MYTRIBOS Malaysian Tribology Society
Jurnal Tribologi
Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Wear performance of Alumina-Zirconia, Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia in machining AISI 1045 steel

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KEYWORDS

Alumina-Zirconia
Alumina-Zirconia-Chromia
Alumina-Zirconia-Magnesia
Tool wear
Machining

ABSTRACT

Cutting tools is very important in determining productivity in machining operation. Small changes in formulation of cutting tools could promotes different performance in tool life and wear mechanism. This study compares wear performance of Alumina-Zirconia (80-20 wt%), Alumina-Zirconia-Chromia (80-20-0.6 wt%) and Alumina-Zirconia-Magnesia (80-20-0.2 wt%) cutting tools. The cutting tools were fabricated with powder metallurgy process and machining trials were performed with AISI 1045 at 250 m/min cutting speed, 0.125 mm/rev feed rate ad 0.5 mm depth of cut. The results reveal that Alumina-Zirconia-Magnesia cutting tools can last up to 298 s, which is 42% longer than Alumina-Zirconia-Chromia and 413% longer than Alumina-Zirconia. Both Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia cutting tools exhibited nearly identical wear mechanisms, with uniform flank wear at the tool edge linked with lower friction and temperature when engaged with workpiece material. For Alumina-Zirconia cutting tool, wear mechanism dominated by severe chipping and fracture.

Received 4 August 2021; received in revised form 21 November 2021; accepted 3 January 2022.
To cite this article: Azhar et al. (2022). Wear performance of Alumina-Zirconia, Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia in machining AISI 1045 steel. Jurnal Tribologi 32, pp.79-91.

1.0 INTRODUCTION

With high productivity demands in the manufacturing sector, there is an urgent need to machine carbon steel-based components in mass production with high accuracy and fine surface finish. Using mild steel as an example, the machining process necessitates the use of a cutting tool that can withstand hot hardness and abrasive while remaining cost-effective in order to ensure high dimensional accuracy and fine surface finish. At the moment, the majority of cutting tools used to machine carbon steel are carbides or high-speed steel (HSS). Since machining of carbon steel is associated with high temperatures, machining with carbide or HSS is typically accompanied by splashed cutting fluids to provide cooling and lubrication. The continuous use of cutting fluids has resulted in an increase in the cost of facilitating drainage systems in machinery facilities, as well as an increase in the risk of contaminant to the environment and skin health for machine operators. As a result, there is a need to mitigate the effects of cutting fluids, as cutting tools that can perform dry would be advantageous for a more sustainable machining process (Bakar et al., 2015, Osman et al., 2018 and Sktani et al., 2018).

Alumina ceramic-based cutting tools are made of a tough ceramic material that contains alumina particles mixed with minor secondary particles that are infiltrated between the alumina matrices. The addition of secondary particles compensates for the brittle nature of alumina primary phase by toughening at the grain boundaries via the crack bridging mechanism. The synergy reaction of Alumina and secondary particles interacts with an interlocking mechanism at the grain boundaries to increase deformation resistance. As a result, Alumina-based ceramic offers high hardness and density, as well as chemical stability and heat resistance, which benefits the machining operation. Following that, Alumina-based ceramics have been used in high-temperature structural and functional parts for abrasive and refractory performance (Fan et al., 2017 and Zadorozhnayaa et al., 2020).

Since the early 2000s, several researchers have been investigating the use of Alumina-based ceramics as cutting tools in the machining of hardened steel. Mondal et al. (2005) successfully developed an alumina-based cutting tool with the addition of partially stabilised zirconia, which was used in machining with C-20 steel. Senthil et al. (2006) investigated variant alumina-based cutting tools and discovered that these materials are capable of machine hardened steels up to 60 HRC with high reliability and long tool life. Dutta et al., (2006) invented the addition of silver to Alumina-based ceramics. Following machining trials, the cutting tool was found to be capable of machining C45 steel at a comparable performance to Alumina-Zirconia cutting tools. Mandal et al. (2011) successfully used an Alumina-Zirconia cutting tool to machine AISI 4340 steel. The wear performance of Alumina-Zirconia is strongly influenced by the depth of cut, followed by cutting speed and feed rate.

