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Computational Study of Erosion Wear of Capillary Used in Laser Solder Ball Jetting Process

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Abstract: Solder Ball Bumper Jetting Process is used for high precision soldering in small area with high productivity. Cemented carbide (WC-Co) is the common material used for capillary due to its high strength and good wear resistance. Small paritcle induced during soldering process could cause particle erosion wear and it is found to be one of the surface failure mostly controlling capillary in-service life. The particles were expected to be hard particle generated by surface wear in the earlier process. This research aims to study the material behavior under particle impact to increase the understanding of capillary failure based on particle impingement erosion wear using Finite Element Method (FEM). The effect of contact paramters, i.e. impact angle of particle and particle size, on failure of capillary tip was studied. The impact angle variation between 10, 30, 60, 90 degree and particle size variation of 0.5, 0.75, 1 micrometer were considered. The result showed that higher angle of impact can lead to higher stress developed while particle size effect depends strongly on the contact area which relies on impact angle. In case of 60 and 90 degree of impact, results showed a trend of decreasing developted stress with increasing particle size. While 10 and 30 degree of impact showed a trend of increasing in developed stress when particle size increased. The research results could be used as guidelines to improve the capillary design or soldering process to incrase the capillary in-service life or minimize the chance for capillary failure at unexpected short time period.

Keywords: Solder ball bumper jet, Soldering, Impact angle, Particle size, Finite element method, Erosion wear.

Introduction

Microelectromechanical systems (MEMS) are combination of mechanical and electrical structures with micron size elements (Ozevin, 2014). MEMS devices are important component to sensors and hard-disk drives (Hirano, 2007). The packaging of MEMS devices needs more advanced technology in processing in miniature area than traditional soldering method. To achieve the requirement, method of laser-based solder jetting technology, Solder Ball Bumper Jet (SB^2-Jet), have been used. The preformed solder ball of this process is singulated from solder ball reservoir to the tip of capillary. After that, the laser pulse is used to melt solder ball and molten solder ball will be jetted out from capillary tip as shown in Figure 1 (Sun, 2012). This type of Laser Solder Ball Jetting process provides high productivity and fulfills all the needs of fluxless soldering, local heating and reflow, no mechanical contact and stress during soldering (Zakel, 2002).

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The process needs high accuracy to process miniature device and the shape of capillary can affect the accuracy of the process. Research have been done to investigate the effect of capillary tip. In 2011, three types of capillary tip shapes shown in Figure 2 were studied and the effect of capillary tip on jetting accuracy is shown here in Figure 3 (Mata, 2011). Cemented carbide (WC-Co) capillary used for this process is usually be changed after capillary tip shows unacceptable defect to keep high precision of such process. Less defect can lead to higher lifetime before capillary rejected from production line which can decrease cost from capillary changing.

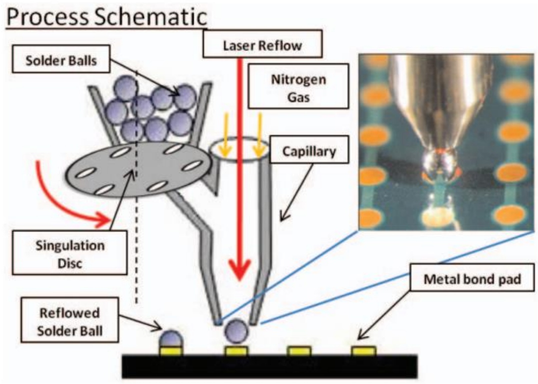


Figure 1. Principle of SB^2-Jet process (Sun, 2012)

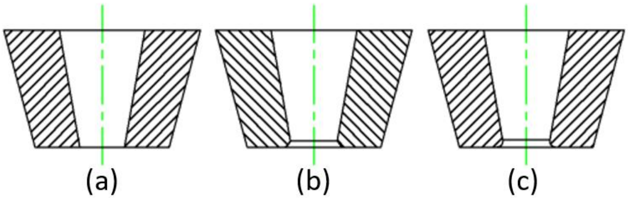


Figure 2. Shape of (a) capillary type A, (b) Capillary type B, (c) Capillary type C. (Mata, 2011)

