

# Sustainable Solution to Low-Cost Alternative Abrasive From Electric Ceramic Insulator Waste For Use in Abrasive Water Jet Machining

Sabarinathan Palaniyappan (✉ [sabarinathan14010@mech.ssn.edu.in](mailto:sabarinathan14010@mech.ssn.edu.in))

Sri Sivasubramaniya Nadar College of Engineering <https://orcid.org/0000-0001-7142-9275>

**Annamalai Veiravan**

Sri Sivasubramaniya Nadar College of Engineering

**Rajkumar Kaliyamoorthy**

Sri Sivasubramaniya Nadar College of Engineering

**Vishal Kumar**

Sri Sivasubramaniya Nadar College of Engineering

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## Research Article

**Keywords:** Ceramic waste, Abrasive machining, Sustainable recycling, Economy, Reprocessing

**Posted Date:** July 6th, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-606563/v1>

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**Version of Record:** A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on March 28th, 2022. See the published version at <https://doi.org/10.1007/s00170-022-09077-4>.

# Abstract

Increasing demand and resource overuse has prompted the exploration of spent secondary materials as a primary raw material for a variety of applications, leading to a more sustainable environment. Spent electric grid ceramic insulator, one of the waste materials of ceramic industry has a good hardness and strength. It can be reused as value added material in Abrasive Water Jet Machining (AWJM) industry. This present work deals with conversion of electric insulator rejects (EIR) into a cost-effective replacement material for abrasive water jet machining process. Mechanical crushing method is opted to generate the abrasive grit for the machining process. Grit generation pattern and the friability of the electric insulator rejects were determined experimentally. The results indicate that the friability of the processed electric insulator rejects is comparable with the commercially available garnet abrasive. Geometric parameters such as sphericity, elongation ratio, and shape factor for the processed electric insulator rejects were studied using scanning electron microscopy. The machining performance indicators for standard aluminium material such as volume of material removal, kerf angle, surface roughness and cutting width were measured for electric insulator rejects and compared with existing garnet abrasive grain. The experimental results of newly generated electric insulator reject abrasive were matched with performance indicators of the garnet abrasive. The observed deviation was lower proving that it can be used as alternative abrasive in the abrasive jet machining process. Cost analysis and recycling ability predict the economical usability of the newly generated abrasives.

## 1 Introduction

Nowadays, solid waste is the major problem for the developing and developed countries [1]. European union itself generates 924 million tons of solid waste every year, out of which, 35% comprises of only building construction and sanitary wares [2]. These wastes are disposed of immediately, resulting in massive landfill fields that are a burden to countries in many ways. Researchers are doing elaborate research to reduce the construction and demolition waste, but the issue of increasing waste leads to natural disasters [3].

Sanitary wares such as toilet bowls, wash basins, urinals, and bathtubs are used on a regular basis by humans. This is due to their affordability, glossiness, and aversion towards chemicals [4]. Even though they are suitable for remote future, their retirement cannot be an option. This may be due to wavering market-fit, and low maintenance as they are predominantly used for household purposes. After primary use, improper disposal of sanitary wares causes a slew of environmental issues, including clogged drains and animal damage. Generally, industrial recycling programs do not care about ceramics because it is a tedious process. The option of transportation and segregation of this solid waste is unsuitable due to extra cost. Instead, the residues can be crushed with crushers and used for any enhanced services resulting in reduced costs. Utilization of these crushed remains a fruitful choice in terms of saving energy and resources, eventually leading to a better living environment. Some researchers attempted to reuse sanitary waste of coarse [5] and fine [6] aggregate in concrete production, as well as particulate

reinforcement in polymer composites [7]. However, the use of sanitary ware in industrial applications has not ended and continues in other core manufacturing industries.

In the aerospace industry, the AWJM process is widely used in the machining of Carbon Fibre Reinforced Plastic (CFRP) composites which are used in the manufacturing of airframes of the fuselage and wings. This technique is equipped by leading aircraft manufacturers in the world viz. Airbus and Boeing [8]. Garnet sand generally is preferred over silica sand in AWJM application because of its ease of crushing and required sharp edges. Nevertheless, it has some short comings viz. presence of ilmenite and chloride compounds, availability in different sizes and hike in price [9]. Therefore, experts have gained interest for a finer substitute or supplementary constituent along with the garnet for improvised machining. This proxy can sensibly bridge the gap of demand and supply. In the Abrasive water jet machining process, [10] repurposed granite waste as an abrasive grain. This study compared the cutting results of reused granite abrasive grain to that of fresh garnet abrasive grain. According to this study, using granite particles as an abrasive grain alternative to the AWJM method is a safer option. Following that, Aydin et al. [11] examined the AJM cutting characteristics of garnet, emery, glass bead and white alumina abrasive grains on marble work content. According to the researchers, fused alumina and silicon carbide have a greater cutting penetration than the standard abrasives. This is due to the abrasive grains' different solidities, which serve as a regulating factor. Percec et al. [12] reviewed the recycling and cutting performance of different corundum abrasives for AWJM process was studied. Corundum abrasive demonstrates promising recycling and efficiency of cut for difficult-to-machine materials. Similarly, several researchers have attempted to replace garnet in abrasive water jet applications, as seen in Table 1.

Table 1  
Research works on replacement of garnet abrasive with other abrasive.

