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A Review on the Erosion Mechanisms in Abrasive Waterjet Micro Machining Of Brittle Materials

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ABSTRACT
Thefabricationofminiaturestructuresoncomponentswithhigh-integritysurfacequalityrepresentsoneofthecuttingedgetechnologiesinthe21stcentury.Thematerialsusedtoconstructsuchsmallstructuresareoftendifficult-to-machine.Manyotherreadilyavailabletechnologieseithercannotrealisenecessaryprecisionorarecostly.Abrasivewaterjet(AWJ)isafavourabletechnologyforthemachiningofdifficult-to-machinematerials.However,this technologyisgenerallyaimedatlargestockremoval.Areductioninthescaleofthistechnologyisanattractiveavenueformeetingthepressingneedofindustryintheproductionofdamage-freemicrofeatures.ThispaperreviewssomeoftheworkthathasbeenundertakenatUNSWSydneyaboutthedevelopmentofsuchanAWJtechnology,focusingonthesystemdesigncurrentlyemployedtogenerateamicroabrasivejet,theerosion mechanismsassociatedwithprocessingsometypicalbrittlematerialsofbothsingle-andtwo-phased.Processingmodelsbasedonthefindingsarealsopresented.Thereviewconcludesontheviabilityofthetechnologyandtheprevailingtrendinitsdevelopment.
Keywords:microabrasivejet,abrasivewaterjet,ductileerosion,viscousflow,difficulttomachinematerials

Nomenclature

C_p	percentageofparticleconcentrationbymass
C_c	percentageofchemicaladditiveconcentrationbymass
d, d_j	jetdiameter(m)
d_n	nozzlediameter(m)
d_p	meandiameterofabrasiveparticle(m)
E_m	elasticmodulusoftargetmaterial(Pa)
H_m	hardnessoftargetmaterial(Pa)
h	channeldepth(m)
K	consistencyindex($Nm^{-2}s^n$)
K_m	fracturetoughnessoftargetmaterial($Pam^{0.5}$)
k_d	dischargefactor
L	jetcompact(orstabilised)length(m)
L/d	characteristiclengthratio
MRR	materialremovalrate(m^3s^{-1})

massflowrateofparticle(kgs^{-1})
besetshallowerthan100nm[3].Othernon-mechanical techniquesincludeLIGA(lithography,electroplating, and

n	flowbehaviourindex
P	pressure(Pa)
Re	Reynoldsnumber
S_n	nozzlestandoffdistance(m)
V	removalvolumeoftargetmaterial(m^3)
v, v_j	jetvelocity(ms^{-1})
v_n	nozzletraversespeed(ms^{-1})
v_p	particlevelocity(ms^{-1})
w	channelwidth(m)
We	Webernumber

Greekletters

f	channelwallangle(rad)
μ	dynamicviscosityofslurry(Pa.s)
σ	dynamicsurfacetensionofslurry(Nm^{-1})
ρ_s	densityofslurry(kgm^{-3})
ρ_p	densityofparticle(kgm^{-3})
$\dot{g}$	shearrate(s^{-1})

I. INTRODUCTION

Miniaturecomponentstructuresarethefundamentalelementsused in modern micro electro-mechanical (MEM), optical,andbiomedicalsystems.Atechnologythatiscapableoffabricatingthesemicro-structureswithhighprecisionandlowcostisinahighdemandinindustry,butplacesatechnolo-gical challenge worldwide. This challenge is intensified bythe increasing requirements for high surface integrity on themanufactured components, as well as the need to processadvanced materials that are continually developed and areoftendifficult-to-machine. Conventionalmachiningtechnologiesareeithernotcapable of processing some of the materials or inevitablycausedamagestothemachinedcomponentsinadditiontotheproductivityandcostconcerns.Toprocessadifficult-to-machine material, it requires a tool having high hardness andgoodwear-resistancesothatthetoolcanengageintothe material and its sharpness can be retained long during theprocess. In current machining practice, cutting tools with thehardness of as high as five times that

of the workpiece areoften referred to [1], and the diamond appears to be a vitalchoice for many such applications. However, sharpening ofsuchtoolsisdifficult[2].Ontopofthat,highmaterialhardness is often associated with high brittleness, so thatcontrollingtheprocessparameterstoavoidcrackformationisdifficult and often requires using very small cutting parameters.Forinstance,experimentsusingasinglepointcuttingtooltoprocessabrittlesiliconcarbidematerialshowedthattofacilitatetheductilemachiningmode,thedepthofcutmust
moulding) and chemical erosion/etching. LIGA is normallyexpensive to perform and cannot process materials whichcannotbepressedintotheLIGAmould.Thechemicalerosion/etching process cannot be used on chemical resistantmaterials without the assist of some toxic chemical gases inaddition to the difficulty in controlling the surface texturesand its low processing rate [4]. Other techniques include theuse of high intensity energy sources such as electrical dischargemachining(EDM)[5]oralaserbeamablation[6] whichusethermalenergytolocallysoftenandremovethe unwantedmaterial.Thehighintensityheatusedinthese processes is a main cause for craters, micro-cracks, thermaldamages and detrimentally tensile residual stresses [7] on themachined component surfaces, so that a post process is oftenrequired by, say, using an abrasive polishing technique. Forfemtosecondlasermachining,otherthanthecostof operationand equipment, the ablation in this technique is material-specific which depends not only on the thermal but also theopticalpropertiesoftargetmaterial.Minimisingtheheataffectzoneinthistypeofmachiningrequiresaproperselectionoflaserparametersinresponsetotheopticalbreakdownandlaserablationthresholdsofthetargetmaterialand is at the cost of production rate. In addition, ablatedmaterialsmayberedepositedatornearthesiteof breakdown,creatingunintendedstructuresordebrisatthemachiningsite[8].

By contrast, AWJ has been increasingly used for themachining of difficult-to-machine materials [9]. In this technique,ajetofwaterandabrasiveparticleslurryatahighpressureis introduced onto the workpiece. While material removal isessentially undertaken by the abrasive particles, the continuousflow of water carries away the heat generated during the processandeliminatesthethermaleffect,makingittheidealprocessforthermal sensitive materials. However, the application has beenbasedmainlyontheuseofultrahighpressurejetofmillimetresin diameter using large abrasives of above 100 μm for quickstockremoval,whereasthesurfacequalityisofminorconcern.Almostallmaterials,includingthehardestand extremelybrittlediamondcanbedeformedplasticallyto someextent.However,this can only be achievable at a nano length scale during thecontact loading [1]. Given the scale and expense of modernmanufacturingintheproductionofdamage-freemicrofeatures,areductioninscaleofthemacroAWJtechnology,suchasusingsmaller nozzles, finer particles or lower pressures, to promoteductile-mode-like material removal has become attractive for industry.