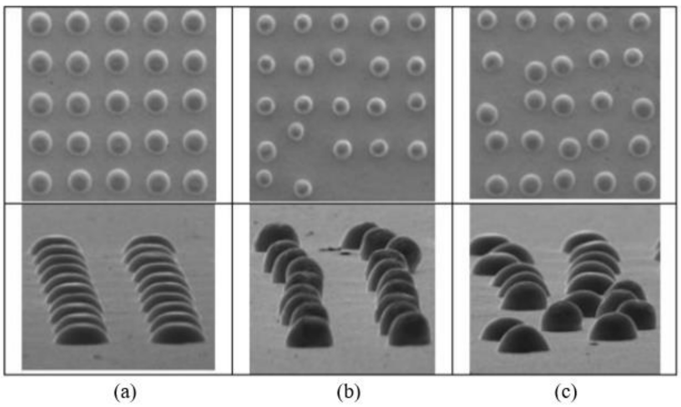


Figure 3. Jetting result of (a) Capillary type A, (b) Capillary type B, (c) Capillary type C. (Mata, 2011)

Erosive wear was found to be one of the main surface failures expected as the process involved fluid flow. The erosive wear resistance of WC-Co carbides obtained by spark plasma sintering method was studied (Wachowicz, 2021). The study showed that erosion rate depends on sintering process of WC-Co and erosion medium. This erosive wear study used quartz particle as erodent particle. The result of this study showed that larger particle impact can lead to more erosion wear. Also, larger impact angle also leads to higher surface deformation and more material removal during impact. Small particle could be induced during soldering process and could be considered as erosive particle. Erosive particle could be chromium and stainless steel from laser jetting system or WC particle from WC-Co cemented carbide capillary wall. Internal crack from manufacturing process can lead to WC grain worn out from crack surface (Mikado, 2017). The particles generated by surface wear in the earlier process, i.e. WC particle, were hard particle which is expected to has a strong effect on capillary surface defect leading to jetting inaccuracy.

This research aims to study the material behavior under particle impact to increase the understanding of capillary failure based on particle impingement erosion wear using Finite Element Method (FEM). The effect of contact parameters, i.e. impact angle of particle and particle size, on failure of capillary tip was studied. The erosive particles were assumed to flow along with molten solder at same velocity as molten solder ball flow velocity during laser solder ball jetting process. This study focused on WC erosive particles due to higher density and Young's Modulus which developed more stress during impact and can lead to more serious failure compared to other metal particle in jetting system. FEM were used to investigate the stress distribution developed during impact and used to estimate the material removal from particle impact based on failure criteria. Higher stress developed lead to lower time for material removal, i.e. lower number of loading cycle or impact to failure. It was observed that once developed stress from particle impact exceed yield strength and exposed to the surface, surface removal take place as expected (Akchurin, 2016). The mechanical properties at room temperature were used for computational study by finite element method. At process temperature, which is around 217 degree Celsius, it is not expected for WC-Co cemented carbide to exhibit significant change in mechanical properties and failure compared to room temperature (Milman, 2013). Nanoindentation technique was employed to obtain the material properties to be used for FEM.

Method

Microstructure Analysis

Microstructure analysis carried on by Scanning Electron Microscope to specified grain size of WC grain which was used to identify size of impact particle used in this study. Grain size was measured by using ImageJ to measure multiples WC grain to find mean grain size and distribution of grain size.

Material Testing by Nanoindentation

Capillary material used in this study assumed to be made of WC-Co cemented carbide available commercially. WC-Co cemented carbide were characterized by nanoindentation technique to accurately capture the properties in small scale. The result of nanomechanical tester showed hardness and Reduced Elastic Modulus. Reduced Elastic Modulus was converted to Young's Modulus using relationship showed in Equation 1.

$$\frac{1}{E_r} = \frac{1-v^2}{E} + \frac{1-v_i{}^2}{E_i} \tag{1}$$

Where E_r, E, E_i represent Reduced Elastic modulus, Young's Modulus of testing specimen and Young's Modulus of indenter, respectively. v and v_i represent Poisson's ratio of testing specimen and indenter, respectively.

Maximum indentation load (F_m), Maximum indentation depth (h_m), Area of contact (A_f) and Young's Modulus (E) were used to calculate yield strain (ε_y) and strain hardening exponent (n) through numerical method according to Equation 2 and 3 (Tunvisut, 2002) to create stress-strain curve for WC material which was later used in finite element analysis.

$$\frac{F_m}{Eh_m{}^2} = 73\varepsilon_y{}^{0.82} - 87.3\varepsilon_y{}^{0.98} - \left(0.24ln\varepsilon_y + 0.39\right)n^{0.26ln\varepsilon_y+0.10} \quad , \tag{2}$$

$$\frac{A_f}{h_m{}^2} = 6ln\varepsilon_y - 178\varepsilon_y{}^{0.13} + \left(4.54ln\varepsilon_y + 5.86\right)n^{0.1ln\varepsilon_y-0.1} + 155.7. \ , \tag{3}$$

