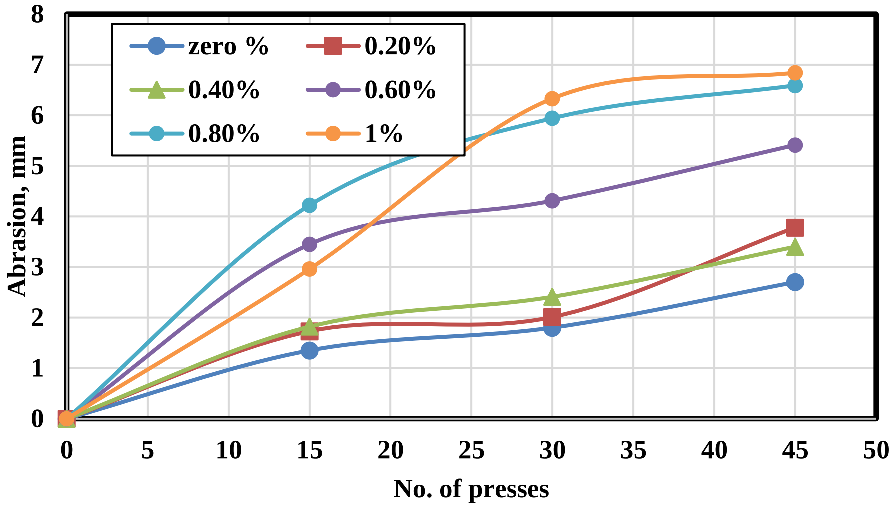
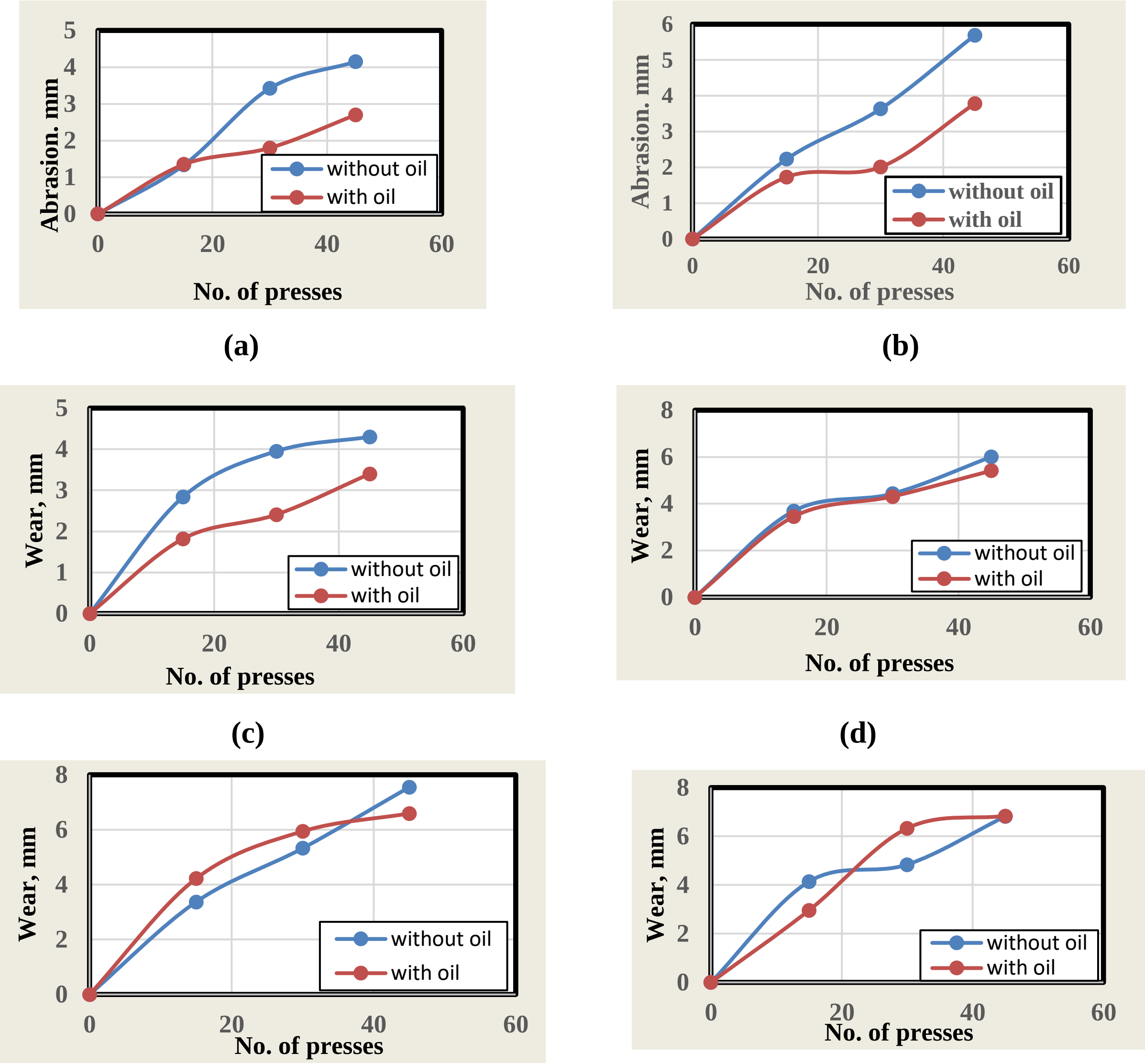