This paper reviews the developments of the micro AWFtechnology for the machining of hard and brittle materials.The review is based on the work that has been undertaken inthe authors' laboratory and focuses on the system employedtogenerateamicroAWJandtheerosionmechanismsassociated with processing different types of brittle materials.Mathematical models to represent the process and estimatethe relevant process quantities are also presented. The reviewconcludes on the viability of the technology and the prevailingtrendinitsdevelopment.

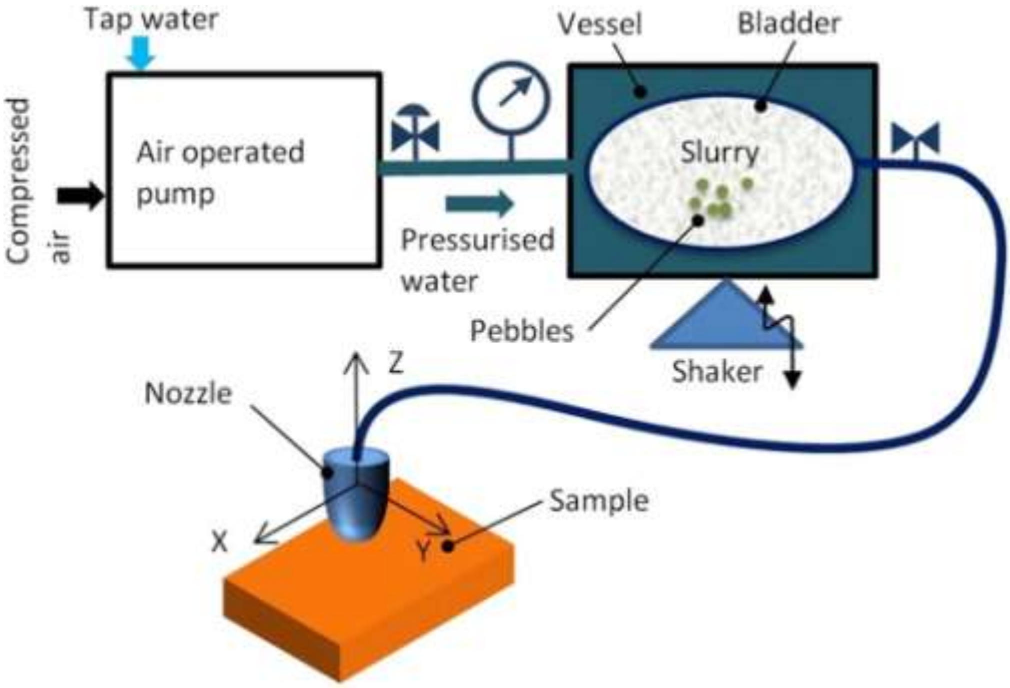

Figure1.AbladdertypemicroAWJmachiningsystem.Reprintedfrom[11],Copyright(2018),withpermissionfromElsevier.

1. Microabrasivejetmachiningsystems

InanultrahighpressuredAWJsystem,theAWJisformedbysupplying abrasives separately into a high pressured waterjetstream. The waterjet stream is formed by a small orifice andflows into a mixing chamber where vacuum is generated,drawing the solid abrasives in, so that it is referred to as anentrainmentsystem.Themixtureisforcedthroughanozzle (orcalledmixingtube),thediameterofwhichistypicalabout 0.8mmto1.6mm[10].Ascale-downofthisworkingprin-cipletoamicro-sizedjetpresentsadifficultysincethepressure in a microjet system may not be high enough tocreate the required vacuum and to entrain the particles in, inaddition to the requirement for precision alignment of theorificeandnozzle. MicroAWJsystemsoftenuseaslurryjetprinciplewherethe particles are mixed with the liquid well before the slurrygoes into the nozzle. The pressure must be high enough toovercomethefrictionastheslurryflowsthroughatiny nozzleof typically about a hundred micrometres in diameter. Thepressurised slurry jet must also provide sufficient energy toinitiate a material removal process on the target material. Onthe other hand, the pressure may not be set too high in orderto avoid damages to the material, particularly those of brittlenature. Furthermore, the divergence of the jet as it is ejectedfrom a micro nozzle must be controlled to meet the precisionofmicromachining.

There have been some studies aiming to scale down theultrahigh pressure AWJ systems, including the reduction insizeofthenozzleandwaterpressure[12]orusingpressurisedwater tank [13]. Pressures used in these scaled-down systemsare typically around 100 MPa, while those in the pressurisedwatertankareabout5MPawhichisnotsufficienttoprocess highwearresistantmaterial.AnumberofmicroAWJsystemshave been constructed and studied in the authors’ laboratory.Figure 1 illustrates one that works better than others. An air-driven liquid pump is used to pressurise water to a desiredpressurebetween2and67MPa.Thewateristhenpassedinto astainlesssteelvessel.Placedinsidethevesselisarubber(orsoftskin)bladderwhichisusedtostore andisolate premixedslurryfromthepressurisedwater.Pressurisedwatersqueezes the slurry through a nozzle assembly. The flow rate of slurrycan be controlled by adjusting the air pressure entering thepumpand/orawaterpressurecontrolvalve.Priortoamachiningprocess,thepressurevesselisvibratedatabout1 Hz by a shaker to allow the slurry to mix uniformly. Somepebbles are added inside the bladder to help with the mixingprocess. In a production environment, two or more vesselsmay be used so that when one is used, the other is refilled sothat continuous operation is possible. A nozzle tube made ofhighwearresistantZrO_2ceramicisplacedinsidethen ozzle assembly.Toeffectivelyisolatethejetflowdisturbance atthenozzle inlet, the aspect ratio (length/diameter) of the tubeshouldbemadegreaterthan50[14].Thisistoensure thatthediameteroftheimpactzonecanbemaintainedapproximatelyasthesameasthenozzlediameter.

