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Fracture in self-lubricating inserts: A case study

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ABSTRACT

A case study is carried out to reveal the fracture mechanism of self-lubricating inserts. The insert is made up of 98.5 wt% Zirconia Toughened Alumina (ZTA) reinforced with 1.5 wt% CuO. The insert is fabricated through the powder metallurgy route, followed by the hot isostatic pressing (HIP) technique (for densification). After densification, the insert is shaped and sized according to ISO SNUN 120408. The workpiece material used for machining is AISI 4340 steel. A conventional NH-26 lathe is used for machining as well as for creating facture inside the insert. In this investigation, the machining operations are carried out till the failure of inserts does not take place. The fracture analysis suggested a synonymous fracture mechanism that occurs for brittle facture (facture without any deformation). The fracture analysis seen through FESEM images observed that the initiation of crack that happened without any dislocation movement results in chipping, cracking, and flaking on the surface. The crack is initialized due to the generation of high localized stresses. The stresses were developed due to the continuous movement of chips concentrated slightly away from the cutting edges. The developed stresses are relieved by creating small cracks beneath the surface. These cracks are propagated in the radial direction without any dislocation-induced plasticity. The mechanism is well confirmed through the FESEM images of fracture specimens.

Selection and peer-review under responsibility of the scientific committee of the Symposium on Failure and Preventive Maintenance of Machineries 2022.

1. Introduction

The application of ceramics components is growing day by day in various areas. So, the fracture behavior alongside the failure mechanism, inside the ceramics is indeed illustrated by its prolonged application. So, the research focused on the fracture mechanism in ceramics revealed many factors like microstructure, homogeneity, mechanical properties, thermal stresses, and resulting stress field were responsible for the fracture. In this context, Danzer et al. [1] rigorously reviewed many possible mechanisms, responsible for the failure in ceramic components. The article concluded with a general statement in which small flaws, create discontinuities inside the microstructure resulting in the formation of small cracks. The developed cracks are propagated in various directions without any relatively immobile and dislocation-induced plasticity. Another review carried out by Wiederhorn [2] on brittle fractures revealed that the formation of cracks was controlled by restricting the crack motion. The motion was stretching to a breaking point that co-relates with the microstructure present on the crack tip. Finally, the article suggested two phenomena i.e. crack tip deflection or crack tip shielding would be a possible way to prevent ceramic failure. Furthermore, many researchers dedicated their research to showing responsible mechanism behind the failure of any ceramic components was similar to brittle failure [3–6]. The nucleation of cracks, macro-cracking, fragmentation alongside growth, and collision of micro-cracks responsible for the failure of ceramics was also studied by many researchers [7–10]. It was also found the microstructure played a vital role in the micro-crack propagation path and micro-cracking for the overall failure of ceramics components. Hence, in this study, an endeavor has been made to elaborate on the failure mechanism that occurred inside the cutting insert (ceramics) due to localized stress developed during machining. The analysis also reveals the micro-crack generation along with its fragmentation and propagation. The phenomenon of failure mechanism was confirmed through the FESEM images taken at different magnifications. Finally, The FESEM images are correlated with the general fracture mechanism cited by earlier researchers.

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2. Preparation of powders and self-lubricating cutting inserts

The composition selected for the fabrication of a self-lubricating cutting insert was 98.5 wt% Zirconia Toughened Alumina (ZTA) doped with 1.5 wt% CuO. The ZTA comprises of 90 wt% Alumina mixed with 10 wt% yttria stabilized zirconia (YSZ). The selection of composition based on the earlier investigation by Singh et al. [11–13] provides efficient lubrication with said composition. The preparation of powder was started with rigorous stirring of 1.5 wt% CuO in alcoholic media, further mixed with ZTA to get the required composite. After mixing the mixture of ZTA/ CuO was put inside a planetary mill (Fritsch, Germany) in an organic media for proper mixing using alumina balls (8–12 mm diameter). After proper mixing, the slurry was placed in an oven for 24 h followed by crushing and calcination at 850 °C. After calcination, the developed composite was mixed with a 5 % PVA solution for proper granulations. The granules of composites were filled inside circular graphite die placed in a hot isostatic pressing furnace. The HIP technique was used to densify the component at a temperature of 1500 °C for 15 min as a soaking time. After densification, the circular specimens were shaped into cutting inserts by obeying ISO SNUN 120408 through a tailor-made jig fixture arrangement using diamond wheels. After getting the proper shape and size the inserts were polished with different mesh sizes of silicon powder followed by diamond paste on bain polishers. After polishing, a flat angle of 20 deg and bevelling (width of 0.2 mm) were provided on each edge of cutting inserts to strengthen the edges. The fabrication process of inserts as well as selection of workpieces was elaborately explained in the earlier research carried out by Singh et al. [14–16].