Finite Element Analysis

Particle impact model was developed to simulate effect of impact angle and particle size. The stress developed near WC-Co surface from particle impact was studied. The impact angle variation between 10, 30, 60, 90 degree and particle size variation corresponding to carbide particle sizes observed were considered, i.e. 0.5, 0.75, 1 micrometer. Figure 4 showed impact model and Figure 5 showed meshing in the contact area. Impact velocity equal to 2.23 m/s was selected based on preliminary study using simplified CFD model (Premjarunan, 2023) which was applied to all cases of particle impact study. Particle material properties obtained from nanoindentation test of the hardest phase of cemented carbide specimen were used. This is to represent the worst case due to WC grain particle worn out from capillary wall.

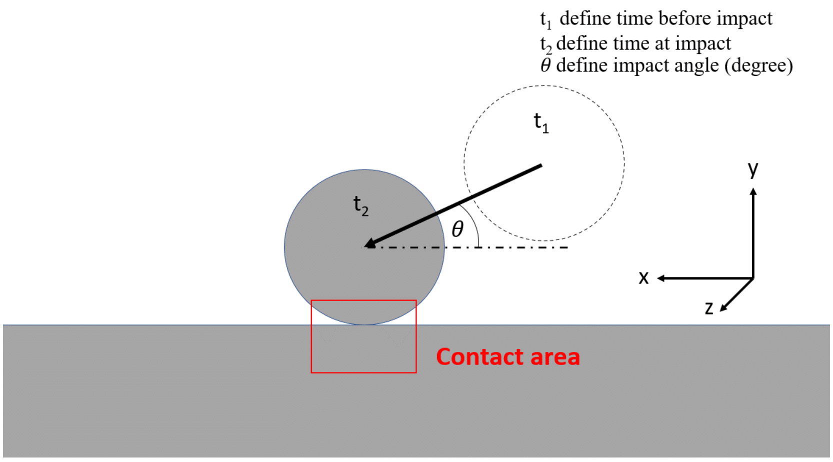


Figure 4. Impact model used in study showing impact step, impact area and impact angle.

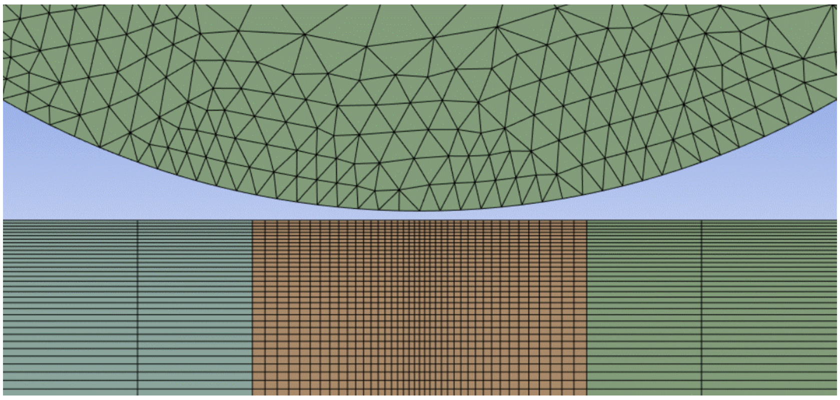


Figure 5. Finite Element model showed meshing in contact area.

The stress developed near impact surface was used to estimate wear volume. Material in the area that experienced stress more than yield strength and exposed to the surface would be the area to fail and be removed as wear debris.

Results and Discussion

Microstructure Analysis

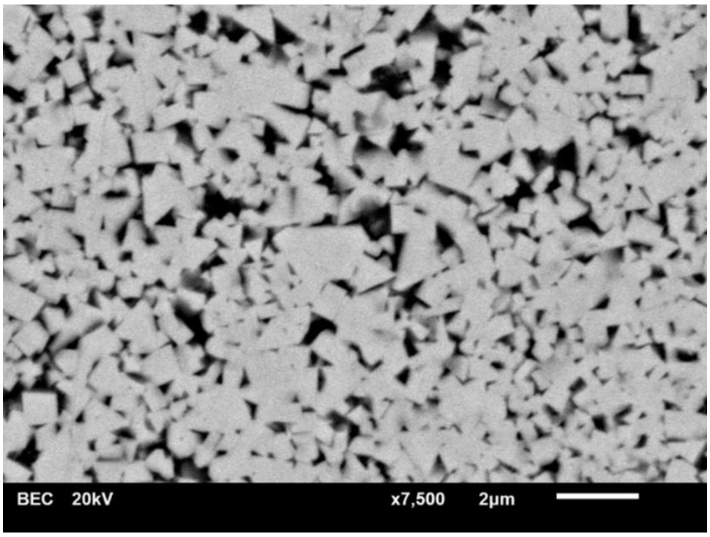


Figure 6. Example of Microstructure of commercial grade WC-Co from Scanning Electron Microscopy