2. ErosionMechanisms

Erosionofsingle-phasedmaterial

Unliketheultrahighpressure(typicallyabove100 MPa)abrasive jet applications where the material can be erodedquickly[15,16],inmicrojetmachiningwithalowerjetpressure(typicallyfrom1to30MPa),thejetenergyisnot sufficient to form a cut immediately. The jet dynamic beha-viour and the response of material to the jet impact are vastlydifferent from those in ultrahigh pressure jet applications.Thisreviewisbasedontheinvestigationsintothemicro-hole formationprocesscarriedoutinthe authors'labora-tory[17,18].

The test samples were 5 mm thick amorphous soda-limesheetswhosepropertieswere2.5 × 10^3 kg m^{-3}indensity,75 MPa.$m^{0.5}$ in fracture toughness, 74 GPa in Young modulusand 5.5 GPa in hardness. The slurry jet was set at P = 3 MPaand contained alumina abrasives of 10 μm in average dia-meter(d_p) attheconcentrationbymassC_p= 2.5%.Theabrasiveswerealuminawiththehardnessof10.79GPaand density of 3.65 g cm^{-3}. The nozzle tube was 0.2 mm in innerdiameter and 10 mm in length, and positioned normally to thesample surface with the standoff distance S_n= 1.5 mm. Toinspect the effect of jet viscosity, a polymeric additive (non-ionic polyacrylamide flocculant type, Ciba Magnafloc 333manufactured byCibaSpeciality Chemicals)wasmixedwith theslurryattheconcentrationbymassC_c=0.25%.

Figure2showsthefeatureofatypicalholeprocessedbya low-pressure slurry jet. Characterised by a cross sectionalshape of 'W', the hole has its open diameter about four timesthejetdiameter.

Figure 3illustrates the fluid flow developed upon a jetimpact. The jet velocity direction is diverted from a potentialflow, which is aligned with the nozzle axis, to a viscous flowwhich is parallel to the target surface [20]. It follows that thekerf profiles created by these jet flow characteristics can bedistinguishedbythreezones:AB,BCandCD,asshownin figure 2(a). The jet impact zone AB is within the centralregionoftheholeunderthedirectimpactofthejet [21],and is smaller than the jet diameter. In this zone, the normalimpact direction does not facilitate material removal in thecuttingwear(orductile)modeandtheassociatedremovalrateis small, so that a ridge is formed in the hole central region.ThezoneBCiscreatedbytheviscousflowsweepingalong thetargetsurface.Thetargetsurfacebecomessteeperwiththeincrease of depth in this zone. While promoting the cuttingwear mode erosion, this also allows the erosion rate to beraised. The surface disturbances of the liquid within the vis-cousflowzonedevelopawavetravellingradiallyoutward,as shown in figures 2(b) and 3(b) [22]. Beyond the BC zone istheCDzonewherethewaveisdiminishedandparticlesare accumulated.Aturbulentflowisformedinthiszonewhichisboundedbytheholeedge.

Upon the impact of an abrasive particle, there are twoforcecomponentsactingonthetargetsurface.Whiletheforcecomponent normal to the target surface facilitates an inden-tationintheworkpiece,thecomponenttangentialtothesurface promotes shearing stresses which may create micro-chips from the workpiece or cause a ploughing action to thesurface. Depending on the attribution of the two forces andthe response of target material to these forces, the removal ofmaterial takes place in brittle or ductile mode [23]. In thebrittle mode removal, cracks are initiated and propagated onthemachiningsurface.Bycontrast,whenthematerialundergoingaductileremovalmode,deformationassociated

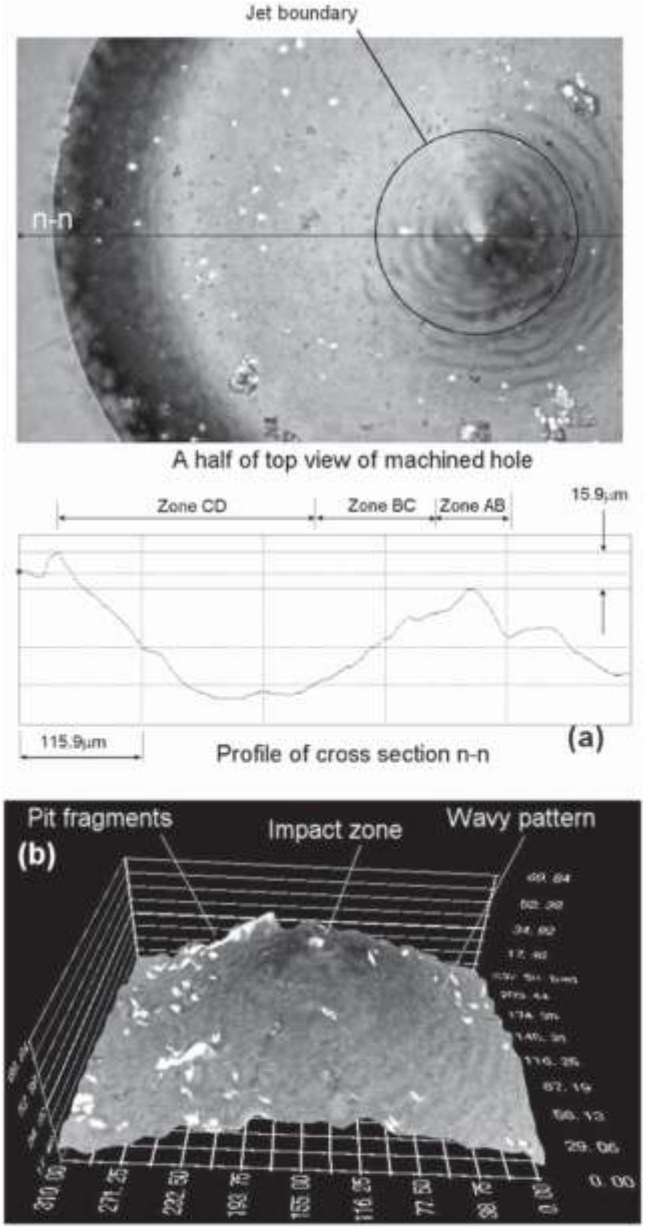

Figure2.Featuresoftheholeafterprocessingfor180sbya3MPaslurryjetof0.2mmindiameter,containing10μmparticles withtheconcentrationC_p=2.5%:(a) topviewandcrosssectionand (b)surfacemorphologyoftheimpactzone(dimensionalunitinμm). Reproducedwithpermissionfrom[17].

