A study on erosion wear performance of Linz-Donawitz sludge filled polypropylene matrix composites

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Abstract. Linz-Donawitz Sludge (LDS) are the fine solid particles recovered after wet cleaning of the gas emerging from LD converters during steel making. The present work includes processing of polypropylene composites filled with different proportions of LDS by compression moulding technique. Solid particle erosion wear trials are performed under different test conditions as per ASTM G 76 following a design of experiment approach based on Taguchi’s Orthogonal Arrays. This parametric analysis reveals that the filler content and the impact velocity are the most significant factors affecting the erosion wear characteristics of these composites.

1. Introduction
Nowadays, composites reinforced with industrial wastes such as blast furnace slag, LD slag, red mud etc. have captured the attention of many important manufacturing sectors such as the construction, automotive and packaging industries due to their light weight and low cost. Recently Pati et al. [1] studied that plasma sprayed LD slag coatings can replace most widely used metallic filler reinforced composites in many applications such as erosion wear. They also observed LD slag as a potential filler in polypropylene based composites with high stiffness-to-weight and strength-to-weight ratios and potentially high resistance to environmental degradation. Padhi et al. [2] studied the tribo-performance analysis of blast furnace slag filled polymer composites and they indicated that these composites, in general, may be suggested in applications like nozzles and diffusers, partition boards, exhaust fan blades, light weight vehicles, low cost building materials etc. Bhat et al. [3] had taken up a research work with an objective to explore the use of red mud as a reinforcing material in the polymer matrix as a low cost option. Yallew et al. [4] studied the sliding wear properties of jute fabric reinforced polypropylene composites. However, only few studies have been done on the tribological behavior of industrial wastes reinforced polymer composites and to the knowledge of the authors, no published paper is available on the study of erosion wear performance of Linz-Donawitz sludge (LDS) filled polypropylene matrix composite. So, the objective of the present research is to investigate the response of the LD sludge reinforcement to the solid particle erosion wear characteristic of the resulting composites.

Increasing applications of polymeric composites for various mechanical parts including gears, wheels, clutches, bush bearing and artificial prosthetic joints require adequate knowledge of their tribological properties, which are different from much better understood tribological properties of metals and ceramics. LD sludge reinforced polymer composite components can be applied in many situations for tribological loading conditions, because the hardness of the components increases with...
increase in LDS content. This increase in hardness is due to the high percentage of FeO in LDS as reported by Das et al. [5]. Work is now in progress to improve the composite’s hardness, strength and wear, since 90% failure in mechanical parts are as a result of tribological loading [6-9].

LD sludge is a by-product of the iron and steel-making industry. In this work, the LDS is collected from Rourkela steel plant (RSP) which uses the LD converter steelmaking process (or basic oxygen furnace steel making process) and, in consequence, produces large quantities of LD sludge. The LDS used in this work is collected in lump form and then crushed and sieved to obtain a particle size of less than 100µm before its application. FeO (79.58%), Fe₃O₅ (2.79%) and CaO (8.9%) are found to be the main components of the LD sludge along with small quantity of P, Al₂O₃, SiO₂, MgO and MnO. At steel plants, the high moisture content of the LD sludge (30–35%) is a significant barrier in its recycling to the sinter plant. It becomes sticky and forms agglomerates after long exposure to the atmosphere. Therefore, LD sludge has to be optimally dried before recycling.

The present work includes the processing and wear characterization of LD sludge filled polypropylene with an objective to find ways to use these locally available inexpensive industrial wastes as an alternate for highly expensive reinforcements for numerous applications.

2. Experimental details

2.1. Composite fabrication

The Linz-Donawitz sludge collected in lump form is first dried in an oven at 110°C and then crushed and sieved to obtain a particle size of 80–100 µm. Compression molding machine is used for fabricating Polypropylene (PP) based composites samples. Rheomix 600 batch mixer is used to melt and mix PP and fillers. The mixing is done as per ASTM standard D-2538. As the mixing is over, the material is taken out from the chamber and it is kept in a hot air oven for about two hours. It is then taken for compression molding. Materials are kept in die which is used to make a composite sheet of thickness 5 mm and area 180 × 180 mm². Compression molding is done as per ASTM D-256 standard. Composites of five different compositions are fabricated. The compositions of various samples prepared for present work with their designation is shown in Table 1.

Table 1. Designation and detailed composition of the composites.

| Designation | Compositions                     |
|------------|---------------------------------|
| S₁         | Neat Polypropylene               |
| S₂         | Polypropylene + 5 wt.% LDS       |
| S₃         | Polypropylene + 10 wt.% LDS      |
| S₄         | Polypropylene + 15 wt.% LDS      |
| S₅         | Polypropylene + 20 wt.% LDS      |