3. Experimental details

The microstructure along with elements of the developed composites was investigated through Field emission scanning electron microscope (FESEM) (Make: CARL-ZEISS-SMT-LTD, Germany, Model: SUPRA 40) and X-ray diffractometry (XRD) in the range of 20° and 70°. After microstructural analysis, the developed insert was placed on a conventional N-26 lathe for machining of AISI 4340 steel. The pictorial representation of the N-26 lathe along with the self-lubricating insert is shown in Fig. 1. The machining parameter selected according to author earlier work that provide optimum machining condition as cutting speed = 300 m/min, feed rate = 0.16 mm/rev, depth of cut = 0.5 mm. The machining operations were carried out till the insert was fractured. After failure, the analysis on the fracture mechanism was investigated through FESEM images.

4. Result and discussion

The investigation starts with the analysis of microstructure for developed composites after densification. The FESEM image of the same is shown in Fig. 2 (a) & (b). The images were taken at the same magnification for comparison. The comparative study clearly illustrated that the grain sizes of developed composites are enhanced by doping CuO.

The presence of CuO inside the composites was analyzed through XRD. The phase analysis carried out by the XRD plot, shown in Fig. 3 reveals the presence of CuO inside the composite.

5. Self-Lubricating phenomenon

The pioneer work on the self-lubricating mechanism was carried out by Alexeyev and Jahanmir [17–18]. The analysis of the researchers revealed that when a soft particle present inside the hard matrix it act as a second phase. During sliding action or application of load the said soft particles are accumulated at the interface, assisted by squeezing action. These soft particles have low shear strength and easily transformed into thin layer due to smearing action. The formed thin layer is responsible for providing lubrication between two sliding surfaces, also known as patchy layer. Therefore, the formation of thin layer between the surface due to squeezing and smearing action is called as self lubricating phenomenon. The pictorial representation of same is shown in Fig. 4 (a), (b), (c) & (d). Fig. 4 (a) & (b) represents the accumulation of softer particle at the interface due to application of load i.e. squeezing action. Fig. 4 (c) & (d) represent the formation of thin layer due to smearing action.

After a micro-structural investigation, the failure analysis of the cutting insert was carried out through FESEM images. The failure that occurred in the tool is shown in Fig. 5. From Figure, the gradual wear has been observed due to continuous flow of chip on the rake face. It is also noticed that the breakage occurred without any relatively immobile or dislocation of grain confirming a brittle breakage. The fracture analysis also reveals that the chipping, cracking, and flaking, takes place due to the generation of microcrack resulting from localized stress created at a significant distance from the cutting edge. The stress is generated due to the continuous flow of chips on the inserts after removal from the workpiece.

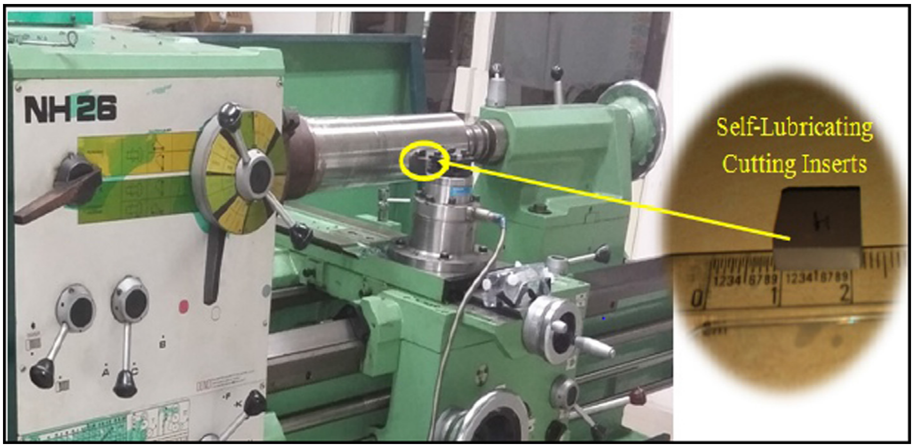

Fig. 1. N-26 Lathe and self-lubricating cutting insert.