with shearing or cutting takes place. A new impact erosionmechanism for ductile materials has been developed to fun-damentallyexplainthematerialremovalprocess,thatis through material failures induced by inertia, elongation andadiabatic shear banding [24]. For consistency, the term cut-ting wear is still used in this paper. Further, the crackedfragments may contribute to the erosion process. It has beenreported that materials eroded by the cracked fragments formsurfaces with the accumulation of the crack edges [25, 26].Because of the jet divergence, a momentum is created thatresults in normal and shear stresses to the target surface [27].As discussed above, the attribution of the two stresses on thetargetmaterialdependsonthefluidflowzonedevelopedon

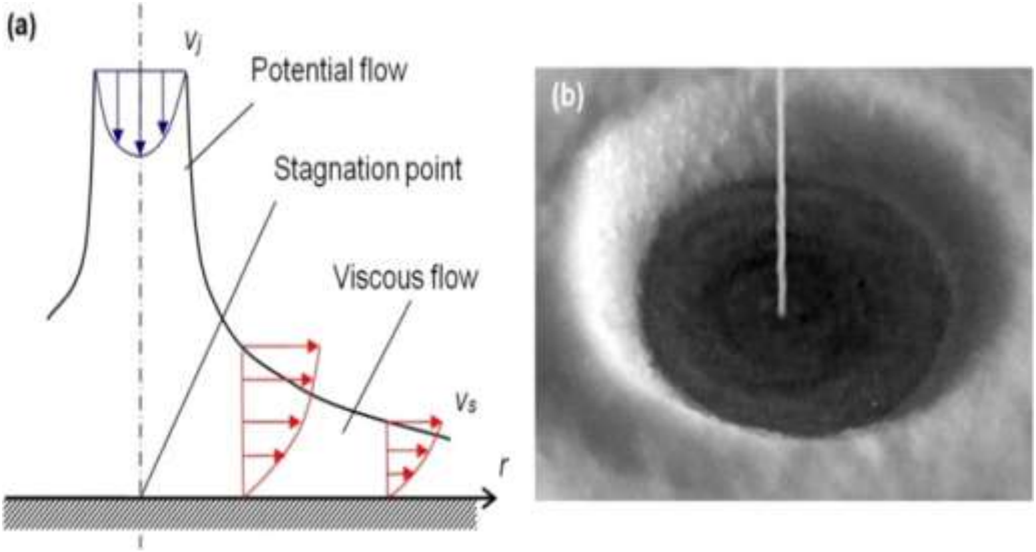

Figure3.Fluidflowdevelopeduponajetimpact:(a) schematic[17]and(b)visualisationofthewavedevelopmentbythejetimpact (machiningconditionasinfigure2)[19].(a)Reproducedwithpermissionfrom[17].(b)Reproducedwithpermissionfrom [19].

material surface. This in turn results in a variation of theappearance of the processed surface. On the surface morph-ology shown in figure 2, some pits are clearly found withinthe AB zone. Within the CD zone, the accumulation of par-ticlesandpossiblypitfragmentspromotesaturbulentmotionthat generates further strikes of particles onto the surface atrandomdirections.Thisparticleladenflowleadstoadecreaseinerosionintheductilemode,ascomparedwiththewavyBCzonewhichappearssmootherthanboththe ABandCDzones. The viscous flow in the BC zone provides a hydro-dynamic film layer that may act as a lubricant or dampinglayer to reduce the friction between abrasive particles andmaterial surface, thereby widening the range of attack anglesfor the cutting wear mode to occur [28]. Further, the fluidflow direction in this zone is favoured for cutting wear byparticles. As a result, a smooth surface without cracks wasgenerated in the BC zone irrespective of the brittleness ofmaterial.Thesesurfacecharacteristicsindicatethepre-dominance of the shearing action, thus ductile erosion modein the material removal process. The appearance of the wavysurfaceisaresultofthewaveenergytransferredtothesurfaceby the wavy viscous flow. An experiment was conductedwhere a polymeric additive was mixed with the slurry toincrease its viscosity. The result shown in figure 4 confirmstheexistenceofawavyviscousflow.

Erosionintwo-phased material

Reaction-bondedsiliconcarbide(RB-SiC) isacompositemade of two major constituents, i.e. silicon carbide (SiC)grains surrounded by a matrix of silicon (Si) [29]. Owing toitsexcellentpropertiesoflightweight,thermalstabilityand chemical inertness, RB-SiC is a favourable material for con-structing devices working in harsh environment, e.g. opticalmirrorsusedinthespace[30].However,asmany otheradvanced materials, RB-SiC is a difficult-to-machine mat-erial.Notonlybecauseofthehardnessandbrittlenessofthe

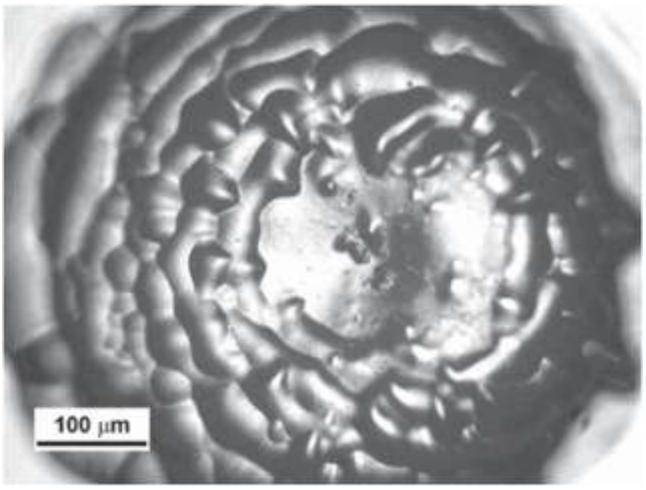

Figure4.Wavypatterndevelopedonaglasssurfaceprocessedafter60sbya2MPaslurryjetof0.2mmdiameter,containing10μmparticlesatC_p=2.5%concentrationbymassandpolymericadditiveattheconcentrationC_c=0.25%bymass.Reproducedfrom[18],withthepermissionofAIPPublishing.