With the advancement of advanced materials processing and technology, the application of Alumina-based cutting tools can be improved further by the addition of tertiary phases such as Ceria, Titanium Dioxide and Titanium Carbide, to name a few (Rejab et al., 2013 and Manshor et al., 2017). It has been reported that adding up to tertiary phase could improve the microstructure of alumina-based ceramic, which improves the characteristics of high hardness, abrasive, heterogeneity, and anisotropy, thereby extending tool life. Furthermore, the tertiary phase would overcome the high brittleness issue of ceramic structures, increasing resistance to cracks, catastrophic failure, and other defects when exposed to thermal and mechanical loads.

In the most recent advancement in Alumina-based ceramic development, the addition of Chromia and Magnesia to the particles matrix capable to alter the microstructure to provide surface strengthening (Singh et al., 2018 and Norfauzi et al., 2019). Consequently, the defects and damages that have a direct impact on the machining performance, reliability, and service life of the parts can be mitigated. It has been reported that the addition of Chromia or Magnesia into an Alumina-based structure facilitates better grains expansion, which would result in mismatch interaction at the grain boundary, since Zirconia would less be affected. Therefore, the addition of Chromia and Magnesia could alter the microstructure of alumina in the form of bimodal microstructure or platelike grains, that can enhance fracture toughness to meet the efficient machining operations requirements (Azhar et al., 2010 and Azhar et al., 2012).

In this study, the wear performance of cutting tools made of Alumina-Zirconia, Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia is being evaluated. All cutting tools were made in the shape of a round RNGN120400 using a powder metallurgy process. Each cutting tool was sintered at specific parameters based on its formulation. CNC turning of AISI 1045 carbon steel was used for the machining trials. Shrinkage, density, hardness, tool life, and wear mechanism are being compared in order to better understand their properties when subjected to heavy mechanical and thermal loads in machining operation.

2.0 EXPERIMENTAL PROCEDURE

Figure 1 shows the procedure to fabricate the cutting tool. The composition for Alumina-Zirconia was created by mixing 80 wt% Alumina and 20 wt% Zirconia. The composition for Alumina-Zirconia-Chromia was created using the 80 wt% Alumina, 20 wt% Zirconia and 0.6 wt% Chromia. The formulation for Alumina-Zirconia-Magnesia was 80 wt% Alumina, 20 wt% Zirconia and 0.2 wt% Magnesia. All cutting tools were made using a powder metallurgy process that began with weighing and ball milling processes, as shown in Figure 1(a-b). These powders were then placed in the mould as shown in Figure 1(c). To produce a green compact, a hydraulic press was used to manually press the ceramic compact before it was pressed in a Cold Isostatic Press, as shown in Figure 1(d-e-f). These compacts were sintered by using a furnace in the form of RNGN120400, as shown in Figure 1(g-h). For Alumina-Zirconia and Alumina-Zirconia-Chromia, the sintering process were performed at 1400^{o}C and 9 hours soaking time. For Alumina-Zirconia-Magnesia, sintering process were performed at 1500^{o}C and 6 hours of soaking time. Ceramic compact shrinkage was measured before and after the sintering process. Furthermore, hardness and density were measured using a Rockwell hardness tester and a densitometer.

Figure 2(a) shows the sintered cutting tool for Alumina-Zirconia, Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia cutting tools. Machining trials for all cutting tools were conducted in dry turning AISI 1045 using the cutting parameters as listed in Table 1. The tool holder shown in Figure 2(b) was used to clamp the cutting tool during machining trials. The CNC turning machine used in this study is depicted in Figure 2(c). Every machining trial was carried out according to ISO 3685 by evaluating tool life when the cutting tool reached average tool wear, Vb at 0.3 mm. An optical microscope was used to observe wear mechanisms.

Figure 1: The procedure to fabricate cutting tool: (a) Preparing and weighing the powders (b) Mixing and ball milling of powders (c) Inserting powders into the mold (d) Hand pressing of powders (e) Cold Isostatic Press of the green bodies (f) Green bodies produced after compacting processes (g) Sintering process using furnace (h) Sintered cutting tools in the form of RNGN120400.

Table 1: Machining specifications.