Sl. No	Operation	Work material	Type of Abrasive	Source
1	Drilling	SS304	Alumina, silicon carbide, and garnet with various mixing ratio	[13]
2	Cutting	Marble and aluminium	Recycled alumina	[14]
3	Cutting	Aluminium 6061 alloy	Garnet, alumina, and silicon carbide	[15]
4	Polishing	Aluminium 7075 alloy	Thermoset amino plastic abrasive	[16]
5	Cutting	Aluminum alloy (Al6063) composite	Alumina and garnet	[17]
6	Cutting	Ceramics	Green silicon carbide	[18]
7	Cutting	Aluminium and SiC reinforced aluminium composite	Garnet and silicon carbide	[19]
8	Cutting	Al7075, composite, glass, and marble	Colemanite powder	[20]
9	Cutting	Polycrystalline diamond	Alumina and silicon carbide	[21]
10	Cutting	Glass	Garnet, alumina, and silicon carbide	[22]
11	Cutting	Aluminium	Recycled garnet	[23]
12	Cutting	Aluminium	Recycled electric grid insulator rejects	Present study, 2021

In line with previous literature reports, the current research is towards the search of replacement material for the garnet in the abrasive water jet machining process. In that regard, the report will concentrate about the use of electric grid insulator rejects in the AWJM process, which would be a feasible idea in this current fluctuating trend. Electric grid insulators are a form of sanitary ware that are in high demand due to the growth of power grid sectors. The energy spent for the production of electric insulator ceramic in various stages is high, with both the glazing and sintering stage being the most energy intensive. This is shown in Fig. 1. Most of the time, after it has served its primary function, this material is called waste. The target of this work is to recycle the energy-intensive material as a value-added material such as abrasive. In terms of energy and economics, the energy spent in mining garnet from mines is greater than the energy spent in crushing electrical insulator waste. The prime motto of this research focuses mainly on electric insulator rejects as an alternative abrasive material for the machining of aluminium material, and the performance, economy, and reusing capability were experimentally measured.

## 2 Materials And Methods

The source for the electric insulator rejects (EIR) were Sri Venkateshwara minerals, India. After getting the rejects, the rejects were hammered and then crushed continuously using the jaw crusher. Further, the wrinkled fragments were separated into various sizes using sieve shaker. Among that, abrasive grit with the size of 80 mesh was separated and then used as an alternative abrasive in AWJM process. For the comparative study, the standard 80 grit garnet abrasive grains were used in the AWJM application.

Optical microscope and Scanning Electron Microscope were used to analyse the morphological features of the reprocessed EIR abrasive grain. The physical properties of the reprocessed and regular grains, such as specific gravity and bulk density, were determined using the gravimetric method. Friability testing measures the toughness of the abrasive grain. Since Hardness and toughness dictate the life of the abrasive grain, measuring the toughness of the grain is mandatory. The friability experiment was carried out in a standard ball mill equipment, as per UAMA B74.8 standard [24].

The geometrical and relative parameters of the garnet and EIR abrasive particles are illustrated in Fig. 2. The relative and geometric dimensions are measured from the captured SEM images of single garnet and EIR grit. The relative dimensions such as elongation ratio is a measure of relative proportion length of the particles with the breadth of respective grit, and the elongation ratio ( $r_E$ ) is mentioned by Eq. 1,

$$r_E = \frac{l_p}{b_p}$$

1

Where  $l_p$  and  $b_p$  length and breadth of the respective particle in  $\mu\text{m}$ .

The geometrical parameters such as shape factor and sphericity represent the particle shape. The sphericity and shape factor of the particle are defined by equations 2 and 3,

$$S_p = \frac{\sqrt{\frac{4}{\pi} \cdot l_p \cdot b_p}}{d_{max}}$$

2

$$F_{shape} = \frac{d_{min}}{d_{max}}$$

3

Where  $d_{max}$  and  $d_{min}$  represent maximum and minimum diameter of the particle in  $\mu\text{m}$ .

The workpiece used for this study is standard Aluminium 6061 alloy and it was purchased from Perfect Metal Works, India. The sample measured 150 mm in length, 150 mm in width, and 15 mm in thickness. The experimental performance and reusability efficiency of reprocessed electric insulator rejects were analysed in the computer controlled abrasive water jet machine (Make: OMAX abrasive water jet machine of model-1530). During the experiment, high-pressure water was passed through pump and various abrasives such as reprocessed electric insulator rejects and garnet were separately fed through the hopper. A nozzle with a diameter of 0.762 mm mixes the abrasives and water, which is then focused via the aluminium workpiece through a focussing tube with a diameter of 0.356 mm. To study the abrasive features of the reprocessed electric insulator rejects, the experimental parameters such as water pressure, stand-off- distance, abrasive flow rate, and traverse rate were kept constant and the parameter ranges are 100 MPa, 4 mm, 100 mm/min, and 285 gm/min, respectively. The parameters for the cutting experiment were selected based on the previous studies [25]; Sabarinathan et al [14] focusing on metallic aluminium cutting. Both abrasive particles were used in the machining of aluminium sample, and the experiments were repeated three times for each cutting condition. The accuracy and variation of the experiment were analysed based on the repetition of the experiment.

Cutting performance of the reprocessed abrasive was compared with standard garnet abrasive by means of volume of material removal, machining time, cutting depth, kerf width and surface roughness of the machined aluminium workpiece. Cutting time was calculated using stopwatch and cutting depth was measured by using digital vernier calliper with accuracy of 0.01mm. The cut zone kerf width was assessed using a video measurement device (Make: VMS 2020). The cut down section's kerf width was measured at the entry and exit points, and the kerf angle was calculated using Eq. (4), as shown below.,

$$\text{Kerf taper angle} = \tan^{-1} \frac{(K_t - K_b)}{2t}$$

4

Where  $t$  is the aluminium sample thickness,  $K_t$  is the kerf top width, and  $K_b$  is the kerf bottom width, all in millimetres.

A non-contact style 3D surface roughness tester was used to measure the surface roughness of the cut down section. In the cut sections, the Talysurf Coherence-correlation interferometry and Talymap platinum software inbuilt algorithm was used to measure the surface roughness parameter such as maximum peak to valley roughness ( $R_z$ ) and average surface roughness ( $R_a$ ) parameter. Finally, using a scanning electron microscope, the surface profiles and cutting features of the machined surfaces were examined.