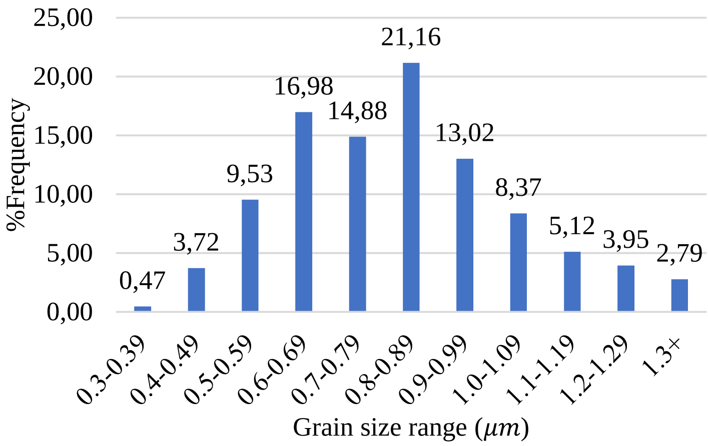


Figure 7. Carbide grain size distribution of KA10 cemented carbide measured from Figure 5.

Example of SEM micrograph shown in Figure 6 with grain size distribution result shown in Figure 7 was measured from multiple samples. Mean grain size measured from ImageJ was found to be 0.83 microns. The size distribution showed highest frequency in the range of 0.5 to 1 micrometer. The results were used to define the range of particle size studied. The variation of particle size of 0.5, 0.75, 1 micrometer were investigated assuming that grain of WC-Co at surface can be worn off early on the process.

Material Testing by Nanoindentation

The typical results obtained from nanoindentation tests including loading-unloading curve shown in Figure 8. The test results from multiple testing at different positions were used to define the properties of WC-Co Cemented carbide. The property of WC hard particle phase was obtained from the results corresponding to the area showing maximum hardness from nanoindentation test. It was used to represent hard phase carbide which was assumed to be impact particle to study the effect of impact from WC grain. Maximum indentation load, maximum indentation depth, reduced elastic modulus, and contact area were used to estimate material constant by Equation 1,2 and 3 and the results are shown in Table 2.

Table 2. Material Properties of WC-Co cemented carbide

Material	Indentation yield strength (MPa)	Strain hardening exponent	Young's Modulus (GPa)	Hardness (GPa)
Average WC-Co surface	2,130	1.62	626	28.89
Hard WC grain	3,440	1.49	781	39.24