SiC constituent, but the difficulty is also due to the non-uniformity of the RB-SiC structure that consists of the hardphase SiC and the softer Si matrix. Under the same appliedstress, the response of these two constituents is distinctivelydifferent. The work in [11] presents an investigation on thematerial removal mechanisms of RB-SiC and the resultingsurfacequalitywhensubjectedtotheimpactof amicroslurryjet.

The material used in this study had the SiC grains ofapproximate35μminsizesurroundedbyamatrixofSiwiththe volume fraction, C_{Si} about 21.5%. Surface roughness ofthesamples,R_a,wasabout14μm.Theslurryjetcontained25μmaluminaparticleswiththemassconcentrationof 15%andwasoperatedatthewaterpressureof25 MPa.Forcomparison,anothermodeoffixedparticlepolishingwas

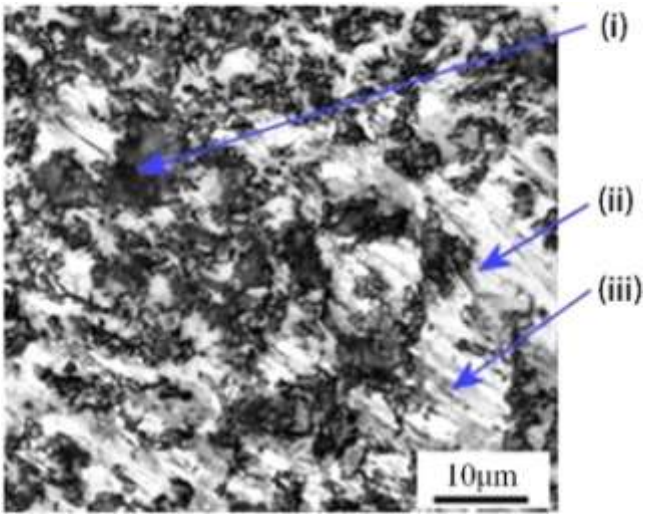

Figure 5.Surfacepolishedafter3minbydiamondabrasives:
(i) brittle fracture of a SiC grain, (ii) embedment of plasticallydeformed Si, and (iii) grooves. Reprinted from [11], Copyright(2018),withpermissionfromElsevier.

conducted, and it was made by using a Struers–TegraForce-1polishing machine.The loadingforceof 20 N wasappliedonthesamplesurfacewhichwasplacedagainsta65μmdia-mondgraineddiskof200 mmindiameterrotatingat30rpm.Figure5showsasurfaceprocessedbydiamondpolish-ing.Large-scaledfracturesintheformofirregularpitsappearonthesurfaceofSiCgrains.Incontrast,theSiportionisfoundtohavebeendeformedplastically.OnthesurfaceofSiphase,thereareanumberofdeepandparallelgroovesalignedwiththeabrasivemotion.ThedeformedSichipswere foundembeddingoverthesurfaceofthefracturedSiCgrains.Figure6illustratesthewearprocessbydiamondpol-ishing.Becauseoftheirextremelyhighbrittleness[31], SiCgrainswhensubjectedtotheindentationofdiamondabrasivesexperienceaninitiationofcracks.Followingtheirrelativemotiontothediamondabrasives,thecracksarepropagatedalongtheSiCgraincleavages.Astheprocesscontinues,thecracksbecomedeepenand,acertaindegree,largefragmentsareformedandconsequentlyremovedfromthegrains,leavingthesurfacewithlargepits.However,theprocessisdifferentfromthegrindingofsingle-phasedSiCmaterialwhere brittle material removal mode is dominant [32]. Of theRB-SiCcompositestructureistheSimatrixwhichcanbeplasticallydeformed,unlikethebrittleSiCgrains.SomepreviousstudiesshowthatamorphoustransformationinSicanbeinitiatedbystress,evenatextremelylowtemperature ofliquidnitrogenboilingpoint(−195 °C) [33],andtheinitiation occurs when indenting the material at a hydrostaticpressure greater than 11–13 GPa [34, 35]. Owing to the wearresistancehigherthanthatofSiC,thesharpnessofthedia-mond abrasives was retained during the process to allow theabrasivestoengagewiththesamplematerialwithsmallcontact areas. As a result, sufficient stresses were developed,raising a plastic deformation on the Si phase. It is noted thatthediamondabrasiveswererelativelylargerthantheSiC grains(65 μm versus 35 μmSiC). During the process, theremovedamorphousSiwasaccumulatedandcompressedintothenearbypockets.Thepocketsincludethespacesbetween thediamondabrasivesandtheprocessedsamplesurface,aswellastheavailablepitsformedbythefracturedSiCgrains.

When comparing with the surface of RB-SiC processedbyaslurry jet,showninfigure7,itisnotedthatnotonlywasthejetpressureused(25 MPa) muchlowerthanthehydro-staticpressurerequiredforinitiatingtheamorphoustrans-formationontheSimatrix(11–13 GPa),theabrasivesofaluminawasalsosofterthantheSiC grainconstituent(20.45 GPa versus 24.53 GPa). Notwithstanding these facts, ahole with a depth of about 141 μm, about four times of theaverage SiC grain size (≈ 35 μm) were formed. The pro-cessedsurfaceappearedwithirregularpatternsofexposed SiCgrainswhicharesurroundedbymicrochannelsformedontheSimatrix.Althoughboththematerialconstituentsarebrittle,therewasnomicrocrackfoundontheerodedsurfaces.ThemechanismofwearonRB-SiCbytheimpactofaslurryjetisclearlydifferentfromthatbydiamondpolishingandthatonthesingle-phasematerialdescribedearlier.Inpolishing,thesameloadisappliedtobothofthematerialconstituentsforthesamedepthofcut.Inslurryjetimpact-inducedmaterialremoval,weartakesplacemainlybythemotionoftheabrasiveswhich can roll, rebound, collide and/or slide freely. Certainly,thealuminaabrasives,particularlywhendrivenbyalowpres-surisedjet,cannotindentintotheharderSiCgrains.Theabra-sive-materialengagementcanbemadeonlyontheSimatrixwhose hardness is lower than that of the abrasives. Followingtheengagement,theremovalofmaterialismadebytwoactionsofshearingandwedging.Theshearingtakesplacebytherollingactionoftheengagedabrasives,whicheventuallycreatesanumberofchannelsalongtheSimatrixandaroundtheharder SiCgrains,asillustratedinfigure7(a).ItisnotedonthedepthoftheholeprocessedinthisworkisfourtimestheSiCgrainsize.