### 3 Results And Discussion

#### 3.1 Particle generation of crushed sanitary ware rejects

In general, abrasive grit used for the AWJM application was 80 mesh grit. The aim of the crushing process is to obtain higher yield of 80 grit particles from the crushing method. Hence, the experiment for crushing of electric insulator rejects were done with different jaw distance. After crushing process, the particles were generated with different grit sizes. The grit yield was calculated by standard weighing and sieve analysis method. The obtained results indicate that the larger jaw distance yields maximum amount of coarse grit particles. If the jaw distance is decreased, there is an increase in the grit yield of medium size grit particles. This is shown in Fig. 3 (a). In all the cases, the lowest jaw distance of 1mm produces the required grit size of 80 mesh particles. Smaller jaw distance increases the effective crushing load, creating more finer fraction. Likewise, a higher crushing load was preferred to get a higher yield of medium grit particles. Figure 3 (b) shows the number of pass required to obtain 80 grit particles during crushing of electric insulator rejects. The results show that as the number of crushing pass is increased, the number of particles produced in the 80 grit increases as well. Similar observation was made on ball mill crushing process of ceramic sanitary ware rejects by Cuhadaroglu and Kara [26].

### 3.2 Friability analysis of recovered electric insulator rejects

Friability analysis gives toughness and life of the abrasives of reprocessed (crushed electric insulator rejects) and standard garnet. Figure 4 depicts the friability results of standard garnet and EIR abrasives. The findings indicate that both abrasives have a similar crushing pattern. In case of EIR abrasive, the crushed down grains are mostly settled in the base pan. However, the garnet abrasive generates a greater number of fines as compared with the EIR abrasives. It means that EIR abrasive has less breakage than the garnet abrasive. Friability percentage of the standard garnet and electric insulator rejects were 29% and 33%. Since both particles have a close friability pattern, the newly generated EIR abrasive particles can be used as an alternative abrasive in AWJM applications.

### 3.3 Mechanical and geometric dimension of recycled abrasive particle

Table 2  
Geometric parameters and mechanical property of abrasive particles.

Parameters	Unit	Garnet	EIR particle
Density	g/cm <sup>3</sup>	4.03	2.64
Sphericity	S <sub>p</sub>	0.844	0.891
Shape factor	F <sub>s</sub>	0.734	0.712
Elongation ratio	r <sub>E</sub>	1.49	1.57
Hardness	Mohs scale	6.5–7.5	6

Table 2 presents the geometric parameter results of studied abrasive particles. The outcome demonstrates that, the elongation ratio of EIR abrasive particle is slightly higher than that of garnet. Likewise, the shape factor of the EIR abrasive particle is lower than the garnet abrasive. It is clear from both cases that the EIR particles are marginally sharper than the garnet abrasive, which is helpful for making indentation on work materials during AWJM process. The density and hardness of garnet were 4.03 g/cm<sup>3</sup> and 6.5 mohs scale. Comparatively, the EIR abrasive particle results in lower density and hardness value of 2.64 g/cm<sup>3</sup> and 6 Mohs scale. Sphericity of EIR particles was higher when compared with garnet abrasives. This indicates that EIR particles have a larger number of sharp edges as compared to garnet abrasive. Qu et al., [27] made a similar observation on the mineralogical properties of various abrasives such as garnet and silica sand on shale minerals.

### 3.4 Cutting feature analysis of standard garnet and EIR particles

Table 3  
Performance results of EIR abrasive with respect to garnet abrasive.

Performance parameters	Garnet	EIR particle	Efficiency
MRR (gm/min)	1.89	1.78	0.94
Cutting width (mm)	0.95	0.84	0.88
Cutting depth (mm)	14.22	12.25	0.86
Cutting wear zone depth (mm)	5.41	4.30	0.79
Kerf angle entry (degree)	5.21	6.74	1.29
Kerf angle exit (degree)	4.47	5.44	1.22
Cutting time (sec)	76.4	74.9	0.98

Table 3 compares the cutting performance of EIR abrasive to that of garnet abrasive particle. Material Removal Rate (MRR) measures the amount of material extracted from the machined surface during the cutting process. The result shows that the higher volume of material (1.89 gm/min) was recorded for garnet abrasive as compared to EIR abrasive. The reason is that garnet abrasive has a higher hardness and a high mass to volume ratio (density), which contributes to a high kinetic energy of the water beam. In present case, the volume of material removal for the EIR abrasive is slightly lower, but it can be matched with the commercially available garnet abrasive. Cosansu and Cogun [20] previously published a report on reusing colemanite powder as a substitute abrasive for garnet abrasive in the AWJM process.

Cutting width is a measure of the actual size of the cutting performed by the water jet coming out of the nozzle. According to Fig. 5, the cutting width of the aluminium sample with EIR abrasive was narrower. When EIR abrasive was used, the top and bottom width of the cut down part were less than 12%. Aydin et



al [10] reported a similar impact on cutting width reduction by using reclaimed granite abrasive as an alternate abrasive in the AWJM process. The experimental results indicate that the cutting width of an aluminium sample with EIR abrasive was close to the cutting width obtained with garnet abrasive.

Kerf geometry is an important parameter for determining the angle of the cutting of the cut down section. In the AWJM process, a cutting slot on work material is seen in two sections: top and bottom width. The top width is often more than the bottom width. According to the experimental findings, the kerf angle at entry and exit was greater for the EIR particle as an abrasive. This is because the EIR abrasive loses its cutting characteristic as well as water jet energy as the water jet penetrates in the thickness direction. When machining thicker samples, the standoff distance between the work and the nozzle increases. This increases the likelihood of obtaining a higher taper angle. As can be seen from the results, garnet abrasive was used to achieve the smaller kerf angle than the EIR abrasive. This is attributable to the garnet abrasive's higher hardness and heaviness. Several researchers made similar observations about the lower kerf angle on glass material with different abrasives such as silicon carbide, alumina and garnet [28][22].