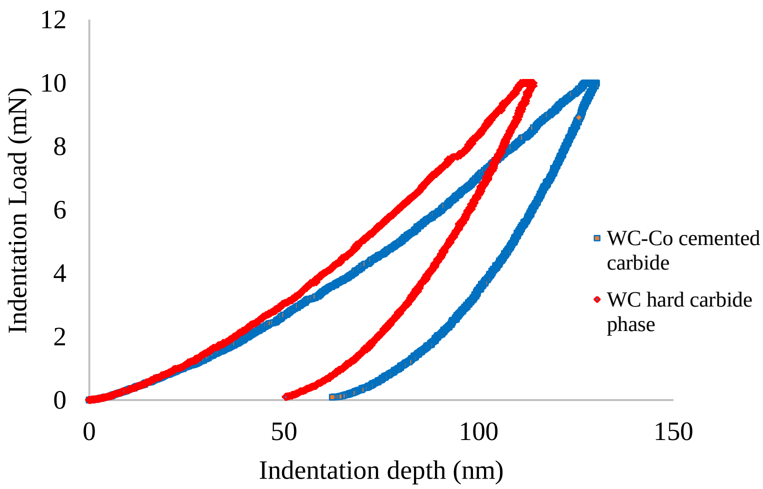
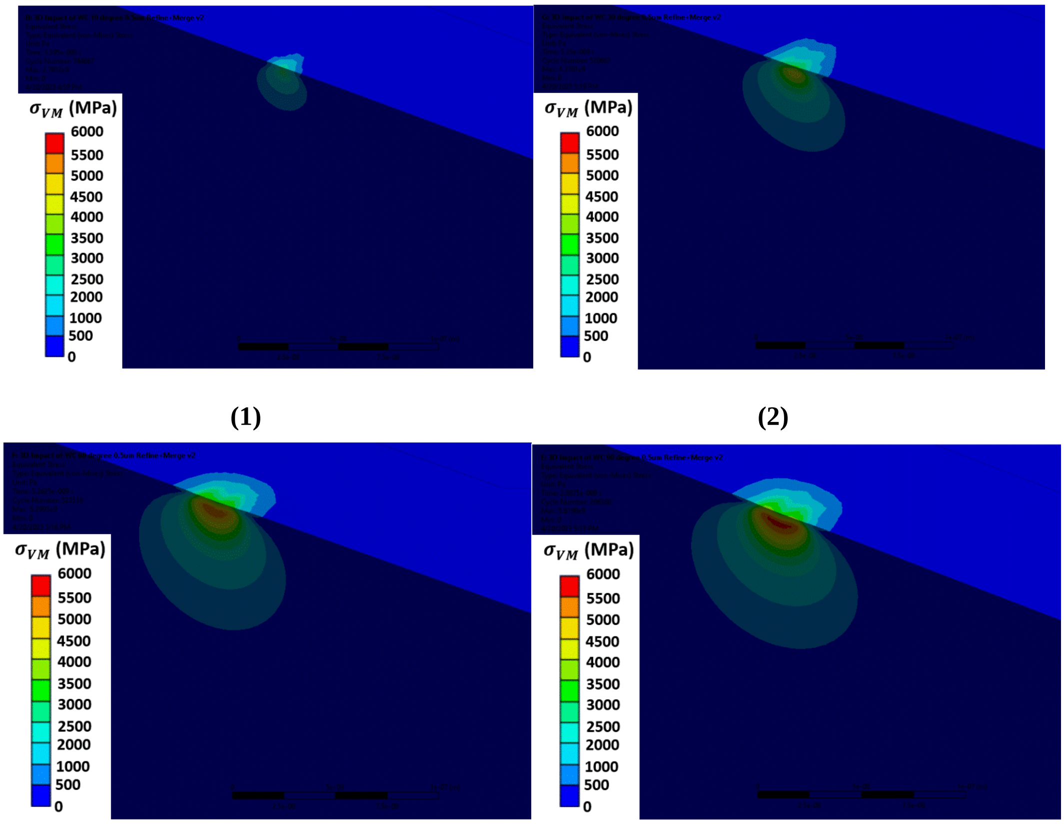


Figure 8. Loading-unloading curve of WC-Co surface

In term of temperature effect during soldering process, i.e., melting temperature of solder used in the process, other study about effect of temperature to mechanical properties showed insignificant reduction of strength until 300 degrees Celsius (Milman, 2013). Hence, the properties obtained from tests carried out at room temperature will be used to represent material properties in the FEM.

Finite Element Analysis

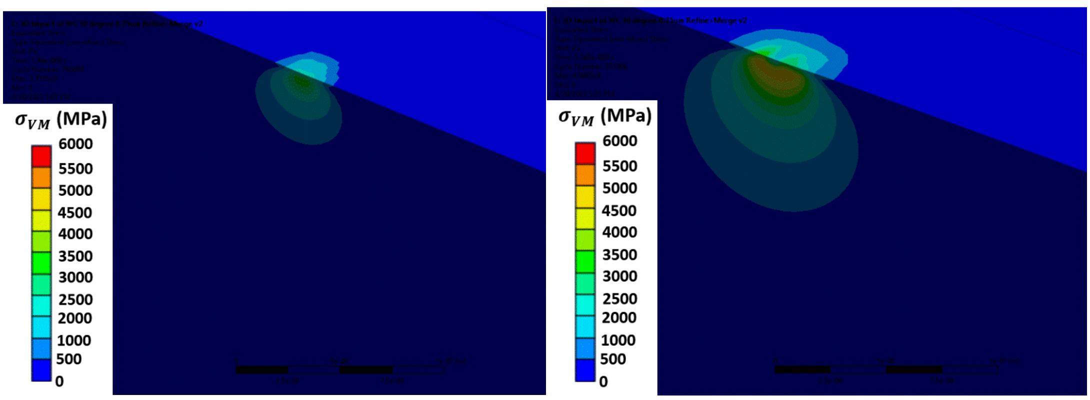
Von Mises stress (σ_{VM}) result of WC-Co surface from FEM showed in Figure 9-11. The particle body was hidden to inspect stress distribution contour from FEM. Distribution pattern revealed larger developed Von Mises stress during impact of particle. Larger impact particle size led to wider distribution of stress. At the same time, higher impact angle also led to larger in distribution of developed stress during impact.