Specifications	Alumina-Zirconia (80-20 wt%) Alumina-Zirconia-Chromia (80-20-0.6 wt%) Alumina-Zirconia-Magnesia (80-20-0.2 wt%)
Cutting Tools	RNGN 120400 (12 mm diameter, 4 mm thickness, round shape)
Tool Holder	CRDN 252543
Cutting Speed	250 m/min
Feed Rate	0.125 mm/rev
Depth of Cut	0.5 mm

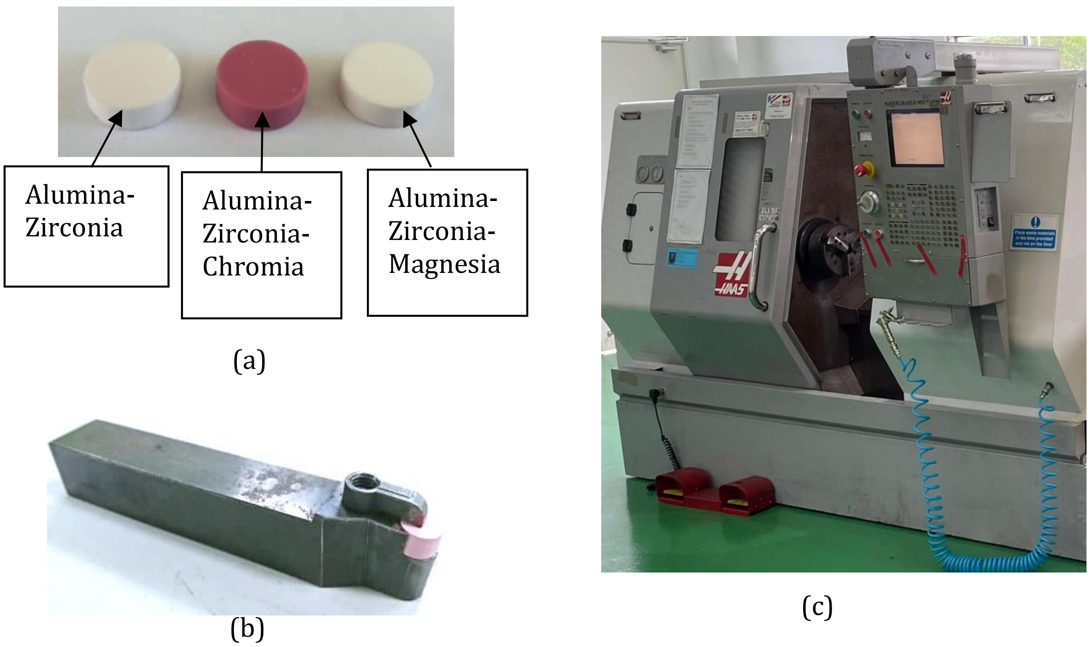

Figure 2: (a) Ceramic cutting tools (b) Fabricated alumina cutting tool with tool holder and (c) setup inside CNC machine for machining trials.

2.0 RESULTS AND DISCUSSION

Figure 2(a) depicts the round-shaped Alumina-Zirconia, Alumina-Zirconia-Chromia, and Alumina-Zirconia-Magnesia cutting tools. Because the cutting tools were made with different formulations, the appearances of each cutting tool displayed unique characteristics, with cutting tool made from Alumina-Zirconia-Chromia appeared in purple coating. Whereas Alumina-Zirconia and Alumina-Zirconia-Magnesia cutting tools displayed in whitish appearances. Shrinkage varies between cutting tools, according to the evidence. Figure 3 shows that Alumina-Zirconia-Chromia has a shrinkage of 6.81%, which is slightly less than Alumina-Zirconia of 8.36%. Meanwhile, shrinkage was measured at 7.73% for Alumina-Zirconia.

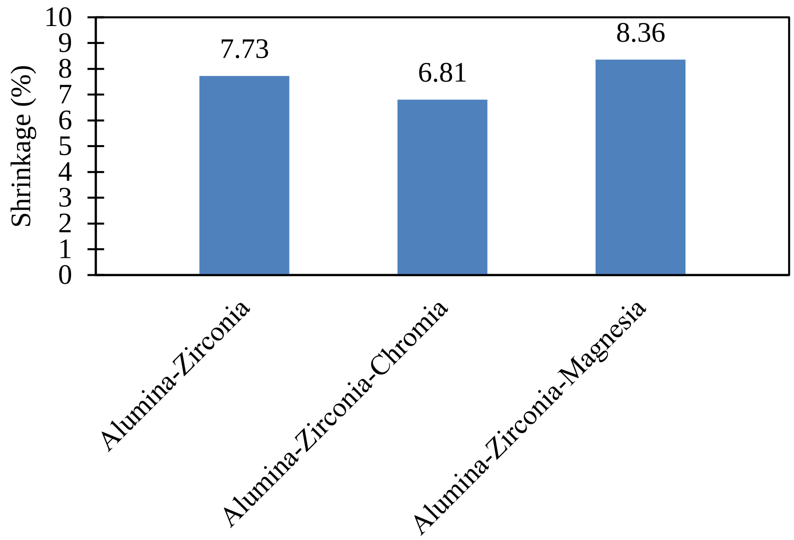

Figure 3: Comparison of shrinkage between Alumina-Zirconia, Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia cutting tools.