The aim of measuring the cutting depth and time is to determine the maximum thickness cut and the time required for machining when deploying new abrasives. Cutting depth is a measurement of an abrasive's ability to penetrate deeper under constant cutting parameters. According to Table 3, the EIR abrasive has a maximum penetration depth of 12.25 in mm and the garnet abrasive has a maximum penetration depth of 14.22 in mm. Hardness and density are two properties that must be considered in order to achieve greater cutting depth. Axinte et al. [21] explained that the hardness of the abrasive determines the cutting wear zone depth and cutting depth when cutting work materials using an abrasive water jet machining method. In both cases, the EIR particle has a lower hardness and density, resulting in a lower cutting depth.

Cutting time for the EIR abrasive was estimated for a 100 mm length of 15 mm thick aluminium sample while keeping the cutting parameters constant. The results reveal that the EIR particle takes 2% longer time than the garnet abrasive. However, the current EIR abrasive will open up a new arena for alternate abrasives that satisfy all of the properties of the garnet abrasive. As a result, this current abrasive could be used to replace garnet AWJM processes.

### **3.5 Surface feature analysis of AWJM machined aluminium workpieces**

Surfaces produced by abrasive machining are divided into two zones: cutting and deformation wear zone. The cutting wear zone has a smooth surface texture, and the deformation zone has craters and valleys. In this study, Fig. 6 shows the surface characteristics such as maximum peak to valley roughness ( $R_z$ ) and average surface roughness ( $R_a$ ) were determined along the thickness direction. The experimental results show that, the highest  $R_a$  and  $R_z$  value of  $4.91\mu\text{m}$  and  $26.77\mu\text{m}$  was observed in the deformation wear zone with the EIW abrasive while machining of aluminium sample. The increased values are due to the abrasive jet's lack of kinetic energy and the water jet's deflection in that deformation

region, which results in uneven cutting of multiple sharp edges by EIR abrasive [29]. Alsoufi et al. [30] found a similar effect of increased surface roughness in the deformation zone on Carrara marble. Increased water pressure, on the other hand, increases the kinetic energy of the water beam, resulting in a smoother cutting operation. In all the cases, the surface roughness of the machined surface was fine at the entrance and became gradually rougher at the exit.

The material removal mechanisms for ductile aluminium material were abrasion and erosion in the cutting wear region, as well as ploughing and micro cutting in the deformation zone. SEM photographs were used to reflect the cutting function of the machined aluminium sample's cut part. Figure 7 (a, b) depicts a SEM image of the cutting wear region of an aluminium sample machined with EIR and garnet abrasives. Because of the ductile nature of the aluminium material, garnet and EIR abrasive grain were embedded in the cutting wear region, as seen in Fig. 7 (a, b). By performing elemental analysis on the respective region, the embodied particle is confirmed to be EIR and garnet abrasive. Many researchers observed the embodiment of garnet abrasive particles on machining surface when machining with ductile materials [31–33].

SEM representations of the cutting wear region of an aluminium sample machined with garnet and EIR abrasives are seen in Fig. 8 (a<sub>1</sub>, a<sub>2</sub>). In the cutting wear region, micro erosion and abrasion is clearly visible, resulting in the forming of a burr. Figure 8 (a<sub>2</sub>) shows that a comparatively larger proportion of burr was formed while machining with EIR abrasive, resulting in an increase in the surface roughness of the cutting wear region.

SEM images of the deformation zone of an aluminium sample machined with garnet and EIR abrasives are seen in Fig. 8 (b<sub>1</sub>, b<sub>2</sub>). Normally, the jet angle at the entrance is shallow and capable of easily penetrating without deflection. As the sample thickness increases, the jet becomes more diversified, resulting in deflection of the abrasive water jet and irregular machining in the form of craters and valleys in the deformation zone. When compared EIR abrasive to garnet, the EIR abrasive produces marginally higher cutting marks, resultant in a higher surface roughness in this region.

### **3.6 Recycling capability of EIR particle**

Reusability of abrasive is calculated in terms of number cycle by recycling EIR abrasive particles repeatedly in AWJM process. The abrasive grains were filtered from the collector tank after each cycle, and then abrasives were sieved. The grits retained at 80 grit sieves were reused in the next machining experiment run. The response of recycling capabilities was measured in terms of total quantity of grains that could be reused in the next cycle. Figure 9 depicts the relative size of EIR grain size represented in optical images after each cycle of operation. It is known that the abrasive efficiency was decreased with each number of consecutive cycles due to continuous size reduction caused by abrasive particle breakage, as compared to fresh abrasive. The first cycle retention quantity for reusing is estimated to be 76 %, the second cycle to be 35 % reused, and the third cycle to be less than 10% of the abrasives reused. This clearly shows that the recycling potential of EIR particles was good before the second cycle; after that, the abrasive's recycling potential is low. Similarly, Babu and Chetty [23] measured the retention

quantity for reusing and the number of recycles for garnet abrasive in AWJM application and found that retention quantity was 31 % in the 4th cycle. This finding leads to a comparison of the performance of EIR recyclability to garnet abrasive, which was found to be less than an order of magnitude.

### **3.7 Sustainable approach on economic aspects of using EIR particle as alternative abrasive**

The use of waste, such as electrical insulator rejects, as one of the primary raw materials for the AWJM application conserves resources. The performance of the EIR abrasive is competitive, and in some cases, it matches the performance of regularly used garnet abrasives. More crushing plants are now commercially available on the market, and they are capable of crushing ceramic waste from its original shape to the appropriate grit size. This will result in cleaner production and improved waste disposal. In terms of cost and environmental considerations, sustainable use of this kind of waste contributes wealth. The cost of electrical insulator waste per kg was approximately ₹27.47 including crushing and sieving cost, while the cost of garnet per kg was approximately ₹52.45. This clearly reveals that garnet consumes almost double the amount of expense as compared to EIR abrasive. It is concluded that the substitution of EIR in the AWJM process would undoubtedly increase the wealth of the abrasive machining industry while also providing greater environmental benefits.