Since wear cannot be made directly on the SiC grains, it isimplied that the removal of the SiC grains takes place byweakeningtheirbondingwiththematerialstructuretocauseaneventualremovalofthewholegrainsfromthesubstrate.

Because of the small volume fraction of Si (C_{Si}≈ 21.5%), thespacebetweenthehardSiCgrainsisgenerallynarrowerthanthe abrasive size. Such narrow spaces prevent the abrasives frompenetrating deeper into the roots of the SiC grains. The wearcausedbytheshearingonSimaybediminished.Astheprocesscontinues,thecomingabrasivesactaswedgesthatweakenthebondandfinallyliftupthewholeSiCgrainsfromthesubstrate,asshowninfigure8.Bythiswedgingaction,micro-cracksmaybeformedattheinterfacebetweentheremainedSiCgrainsandthesurroundingSibond.Nevertheless,theshearinducedbytherolling action of abrasives again takes place to smoothen thenewlycrackedsurfaces,resultinginthecrack-freesurfaceas showninfigures7and8(b).

Itisfeasibletousealow-pressureslurryjetcontaining abrasives that are softer than the SiC grains, to machine RB-SiCcomposite without causing any brittle fracture. The abrasivewearonRB-SiCinvolvesdifferentmechanismsintheSiand

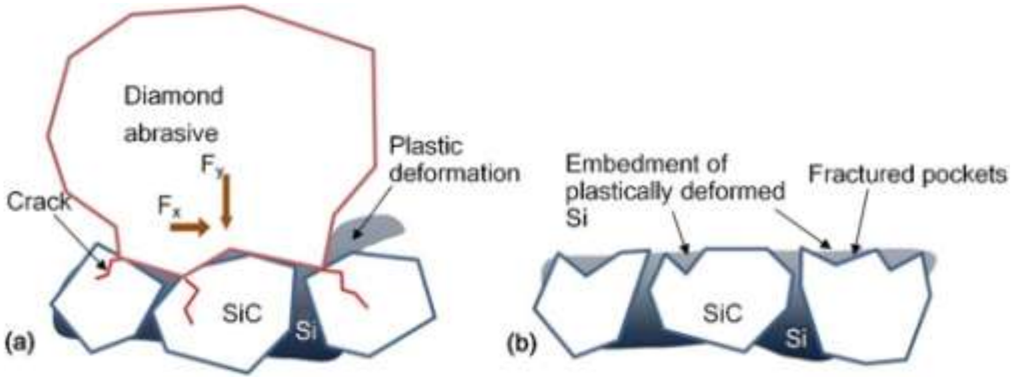

Figure6.SchematicofwearprocessonRB-SiCbydiamondabrasives:(a)formingofcracksonSiCgrainsandplasticdeformationonSimatrix;and(b)embedmentofSiinthefractured pockets ofSiC grains.Reprintedfrom[11],Copyright(2018), withpermission fromElsevier.

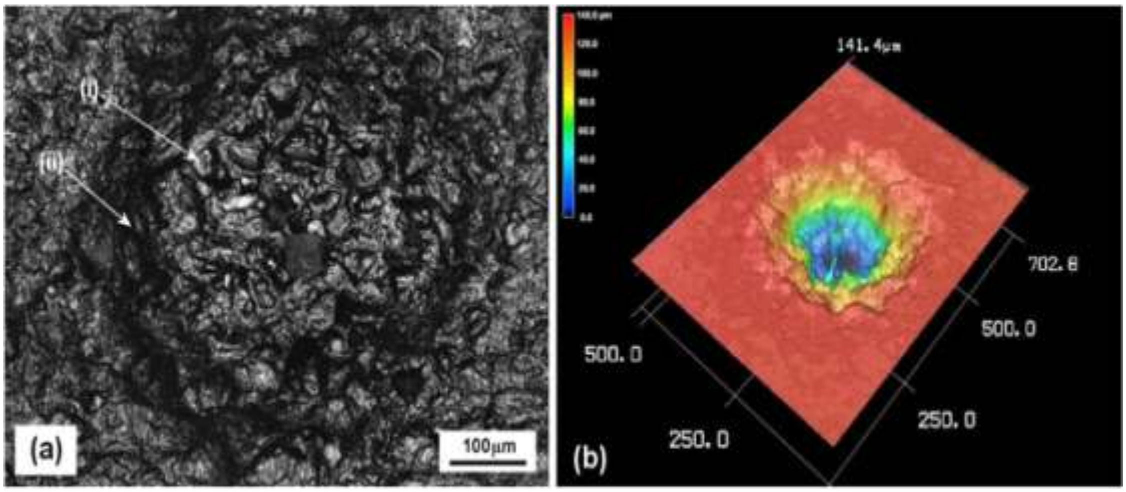

Figure7.Topology(a)and3Dprofile(b)ofRB-SiCsurfacesprocessedafter10sbyslurryjet((i)exposedSiCgrainsand(ii)channels).Reprintedfrom[11],Copyright(2018),withpermissionfromElsevier.

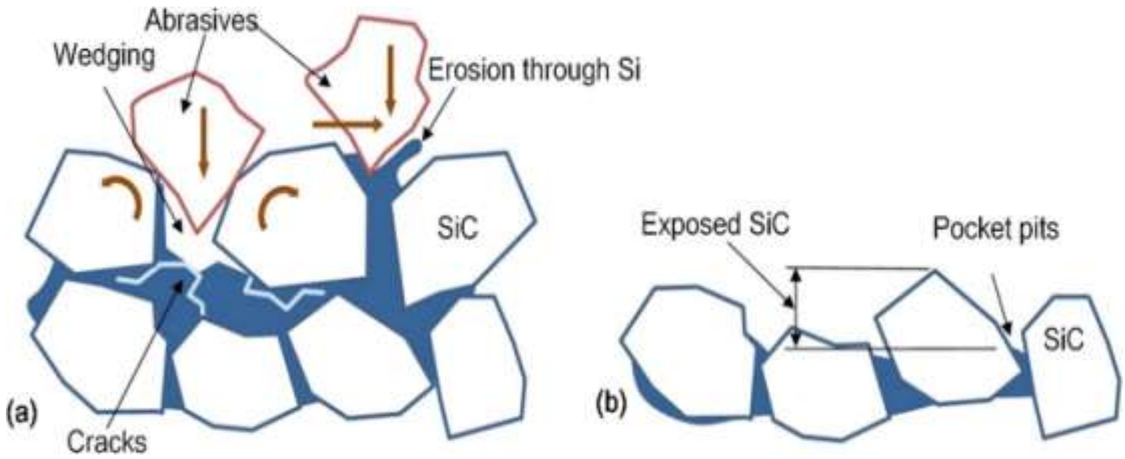

Figure8.SchematicofthewearprocessofRB-SiCbytheimpactofanaluminaslurryjet:(a)materialremoval,and(b)exposedsurface.Reprintedfrom[11],Copyright(2018),withpermissionfromElsevier.