Fig. 14 Abrasion located at the corners of punches.

As shown in Fig. 13, an orderly behavior is noticed at 15 presses beginning from zero nanoparticles content that has the lowest abrasion values. While at 30 and 45 presses the previous arrangement had a disordered arrangement made by the 0.8 wt. % specimens crossing to the highest abrasion values. At 45 presses, 0.4 wt. % and pure specimens almost have the same abrasion performance.

By adding 3.5 wt. % paraffin oil to the composite, the behavior has more complexity compared with no oil content shown in Fig. 15, pure specimen maintained its position as being abrasion resisting as it was with no oil addition. While most one effected by abrasion was located at 1.0 wt. % and 0.8 wt. %.



(a) (b)

(c) (d)

(e) (f)

Fig. 15 Reduction in radius as a function of number of presses, with and without paraffin content for: (a) pure epoxy; (b) 0.2 wt. %; (c) 0.4 wt. %; (d) 0.6 wt. %; (e) 0.8 wt. %; (f) 1.0 wt. % aluminum oxide content.

By investigating the curves shown in Fig. 15, paraffin content caused almost an overall retraction on the abrasion values which can be clearly seen at (Fig. 15 a), pure specimen nearly had the same reduction after performing 15 presses followed by a separation in either 30 or 45 presses. This separation still exists in 0.2 wt. % and 0.4 wt. % which also the enhancement occurred at paraffin addition (Fig. 15 b and c). A correspondence behavior between paraffin and paraffin free content is shown in Fig. 15 d. In Fig. 15 e, a reverse effect when adding 0.8 wt. % aluminum oxide is occurred, which made enhancement takes place at zero paraffin content, followed by a crossover point after pressing 37 times. As for 1.0 wt. % nanoparticles content, Fig. 15 e, the composites filled

by paraffin enhanced the abrasion up to appoint at which a crossover behavior is located at nearly 25 number of presses then meeting once again after pressing 45 times.

CONCLUSIONS

Based on this study, the following conclusions can be drawn:

1. The fabricated polymeric dies have been experimentally proven to be effective in sheet metal forming, including high freedom of design modification, low manufacturing costs and low processing time.

2. Reinforcing epoxy with aluminum oxide nanoparticles with no paraffin content has a deterioration effect upon yield compressive strength.

3. Adding paraffin oil to the reinforced epoxy can increase gradually the yield compressive strength.

4. Adding paraffin reduces the wear located at the corners of punches, the lowest deformation (2.7 mm) was observed for epoxy filled by paraffin oil.

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