## **4 Conclusion And Future Recommendations**

This paper reports that, ceramic industry waste can be sustainably reused as low-cost alternative abrasive material for the AWJM applications. The results are summarised below;

1. During crushing of Electric Insulator Rejects (EIR) abrasive particle, as the jaw distance decreases the yield of 80 grit increases until 1 mm of jaw distance.
2. Friability percentage of the standard garnet and electric insulator rejects were 29% and 33%. Both the particles show very close friability pattern. The geometrical results of produced electric insulator rejects particle shows higher elongation ratio and sphericity, when associated with garnet abrasive.
3. The cutting performance indicators such as material removal rate, surface roughness and kerf angle of the machined surface depict that, the reprocessed EIR abrasive does not possess superior results than the garnet abrasive. But the performance of EIR abrasive matches with the commercially available garnet abrasives.
4. Cost effectiveness for long operation is beneficial by using newly produced EIR abrasive. The cost of electric insulator waste per kg is around ₹27.47, compared to the cost of garnet which is ₹52.45 per kg. This shows that EIR abrasive recycling has a cost advantage.
5. The reusability of EIR abrasive for first, second and third cycle of cut were 76%, 35% and 10% respectively.

From the point of future recommendation, this kind of aluminosilicate minerals (EIR) can be reused for rough cutting and long run process for the machining of aluminium samples.

# Declarations

**Funding:** The project was supported with the Ministry of Mines, Government of India, New Delhi for funding support [Grant number- Met4-14/10/2019].

**Conflict of Interest:** The authors declare that they have no conflict of interest.

**Availability of data and material:** Not applicable.

**Code availability:** Not applicable.

**Ethics approval:** Not applicable.

**Consent to participate:** Not applicable.

**Consent for Publication:** Not applicable.

**Author contributions:** P. Sabarinathan - Conceptualization, Investigation, Writing- Review & Editing, K. Rajkumar- Resources, Supervision, & Validation, V.E. Annamalai - Data acquisition, Visualization, & Project administration, K. Vishal - Data acquisition and Validation.

## Acknowledgement:

Authors wish to thank the Ministry of Mines, Government of India, New Delhi for funding support [Grant number- Met4-14/10/2019].