The shrinkage of ceramic structure closely related with the mechanisms of particles packing during sintering process. There were several stages of particle packing involved when ceramic powders exposed to the elevated heat. The initial stage refers to the expansion of ceramic particles, which started with grain growth of ceramic particles due to the thermal expansion from heat treatment. When the ceramic powders were sintered beyond 1400^{o}C as performed in this study, partial of Chromia or Magnesia were reacted with Alumina, resulting alteration between Alumina and Zirconia structure (Bondioli et al., 2000 and Riu et al., 2000). At this point, the porosity between particles began to decrease resulting improvement in structural density. Because the particles used in this study included up to three phases with varying particle sizes, the compaction of the ceramic structure was determined by the thermal expansion of each particle. Since ZrO_2 particles has a larger thermal expansion than Al_2O_3 (Azhar et al., 2012), the addition of Zirconia has slowed the grain growth of Alumina, limiting their grain expansion. Smaller grain size Zirconia could infiltrate the porosity between large particles, allowing for better particle packing arrangement and increasing density. The presence of large thermal expansion of ZrO_2 particles in the Al_2O_3 structure that contained large alumina particles and smaller zirconia particles has reduced the space for Al_2O_3 grain growth. At the same time, high sintering temperatures increased particle liquidity, forcing them to diffuse when they came into contact with each other. Once diffused, the separation distance of the mass centers between particles would also decrease, resulting in shrinkage along the sintered particles (Hadzley et al., 2019 and Norfauzi et al., 2019).

In terms of physical properties, Figure 4 shows the differences in hardness and density between these cutting tools. Alumina-Zirconia-Magnesia had a maximum density and hardness of 4.05 g/cm^3 and 72 HRC, respectively, whereas Alumina-Zirconia-Chromia had 3.82 g/cm^3 and 71.03 HRC. The density of Alumina-Zirconia is slightly higher than Alumina-Zirconia-Chromia at 3.85 g/cm^3 with slightly lower hardness of 70.07 HRC hardness.

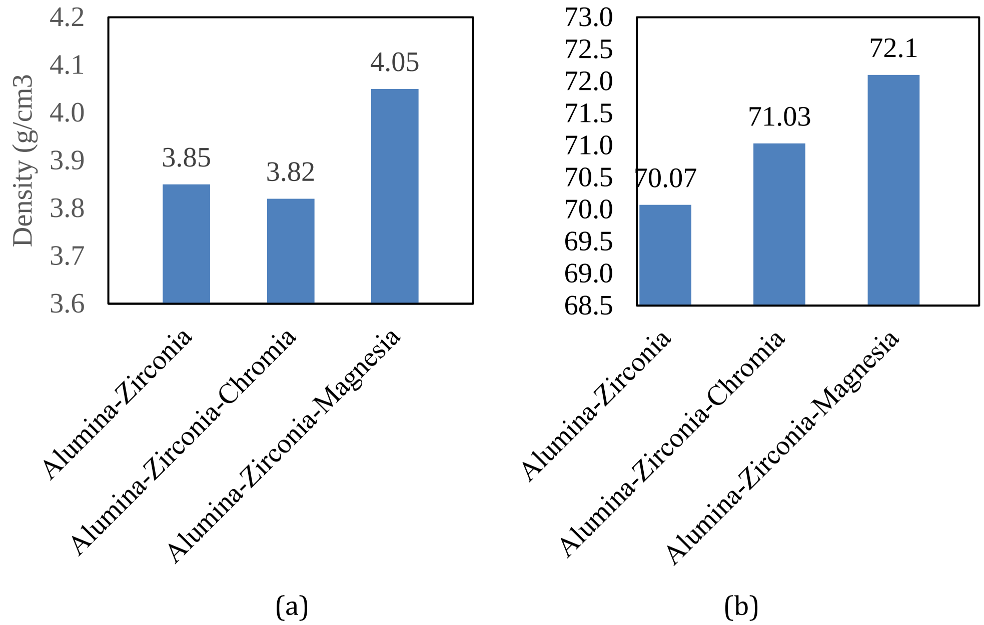

Figure 4: Comparison of mechanical properties for Alumina-Zirconia, Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia cutting tools in terms of (a) density and (b) hardness.