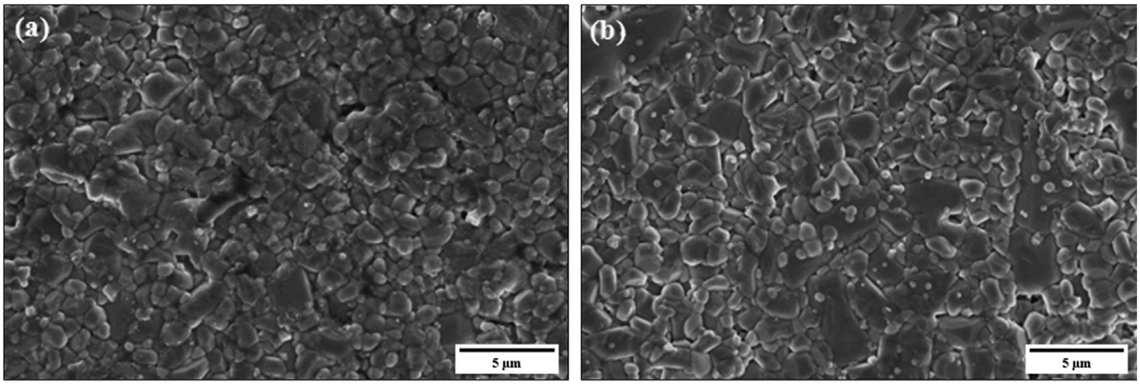

Fig. 2. (a) FESEM image of ZTA (b) FESEM image of ZTA/CuO.

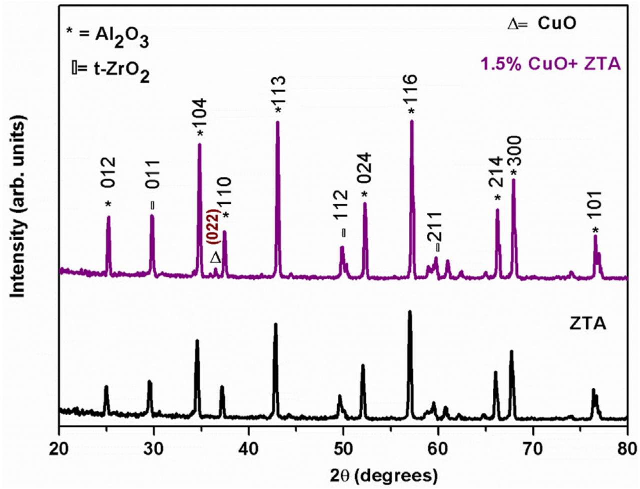

Fig. 3. XRD plot of ZTA and CuO reinforced ZTA.

The said mechanism was earlier modelled and demonstrated by Kumar et al. (2018) [19] & Evans et al. [20]. The model of fracture mechanism is pictorially represented in Fig. 6 (a) & (f). Researchers found that the major factor responsible for crack initiation and propagation is applied load and material properties. Evans et al. (1978) illustrated that the localized stress develops at the surface is relived by generating minor cracks and these cracks are developed in opposite side of applied load shown in Fig. 6 (a) to (c). But when the load is removed the developed primary crack closes (crack closure) resulting in a radial flow of micro-cracks in a different direction. A similar phenomenon is shown in Fig. 6 (d) to (f). This mechanism is exclusively for brittle material and confirm through the FESEM images postulated above in Fig. 4 for the failure of ceramic materials obeys brittle fracture. Hence, it can be concluded that the localized stresses generate micro-cracks beneath the surface responsible for the radial propagation of cracks in different directions. The propagation of cracks in the radial direction is responsible for chipping, cracking, and flaking turns into the failure of cutting inserts

6. Conclusion & scope

A homogeneous composite of ZTA/CuO was prepared using the powder metallurgy route, and densify through the HIP technique. The solid circular specimens were shaped and sized according to ISO SNUN 120408 insert for machining of AISI 4340 steel. The fracture mechanism of the inserts was thoroughly investigated after the failure occurred inside the inserts. The failure mechanism obeys brittle breakage like chipping, cracking, and flaking due to the generation of micro crack resulting from localized stress created at a significant distance from the cutting edge. The mechanism is confirmed through the FESEM images that describe the generation and radial propagation of cracks in a different direction. It was found that due to continuous flow of chip a localised stresses are developed beneath the rake surface away from cutting edges. This localised stresses creates small micro-cracks beneath the surface. The propagation of such cracks causes the chipping of large bulk material from the surface without any deformation, which is responsible for failure of the insert.

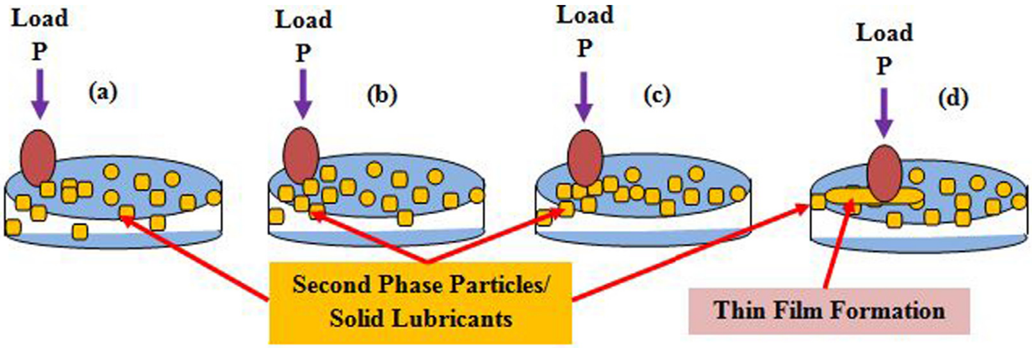

Fig. 4. Systematic representation of self-lubricating mechanism.