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## Figures

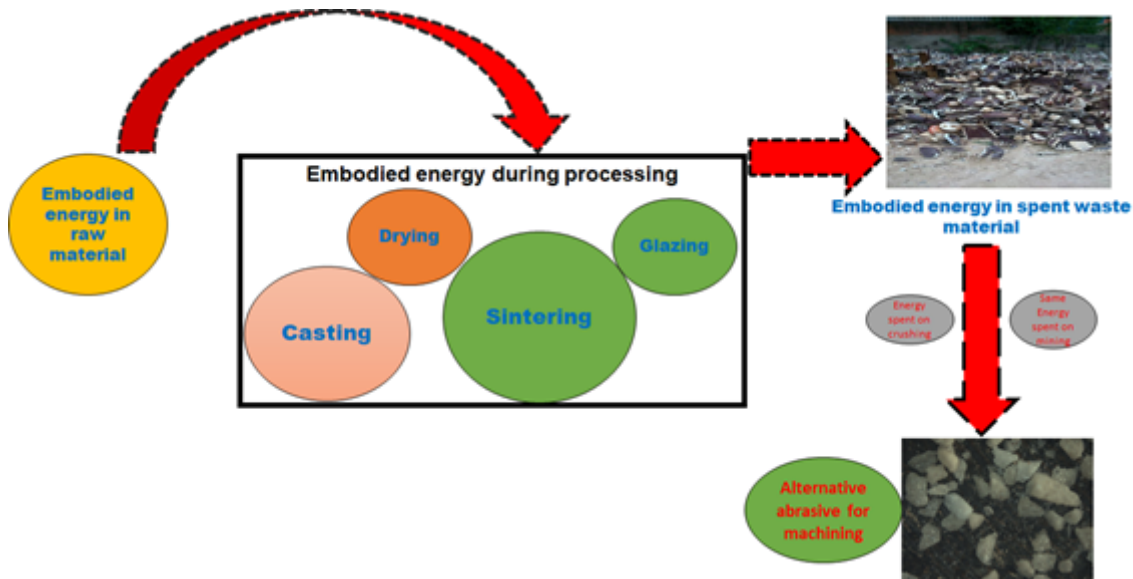


Figure 1

Energy embodiment chart of the spent ceramic waste

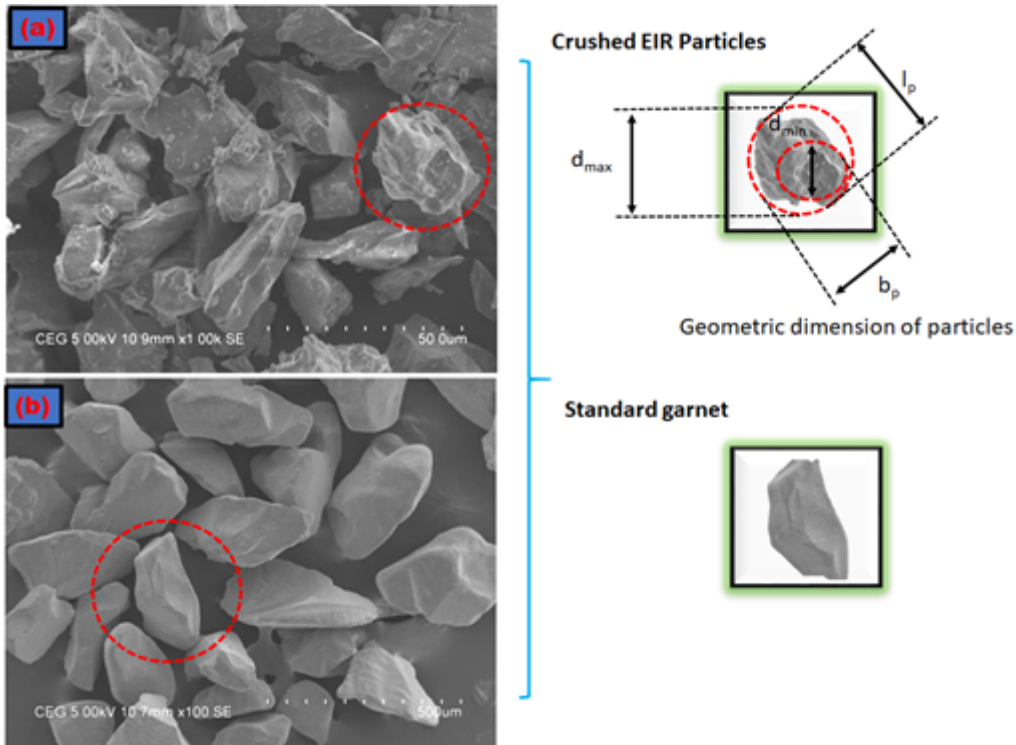


Figure 2

Geometric measurement of 80 mesh abrasive (a) EIR grit and (b) garnet.

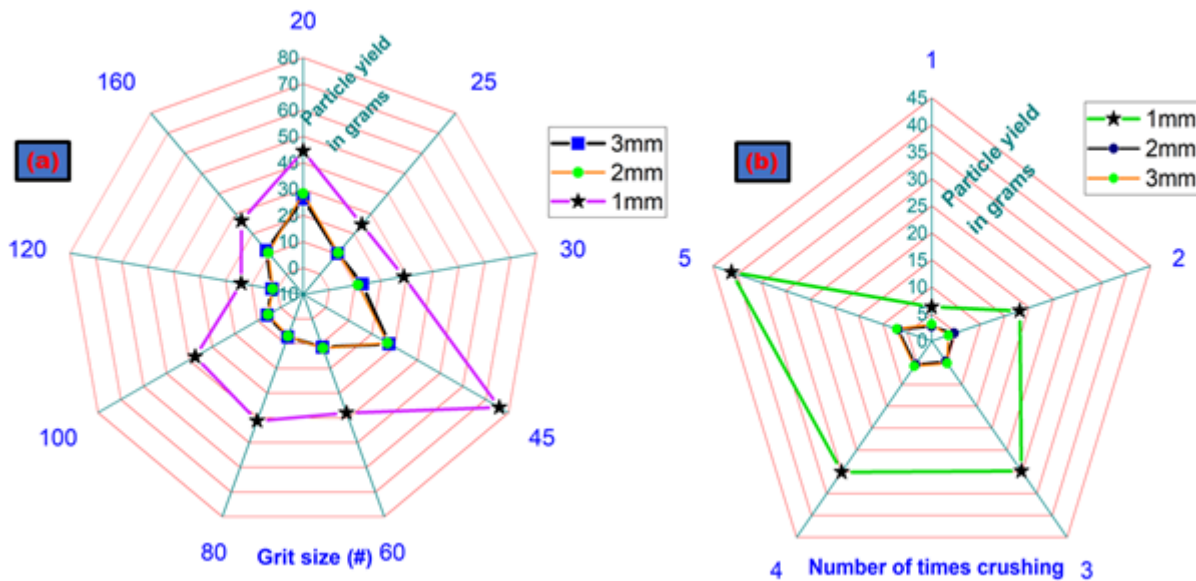


Figure 3

Crushing pattern of electric insulator rejects (a) grit sizes with varying jaw distance and (b) 80 grit yield with number of crushing pass