The density and hardness of Alumina-Zirconia compacts is influenced by the homogeneity of particle packing between Alumina-Zirconia powders. The addition of Zirconia has limited the grain growth of Alumina, restricting their grain expansion. Smaller grain size of Zirconia could infiltrate the porosity between large particles, allowing for better particle packing arrangement and increasing density (Elsen and Ramesh, 2016 and Norfauzi et al., 2019). The role of Magnesia in amplifying the sintering rate of Alumina to increase the grain growth was explained in the literature (Singh et al., 2018). Such high grain growth rate provided pinning effect in the grain boundaries to increase densification and improving barrier of grain dislocation when force is applied, resulting in higher fracture toughness. The change in density for Alumina-Zirconia compact when Chromia was added were caused by Chromia's reaction with the Alumina particles. When sintered at high temperature, a portion of Chromia has evaporated and began to react with Alumina near the area of free surface of cutting tool. On the same time, some other portion of cutting tool especially at the middle area remained unaffected due to less chromia existence, promoting bimodal grain distribution (Singh et al., 2016). As the sintering process progressed, the reaction of Chromia and Alumina increased steadily at the surface resulting better particle diffusion, which facilitates the interlocking mechanism at the top portion of cutting tool. This could make Alumina-Zirconia-Chromia has better hardness but lower density than Alumina-Zirconia.

Figure 5 depicts a tool life comparison for Alumina-Zirconia, Alumina-Zirconia-Chromia, and Alumina-Zirconia-Magnesia. The machining trials were held at the cutting speed was 250 m/min, the feed rate was 0.125 mm/rev, and the depth of cut was 0.5 mm. The graphs showed a linear trend in the development of tool wear for all cutting tools studied. The Alumina-Zirconia-

Magnesia cutting tool clearly outperformed the Alumina-Zirconia-Chromia cutting tool, with a maximum tool life of 298s, which is 42% longer than the Alumina-Zirconia-Chromia at 174s. This is because the Alumina-Zirconia-Magnesia cutting tool has a higher hardness. Cutting tool made of Alumina-Zirconia was obviously unsuitable for machining because the tool life was only 58s. The brittleness structure possessed by the Alumina-Zirconia cutting tool allows easy catastrophic failure, despite the fact that Zirconia is already present in the Alumina structure.

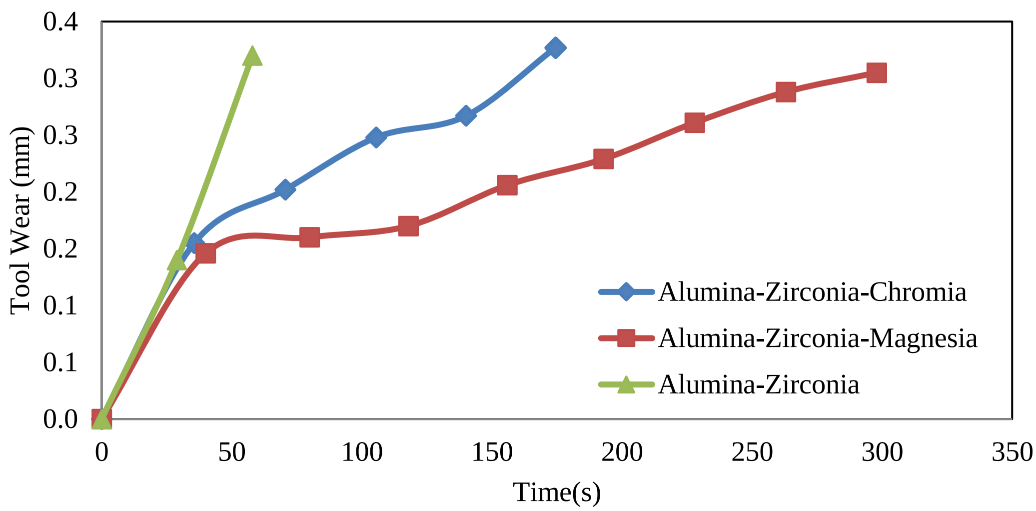

Figure 5: Comparison of tool life for Alumina-Zirconia-Chromia (80-20-0.6 wt%) and Alumina-Zirconia-Magnesia (80-20-0.6 wt%) at the cutting Speed 250 m/min, feed rate 0.125 mm/rev, depth of cut 0.5 mm

Figure 6 shows a comparison of wear mechanisms for Alumina-Zirconia, Alumina-Zirconia-Chromia, and Alumina-Zirconia-Magnesia cutting tools. In the case of Alumina-Zirconia, severe chipping and fracture can be seen at the workpiece contact area, as shown in Figure 6(a). The cutting edge had developed severe notch wear, which allowed for catastrophic failure within a few seconds of machining. This demonstrates that, despite the addition of ZrO_2 to the Al_2O_3 structure, there is still evidence of brittleness at the cutting edge.