2.2. Erosion wear test

Solid particle erosion tests are carried out in air jet erosion set up to examine the erosion rate of the fabricated composites. The particle feeder is so adjusted that the mass flow rate of erodent is 3 g/min. Before conducting the test, the average velocity of the erodent coming out of the nozzle is measured using the standard double disc method [10]. These accelerated particles having substantial momentum and kinetic energy impact on the specimen, which can be held at various angles. Square samples of size 20 mm × 20 mm with 5 mm thickness are employed for erosion tests. All control parameters such as impact velocity, impingement angle, erodent size, erodent temperature and filler content are set before starting the test. These accelerated particles impact the specimen, which can be held at various angles with respect to the impacting particles using an adjustable sample holder. In the present study silica sand is used as erodent. Erodent size was measured using a LASER Particle Size Analyzer of Malvern Instrument make. The solid particle erosion test rig used in this work is equipped with an electric heating element in the erodent chamber and also with a temperature regulator using which the erodent temperature at five different values are maintained. Scanning electron micrograph of the silica
sand is shown in Figure 2 (a). During these experiments, initial and final weights of the specimens are measured. The specimens are weighted both before and after the tests to an accuracy of ±0.01 mg in precision balance. The conditions under which the erosion tests were carried out are listed in Table 3.

2.3. Experimental design
The Taguchi method is a commonly adopted approach for optimizing design parameters. Since experimental procedures are generally expensive and time consuming, the need to satisfy the design objectives with the least number of tests is clearly an important requirement. For the elaboration of experiments plan the method of Taguchi for five factors each at five levels is used. Table 2 shows the five levels taken by each factors. The signal to noise (S/N) ratio for minimum wear rate can be expressed as ‘smaller is the better’ characteristic and can be calculated as the logarithmic transformation of the loss function as shown below:

\[
\frac{S}{N} = -10 \log \frac{1}{n} \sum y^2
\]

where, y is the observed data and n is the number of observations. For minimization of wear rate, with the above S/N ratio, ‘Lower is better’ characteristic is suitable.

Table 2. Control factors and their selected levels of dry sliding wear.

| Control Factor          | Level | Units |
|-------------------------|-------|-------|
| A: Impact velocity      | 1     | m/sec |
| B: Impingement angle    | 2     | degree|
| C: Filler content       | 3     | wt.%  |
| D: Erodent size         | 4     | μm    |
| E: Erodent temperature  | 5     | °C    |

3. Results and discussion
The test output is erosion rate (E_r) and their corresponding S/N ratios obtained by Taguchi L_{25} orthogonal array for all the 25 experiments are presented in Table 3. From the S/N ratio output, it is observed that among all the five factors considered for the analysis, the erosion rate is mostly affected by the LDS content in the polypropylene composite followed by the impact velocity, impingement angle, erodent size and erodent temperature (Table 4). The analysis shows that at impact velocity (A) of 32 m/s, impingement angle (B) of 60 degree, LDS content (C) of 20 wt. %, erodent size (D) of 250 μm and erodent temperature (E) of 60 °C, the erosion rate is minimum as evident from Figure 1.

Table 3. Experimental design using L_{25} orthogonal array and the wear test results for PP-LDS composites.

| Test Run | A  | B  | C  | D  | E  | E_r | S/N Ratio   |
|----------|----|----|----|----|----|-----|-------------|
| 1        | 32 | 30 | 0  | 50 | 50 | 30  | 64.697 -36.2177 |
| 2        | 32 | 45 | 5  | 100| 40 | 30  | 45.910 -33.2381 |
| 3        | 32 | 60 | 10 | 150| 50 | 30  | 40.944 -32.2438 |
| 4        | 32 | 75 | 15 | 200| 60 | 30  | 35.143 -30.9168 |
| 5        | 32 | 90 | 20 | 250| 70 | 30  | 30.305 -29.6303 |
| 6        | 40 | 30 | 5  | 150| 60 | 30  | 53.583 -34.5805 |
Figure 1. Effect of control factors on erosion rate of Polypropylene-LDS composites.

Table 4. Response table for minimum erosion rate of PP-LDS composites.

| Level | A      | B      | C      | D      | E      |
|-------|--------|--------|--------|--------|--------|
| 1     | -32.45 | -34.88 | -36.82 | -34.21 | -34.28 |
| 2     | -33.45 | -34.14 | -34.64 | -34.26 | -34.15 |
| 3     | -34.20 | -33.70 | -34.25 | -34.21 | -34.23 |
| 4     | -34.94 | -33.75 | -33.20 | -34.06 | -33.95 |
| 5     | -35.57 | -34.15 | -31.71 | -33.87 | -34.01 |
| Delta | 3.12   | 1.18   | 5.12   | 0.39   | 0.32   |
| Rank  | 2      | 3      | 1      | 4      | 5      |
The morphology of the worn surface of polypropylene composite with 10 wt. % LDS with an impingement angle of 90 degree is illustrated in Figure 2 (b). It shows the formation of small craters due to penetration of hard sand particles onto the surface causing material removal mostly from the softer matrix phase.

4. Conclusions
- LDS which is an industrial waste can be gainfully used as a potential filler material in polypropylene matrix composites.
- Solid particle erosion wear characteristics of these composites can be successfully analyzed using Taguchi experimental design scheme.
- The effects of filler content and impact velocity on the wear rate are more compared to other control factors.
- LD sludge is found to possess good filler characteristics as it improves the erosion wear resistance of the neat polypropylene.

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