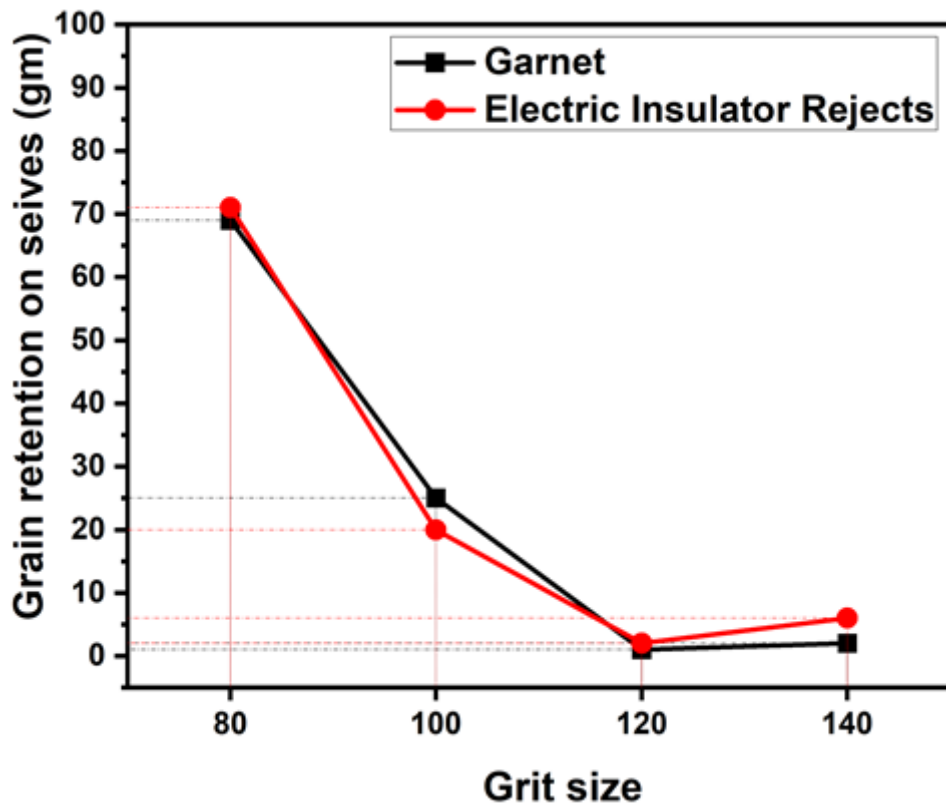


Figure 4

Friability pattern of new garnet and EIR particle



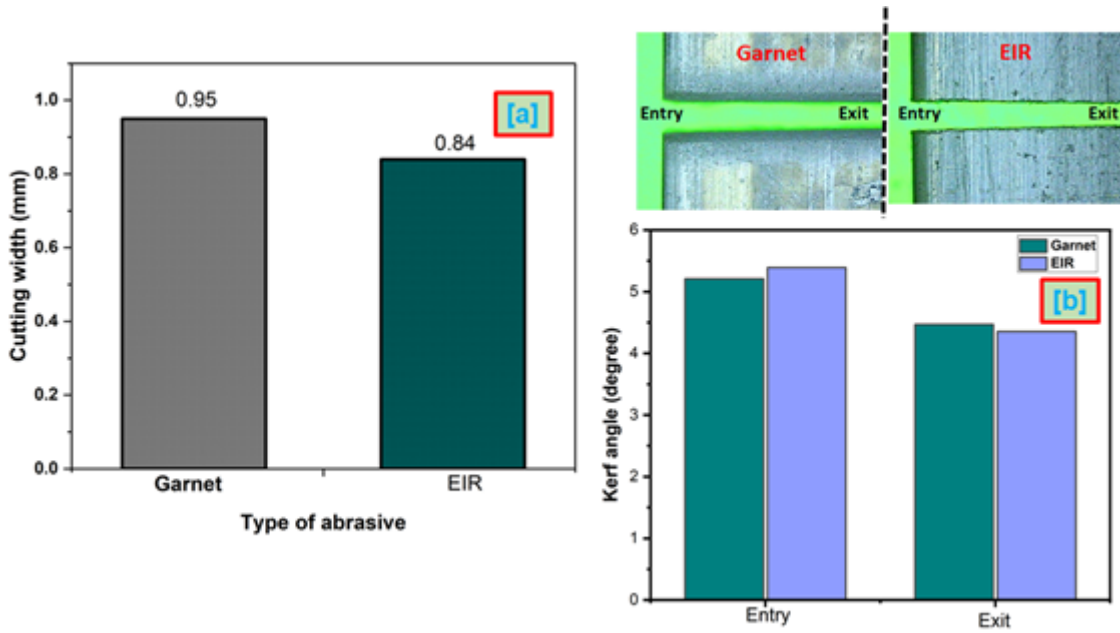


Figure 5

Performance results of machined surface (a) Cutting width and (b) Kerf angle

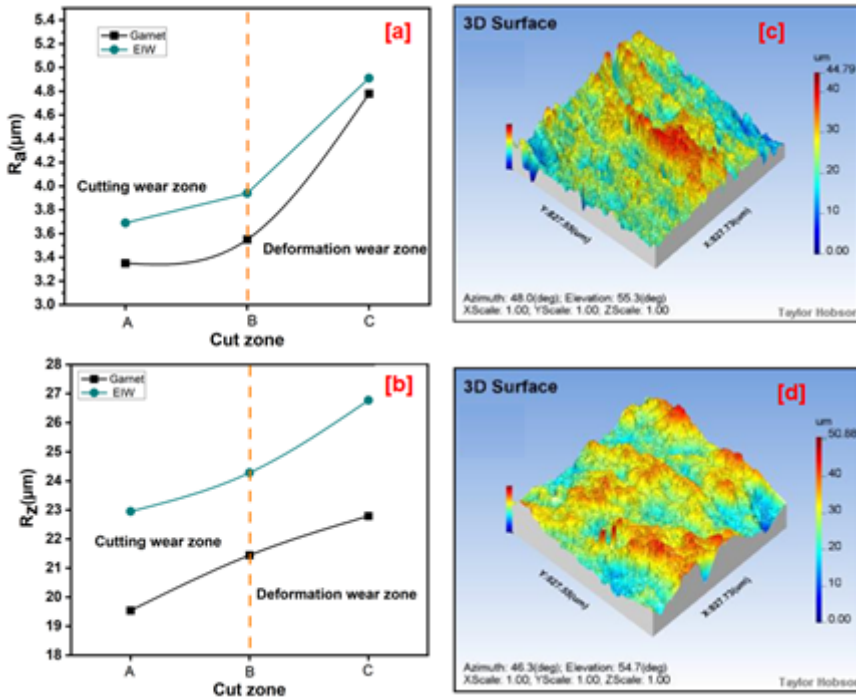


Figure 6

(a) Ra, (b) Rz values of two different abrasive machined surfaces, (c) 3D surface profile of the striation zone @ garnet and (d) striation zone @ EIR particle