The wear behavior of an Alumina-Zirconia-Chromia cutting tool is depicted in Figure 6(b). Early in the machining process, wear began in a uniform region with no flaking or chipping as the cutting tool tip presented a more stable edge. As the machining progressed, the wear pattern revealed a uniform flank wear area throughout the contact region with the workpiece. There was little evidence of notching, chipping, flaking or built-up edge formation along the worn region. This demonstrates that the addition of Chromia to the Alumina-Zirconia provided stronger cutting edge to resist deformation when exposed to the interfacial cutting loads.

Figure 6(c) depicts the progression of wear behavior for an Alumina-Zirconia-Magnesia cutting tool. Early machining stage indicates that wear began in a uniform region with no flaking or chipping. The cutting tool tip displayed a stable edge, similar to Alumina-Zirconia-Chromia at the same cutting condition. There is sign of built-up layer formation, especially when machine performed beyond 228s, represented by the bluish appearance at the flank wear area. Built-up layer is a thin molten metal that attach of the tool surface as a result of high pressure and temperature during workpiece-cutting tool engagement. Such thin molten layer providing protection by reacting like solid lubricant to reduce friction. Therefore, the existence of built-up layer could increase wear barrier to the tool surface and consequently extending the duration of tool life (Fiorini & Byrne, 2016). Elsewhere, evidence of built-up edge, notching, chipping, and flaking were hardly seen along the worn region.

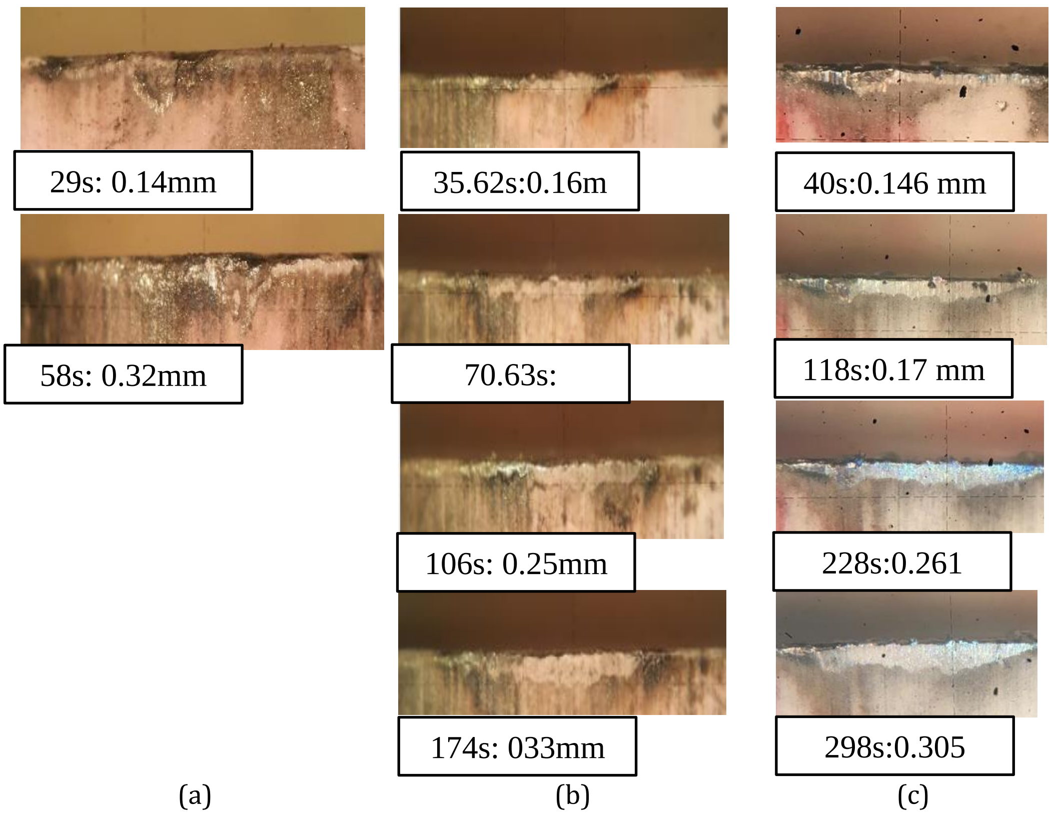

Figure 6: Wear development of cutting tools made from a) Alumina-Zirconia, b) Alumina-Zirconia-Chromia and c) Alumina-Zirconia-Magnesia at cutting speed of 250 m/min and feed rate of 0.125 mm/rev.