(1) **(2)**

(3) **(4)**

Figure 9. Von Mises Stress obtained from FEM by ANSYS Explicit Dynamics at particle size of 0.5 μm at same contour plot range of (1) Impact angle of 10-degree (2) Impact angle of 30-degree (3) Impact angle of 60-degree (4) Impact angle of 90-degree.



(1) **(2)**

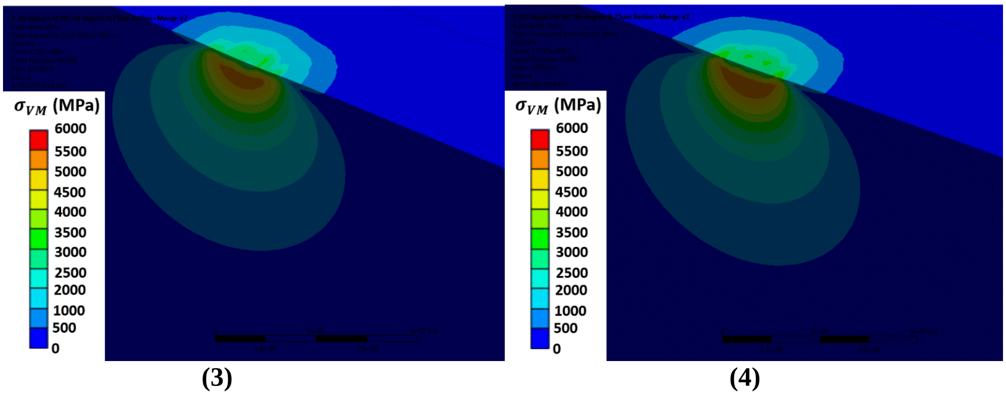


Figure 10. Von Mises Stress obtained from FEM by ANSYS Explicit Dynamics at particle size of 0.75 μm at same contour plot range of (1) Impact angle of 10-degree (2) Impact angle of 30-degree (3) Impact angle of 60-degree (4) Impact angle of 90-degree.