SiCconstituents.Indiamonddiskpolishing,brittlefractureisdominant on the SiC phase and there are depositions of theplasticallydeformedSiphaseonthefracturedSiCsurface.Bycontrast,wearcausedbyslurryjettakesplacemainlythroughweakeningtheSibondbyerosionandwedgingaction,whicheventuallyreleasestheSiCgrainfromthematerialstructure.

3. Processmodels

Jetstability

Aliquidjetasejectedfromanozzleisnolongerconstrainedbythenozzleinnerwall,but contactswiththe atmosphericair.The

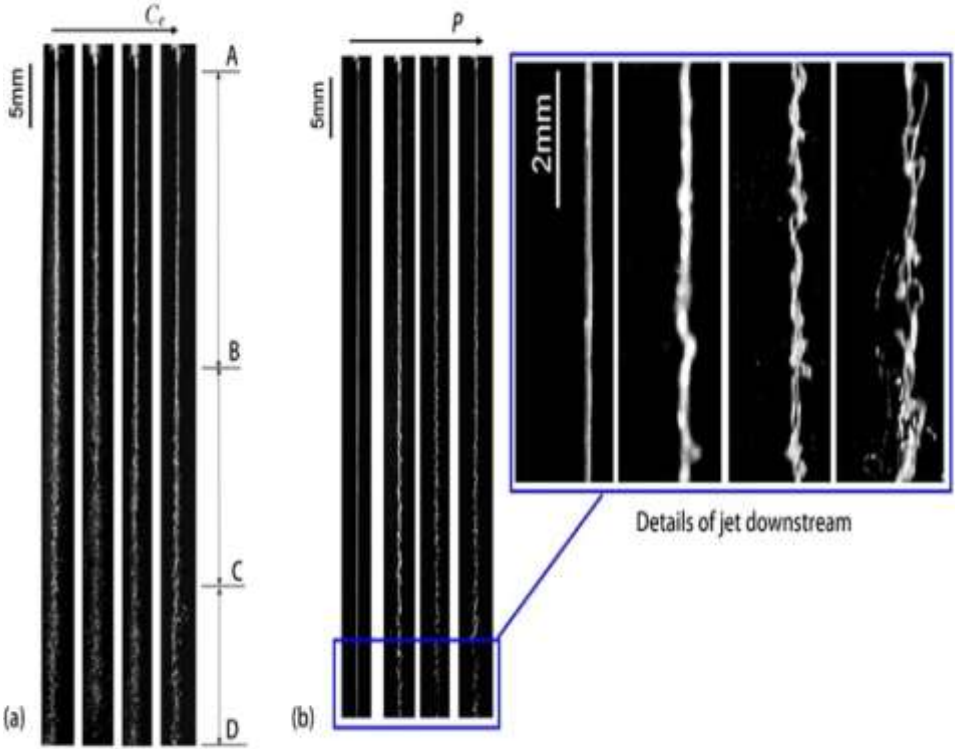

Figure9.Jetstabilitybytheeffectof:(a)chemicalconcentration,C_c,varyingfrom0,0.1%,0.25%to0.5%(P=2MPa,d=0.84mm); and (b) pressure,P,varyingfrom1,2,3to4MPa(d=0.84mm,C_c = 0.25%,C_p= 5%andd_p= 10μm).Reprintedfrom[36],Copyright (2008),withpermissionfromElsevier.

Table1.Testingconditionsinthestudyofjetstability.Reprintedfrom[36],Copyright(2008),withpermissionfromElsevier.

Nozzlediameter,d(mm)	0.19,0.50and0.84
Pressure,P(MPa)	1,2,3and4
Polymeradditive(%bymass),C_c	0(wateronly),0.1,0.25and0.5
Particlecontent(%bymass),C_p	1and5
Particlemesh(andsizeinbrackets)	600(d_p=25μm),1000(15μm),and1500(10μm)

jetbecomes diverged and depending on the distance from thenozzleexit,differentflowregimesaredeveloped.Unliketheuseof solid cutting tools, where the depth of cut can be easilycontrolled and the tool/workpiece contact area can be deter-mined,inthejetcuttingtheseparametersdependonthekineticbehaviouroftheejectedjet.Whereasthedivergenceenlargestheimpactzone,thechangeintheflowregimeleadstoavariationofvelocitydistributionwithinthejetcrossectionalareawhenimpacting on a target. These changes potentially make thecontrol of liquid jet difficult. This is particularly important inmicrojet machining where precision is of major concern. Inaddition, as discussed above, viscosity of the slurry used in anon-throughcutinmicrojetmachiningplaysanimportantroleinthebehaviouroftheviscousflowthatgovernsthemorphologyofthemachinedsurface.Inthiswork[36],ajetcompactlengthmodel was established to present a mathematical relationshipbetweenthejetstabilitymeasuresandthejettingparameters.

Table 1 [36] shows the test conditions. To examine theeffect of surface tension and viscosity of the jet, a polymericadditive(nonionicpolyacrylamideflocculа nttype,Ciba Magnafloc333manufacturedbyCibaSpecialityChemicals) was mixed with the slurry. The jet images were obtained atsteady state of flow using the stroboscope method [37] withtheilluminationflashingof3μs.

Figure 9(a) shows instantaneous images of the jets sub-jectedtodifferentconditionsofchemicalconcentration.