Overall, machining with Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia cutting tools resulted in uniform flank wear and a sharp nose radius, allowing the cutting process to continue. The wear presented by the Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia cutting tools remained clean, indicating that the heat generated is minimal as a result of the lower friction and cutting force throughout machining period.

Figure 7 represents a close-up observation of the cutting tools under investigation. The cutting tool for Alumina-Zirconia showed chipping at the tool edge, representing the brittle structure of the tool edge. As a result of edge chipping, the penetration of damaged tool edge could increase cutting force, causing the cutting temperature to rise even further. A partial of the chip began to melt and became attached at the heat-affected region along the tool edge. The attachment layer at the cutting tool's edge promotes adhesive wear, which can be aggravated into diffusive wear as the machining prolonged. If the cutting tool is exposed to cutting heat for an extended period of time, such attachment molten layer may amplify into oxidative wear (Lin et al., 2020 and Moreno et al., 2021). Therefore, the formulation of 80-20 wt% Alumina-Zirconia cutting tool is insufficient to perform efficient AISI 1045 machining under the conditions investigated.

Figure 7(b) demonstrates a close-up view of the wear mechanism for an Alumina-Zirconia-Chromia cutting tool. An examination of the flank face reveals the adhesion of a thin layer of molten metal appeared in different color from the tool surface. When machining with Alumina-Zirconia-Magnesia, wear appeared similarly to Alumina-Zirconia-Chromia with evidence of thin molten layer smeared on the flanks face, as shown in Figure 7(c). The wear characterizes as clean, with minimal formation of adhered layer. Evidence from Figure 7(b) and Figure 7(c) indicate that adhesive wear dominated wear mechanisms on the affected cutting zones. Similar observation also found in Norfauzi et al. (2019). Adhesive wear occurs when a portion of AISI 1045 becomes detached from the workpiece and becomes trapped at the cutting interface. Such trapped material began to melt, aided by the high temperature and pressure. When the contacted surfaces were scratched in the opposite direction, the molten portion of AISI 1045 slid on the cutting tool surface and reacted as a layer to reduce friction. Furthermore, such a layer covers the cutting tool from direct contact with the chip and possibly increases thermal conductivity to absorb heat from the penetrating cutting zone, resulting in less wear (Ahmed et al., 2019, Sarjana et al., 2020 and Ahsana et al., 2021). This is demonstrated in Figure 6, where the tool life was recorded in the range of 174s, which was greater than machining with an Alumina-Zirconia cutting tool at 58s. Whereas, machining with Alumina-Zirconia-Magnesia cutting tool contributed maximum tool life of 298s with stable cutting edge throughout machining period.

CONCLUSIONS

This study compares Alumina-Zirconia, Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia cutting tools made using the powder metallurgy process. All cutting tools were prepared in a similar shape of RNGN120400 and tested using AISI 1045 machining trials. Several conclusions can be drawn from the experimental results and observations, as follows:

(a) Fabrication of cutting tools by powder metallurgy involving with ball-milling, pressing, and sintering processes capable of producing solid Alumina-Zirconia, Alumina-Zirconia-Chromia and Alumina-Zirconia-Magnesia cutting tools.
(b) Alumina-Zirconia-Magnesia shrank at a higher rate of 8.36% than Alumina-Zirconia-Chomia, of 6.81% and Alumina-Zirconia, of 7.73%.
(c) Alumina-Zirconia-Magnesia performs better density and hardness of 4.05 g/cm^3 and 72 HRC, as opposed to 3.82 g/cm^3 and 71.03 HRC for Alumina-Zirconia-Chromia and 3.85 g/cm^3 and 70.07 HRC for Alumina-Zirconia
(d) Machining AISI 1045 with Alumina-Zirconia-Magnesia resulted in a maximum tool life of 298s, which is 42% longer than Alumina-Zirconia-Chromia at 174s and 413% longer than Alumina-Zirconia at 58s.