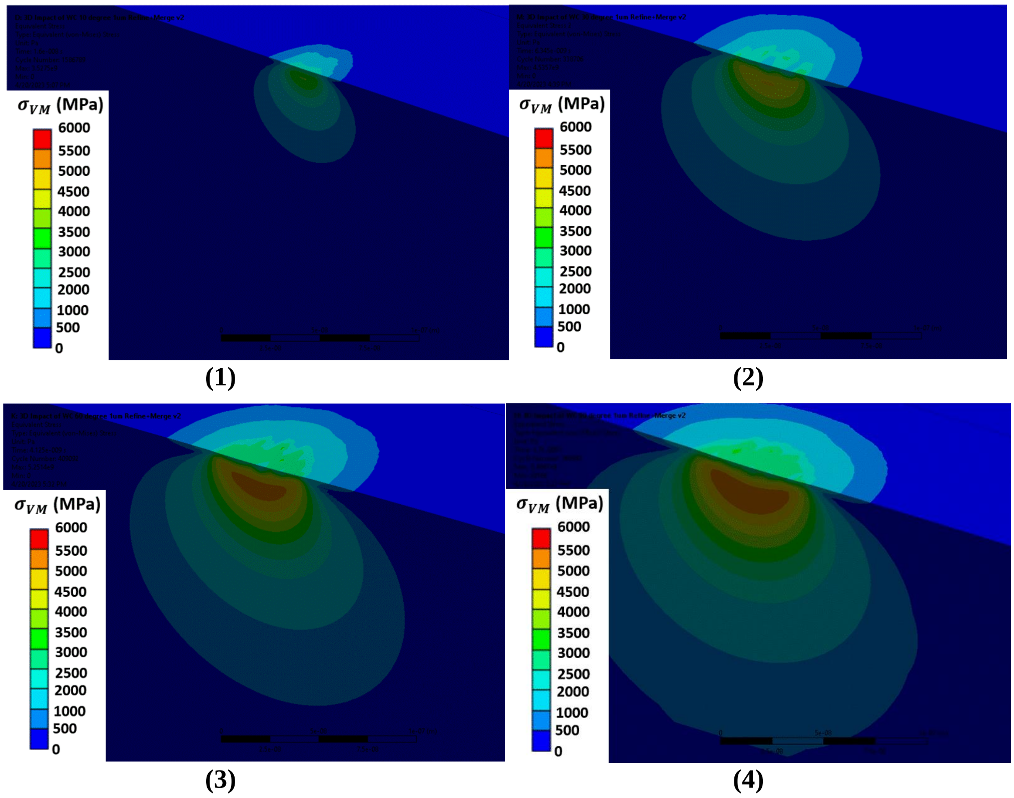


Figure 11**.** Von Mises Stress obtained from FEM by ANSYS Explicit Dynamics at particle size of 1 μm at same contour plot range of (1) Impact angle of 10-degree (2) Impact angle of 30-degree (3) Impact angle of 60-degree (4) Impact angle of 90-degree.

Relationship between maximum stress and impact angle and maximum stress and impact particle size were also considered and showed in Figure 12 and 13, respectively. The result showed effect of impact angle and impact size of particle to stress developed at WC-Co cemented carbide material.

The result plot from Figure 12 showed developed stress increased when impact angle increased. In term of particle size effect, the result from Figure 13 showed increased trend of stress when particle size increased in case of 10 and 30 degree. However, at 60 and 90 degree of impact showed stress slightly decreased when particle size increased. The result showed that Von Mises stress developed around the contact area depends on both particle size and impact angle. For the same material or material with the same density, increasing of particle size led to an increase in particle mass resulting in higher impact force expected during impact. However, particle size increasing did not found to lead to increasing developed stress in all cases because of variation of contact area from different impact angle and particle size during impact. Higher contact area would result in lower stress associated with the same impact force.

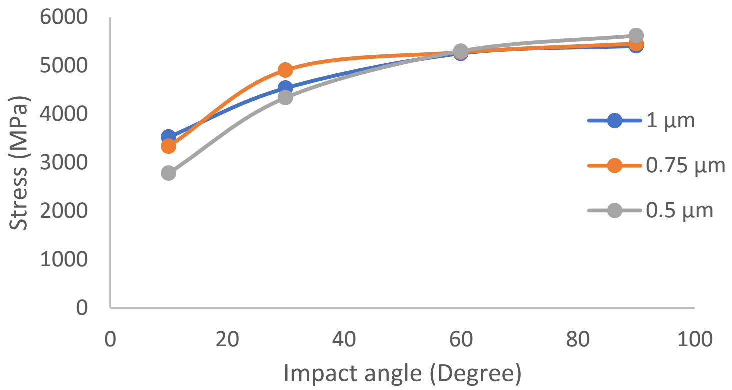


Figure 12. Developed Von Mises stress during impact of different angle of particle

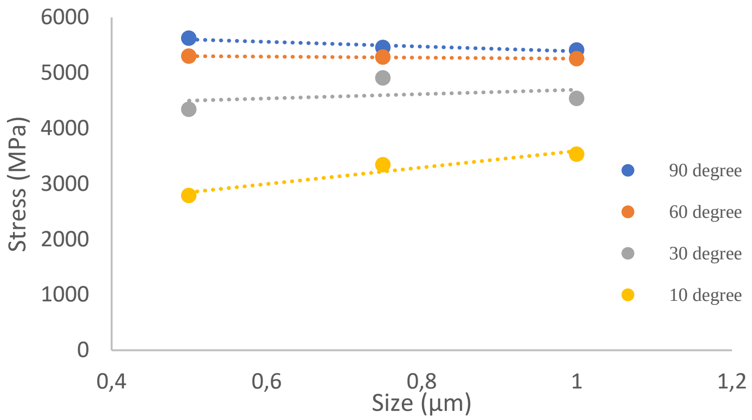


Figure 13. Developed Von Mises stress during impact of different size of particle

Wear depth and wear debris size was then be estimated from Von Mises stress distribution contour from finite element results. Yield criteria was used to estimate wear volume and the yield strength of WC-Co cemented carbide is 2,130 MPa as showed in result from Table 1. The stress distribution countor was replotted with different contour level range being redefined to define the wear volume more conveniently as showed in Figure 14. Wear length in 3 axes was measured and showed in Figure 14 as L_x, L_y, L_z for length in x, y, and z-axis, respectively. Wear volume ($V_{Ellipsoid}$) was calculated assuming wear shape as half ellipsoid shape using Equation 4 assuming that area under the surface which showed stress lower than yield strength was not worn out. L_x and L_z define maximum length of stress distribution at the surface while L_y defines maximum depth.