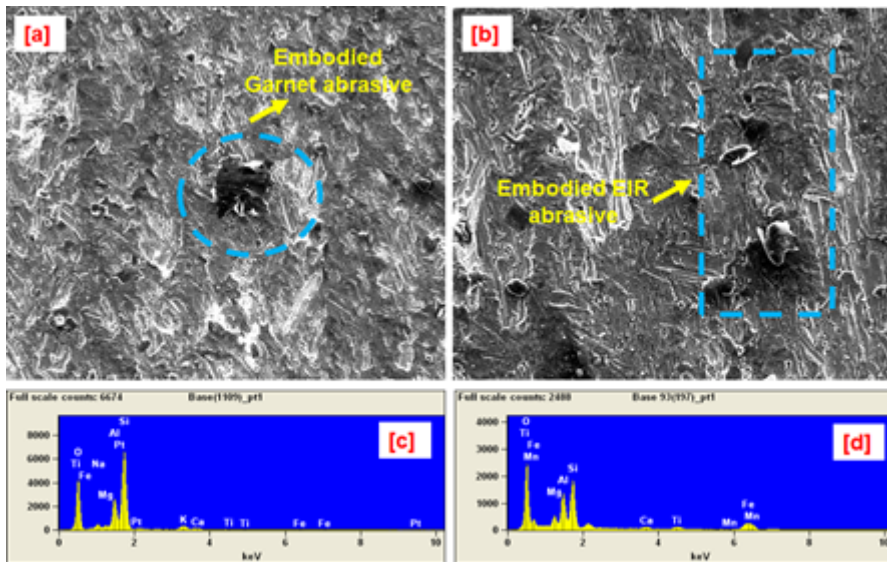


Figure 7

SEM images of cutting wear zone of machined aluminium surface (a) garnet, (b) EIR particle, (c) EDAX analysis of garnet and (d) EDAX analysis of EIR particle

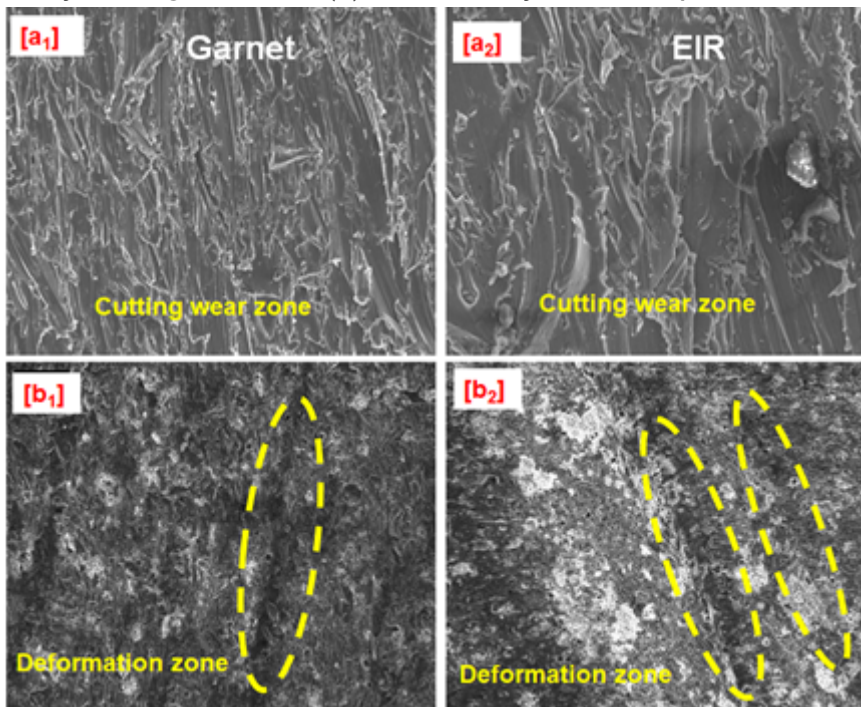
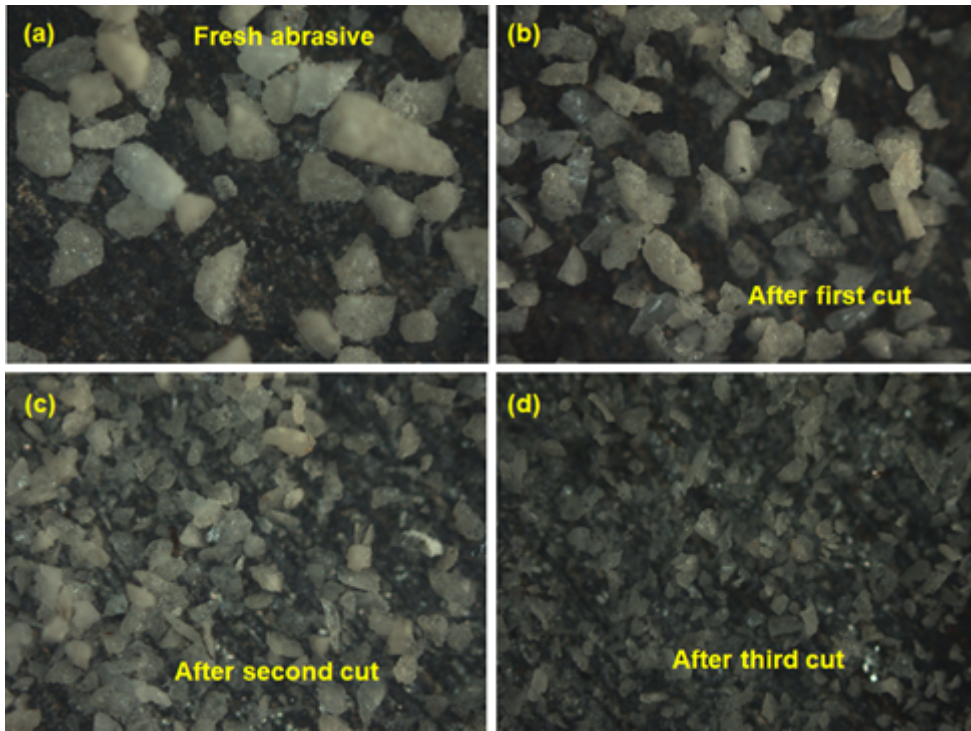


Figure 8

SEM image of machined aluminium sample (a1, a2) cutting wear zone of using garnet and EIR abrasives, (b1, b2) Deformation zone of garnet and EIR abrasives.



**Figure 9**

Recycling capability of EIR abrasive particle (a) fresh abrasive (b) recycled abrasive after first cycle (c) recycled abrasive after second cycle and (d) recycled abrasive after third cycle