ACKNOWLEDGMENTS

This paper was presented at MITC2020NE. The authors would like to thank the Zamalah UTeM Scheme and Universiti Teknikal Malaysia Melaka (UTeM) for their support that enabled this work to be carried out.

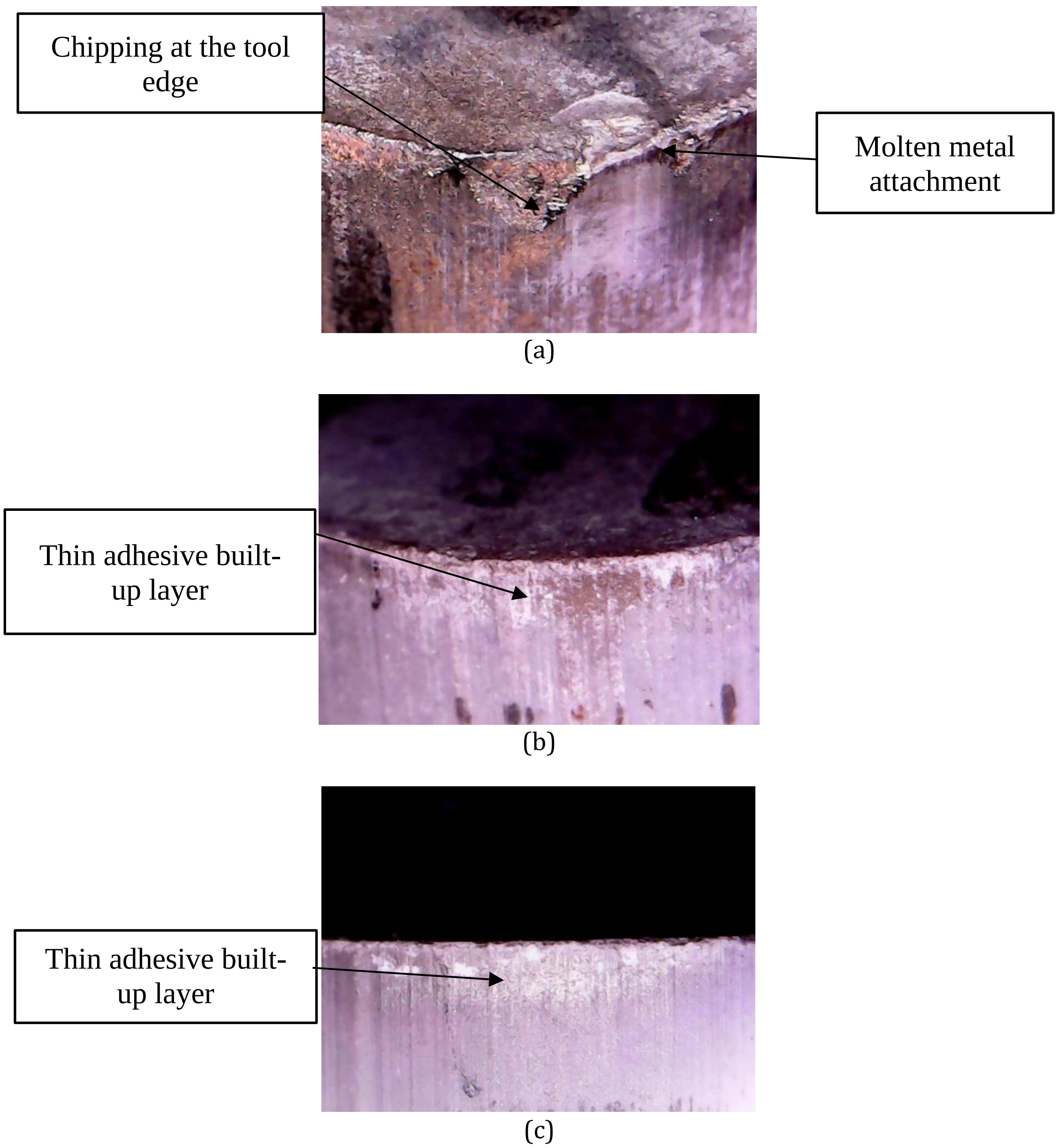

Figure 7: Close-up observation of wear mechanism for a) Alumina-Zirconia, b) Alumina-Zirconia-Chromia and c) Alumina-Zirconia-Magnesia.

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