$$V_{Ellipsoid} = \frac{4}{3}\frac{(\pi L_x L_y L_z)}{2} \quad , \qquad (4)$$

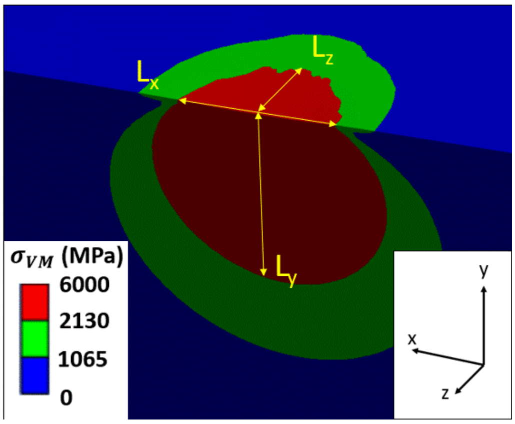


Figure 14. Redefined Von Mises stress contour for calculation of wear volume.

The calculated wear volumes from applying yield criteria to define material failure based on developed Von Mises stress during impact from FEM are shown in Figure 15. The wear volume showed that impact angle and particle size increasing can lead to increasing wear volume. Increasing in particle size led to slightly decrease in maximum Von Mises stress in some cases depending on impact angle and particle size. For cases with increasing of the area of impact which resulted in wider area with plastic deformation, i.e., area with stress higher than yield strength of material, could result in higher wear volume. Note that, in this work, material failure causing material removal based on yielding failure was assumed as it is expected that the number of cycles to failure of such material would be found shortly once plastic deformation observed.

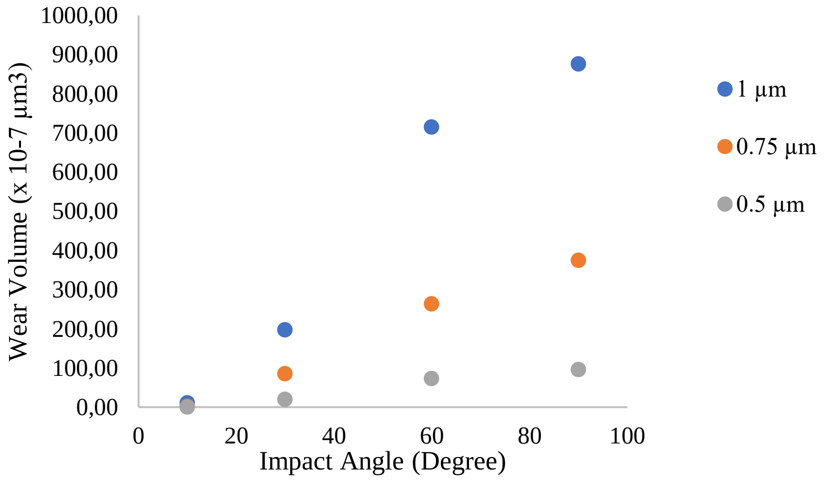


Figure 15. Calculated wear volume of different impact angle and particle size of impact particle

Conclusion

This research aims to study the effect of contact parameters, i.e., grain size of WC and impact angle, on stress distribution and failure of capillary tip made of WC-Co cemented carbide from particle impingement erosion wear using Finite Element Method (FEM). The impact angle variation between 10, 30, 60, 90 degree and particle size variation of 0.5, 0.75, 1 micrometer were considered. The result showed that increasing in impact angle led to higher stress during impact of particle. In case of impact particle size increased, results at 10 to 30 degrees showed increasing of stress when particle size increased. For higher angle of impact of 60 to 90 degrees, maximum stress showed slightly decreased trend when particle size increased due to expanded contact area during impact. However, wear volume results determined based on yield criteria showed that more wear volume were observed when impact angle increased for all particle size.

The results could be useful to improve lifetime of the specimen based on capillary surface change as it affected jetting accuracy. Reduction of grain size can lead to decreased wear volume under current assumption that WC hard particle worn out from early process was expected. Decreasing grain size can lead to lower stress distribution due to lower mass.

Recommendations

The current model could be extended to study particle erosion wear in other application with different impact conditions such as different contacting materials, impact velocity. The model can also be used to study material failure based on other failure mechanism such as micro-fracture to include the effect of initial cracks.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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