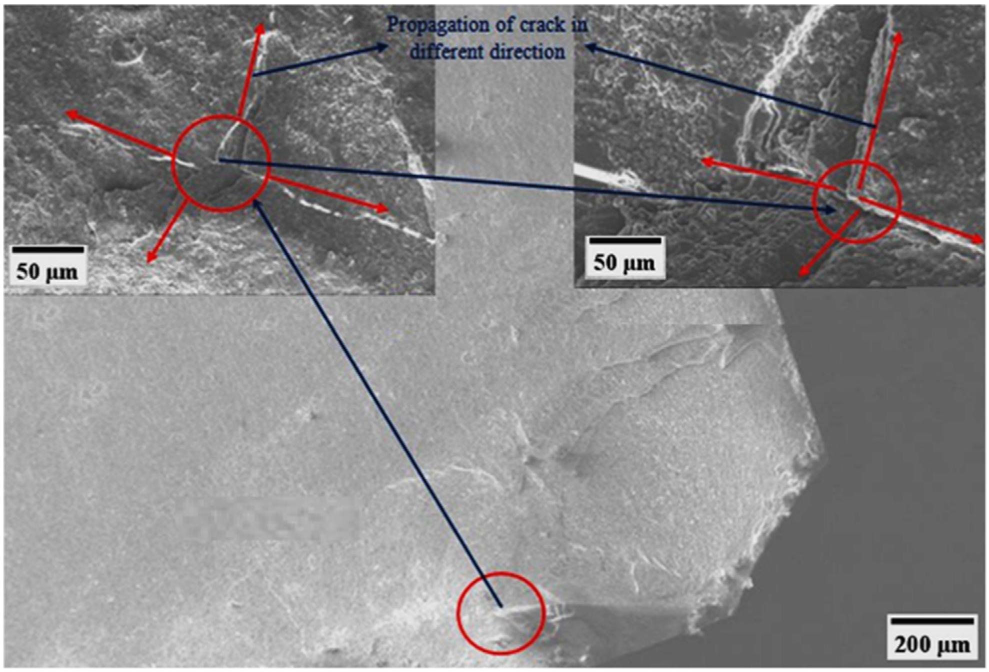

Fig. 5. Failure of cutting inserts due to high stress developed during a long time of machining.

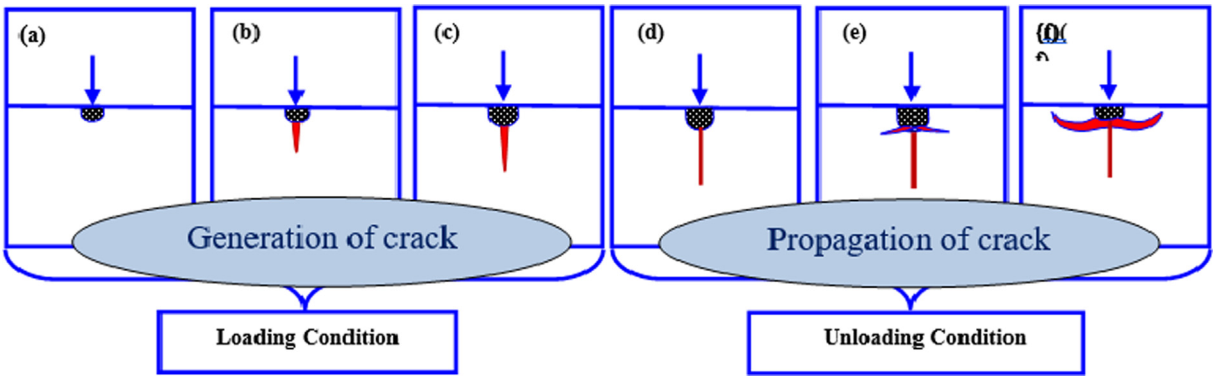

Fig. 6. Schematic representation of crack propagation in brittle materials.

CRediT authorship contribution statement

Ayush Pratap: Conceptualization, Methodology. **B.K. Singh:** Validation, Formal analysis, Writing – original draft, Visualization. **Neha Sardana:** Conceptualization, Methodology, Software, Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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