Typically, a jet consists of three zones: AB, BC and CD.These zones are indicated in figure 9(a) for the most rightflowwhereC_c=0.5%.InthecompactzoneAB,thejetisin good coherenceand itslength ismeasured asa compactlength, L. The stability of the jet maintains until reaching thestage where disintegration occurs in the zone BC. Fartherfrom the jet nozzle is the zone CD where the jet has totallylostitsstability,formingdrops.Incontrastwiththeuseof water only slurry solution (C_c= 0) where the disintegrationofwaterjetoccurredsomewhereclosetothenozzleexit,the compact lengths (L) were increased by increasing the polymeradditive in the jet. On the surface of a liquid jet, oscillationsandperturbationsoccursasaresultofthecompetition between cohesive and disruptive forces [38]. The cohesion isformedbysurfacetensionthatrestrainstheliquidfrombreakingupintodrops.Incontrast,thedisruptionispromoted byaerodynamicforcesactingontheliquidsurface.Whenthemagnitude of the disruptive forces exceeds the surface ten-sion, break-ups occur. The role of liquid viscosity, on theotherhand,istoinhibitthegrowthofinstabilitiesand gen-erally delay the onset of disintegration [37, 39–41]. For thepolymericfluidsusedinthisstudy,theenhancementofjet stability is mainly attributed to the increase of viscosity sincethe surface tension is reduced when increasing the chemicalconcentration[42].

Theeffectsofjetpressureonthejetstabilityareshownin figure9(b).Atalowpressureof1MPa,thejethasaverylarge compactlength.Thisisprobablybecausethejetbehavedunder Rayleighmanneroflaminarflowwherethe disintegrationofjetwascausedmainlybydilatationalwaves.This type of waves is developed by rotationally symmetricaloscillationofthejetwhereanydisturbancesisdampedoutbythefluidviscosity.Thejetbecomesunstableanddisintegratesonly when the incidental internal perturbations cause narrowbands to develop in the jet to a certain critical stage of thewavelength[43].AccordingtotheWebertheory[38],thewaveformationisinducedbytherelativevelocityofairtothe outer layer of jet on which the air friction shortens thecritical wave length. Jets injected at low pressures have lowvelocities, thus receiving a low air friction so that it is morestable. The promotions of the air friction to the jet surface athigherjetvelocitiesincreasethewaveamplitudesand shortenthewavelengths.Enlargedviewsofthisphenomenonare shownontherighthandsideoffigure9(b)forthejetwave

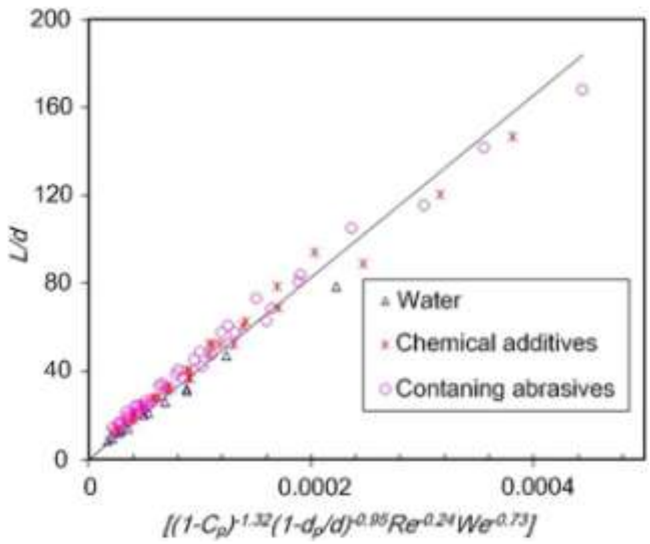

Figure 10.Modelpredictions(solid line) versusexperimentalmeasurements(dots).Reprintedfrom[36],Copyright(2008),withpermissionfromElsevier.

Thepowerlawformulationapproachwasappliedtofurt herdevelop equation(1) inwhich thecoefficientandexponents of the power law patternsat20mmdownstreamfromthenozzleexit.Itcanbe

L

noticedthatwaveamplitudesincreaseandwavelengths decrease as the jet pressure increases from 1 to 4 MPa, wherethewavepatternsmaybeconsideredasadilatatio nalwavein1 MPa,sinuouswavein2 MPaandadistortionofwaveaxes

in3and4MPa.

The aforementioned physical understanding shows thatthe stability of a jet is governed by the internal and externalfactors. By superimposing the two causes, the stability whichis represented by the compact length, L can be analysed anddetermined. Theinternaldisturbances are associated with the fluid properties including slurry density (ρ_f), surface tension(σ), viscosity (μ), particle size (d_p) and particle concentration(C_p).Theexternaldisruptionisformedby thefrictionbetweenthejetsurfaceandtheatmospherica ir,thatinturnisadirectresultofthejetvelocity(v_j)orjetpr essure(P).Usingthe Buckingham Π theorem, the $f(P_1,P_2,P_3,P_4,P_5)=0$, wherethedimensionlessparametersaredefinedas (1)

$P_1=\frac{L}{d}$

$P_2=Re=\frac{rvd}{m}$

characteristiclengthratio,representingthejet stability

$P=We=\frac{rv^2d}{s}$ Webernumber,expressingtheliquidinert ia

3

$P_4=C_p$

$P_5=\frac{d_p}{d}$

force/thesurfacetensionratio

representingtheeffectofparticleconcentration

representingtheeffectofparticlesize

erialpropertieshavebeendevelopedsuchasth osein[44].

equation were obtained usingmulti-variable regression of the experimental data. At a 95%confidencelevel,itgave

$$\frac{L}{d}=4.1\times10^5(1-C_p)^{-1.32}\left(1-\frac{d_p}{d}\right)^{-0.95}Re^{-0.24}We^{-0.73},$$
(2)

above parameters can begroupedas[31] whereunitsoftheparametersareinSIsystem.Figure10 showstherelationshipexpressedinequation(2),where experimentaldataarealsoplottedforcomparison.

Itcanbeconcludedthatthejetstabilitycanbestrengthen edbytheadditionofpolymericadditivesthatincreasest heliquidviscosity.Bycontrast,thefrictionbetween the surrounding air and the jet surface promotes jetbreak-up, and this external effect increases when increasingthe jet velocity. The parametric model developed provides anessentialmeans towardsoptimizing the liquid and jettingparameters to maximize the jet stability and ultimately toenhancethecuttingperformanceofmicrojets.

Processperformance

Itisclearthatthemicromachiningtechnologyusingami crojetcancreateacutorchannelwithawidertopand

Reynoldsnumber,expressingtheliquidinertial force/viscousforceratio

narrower bottom, so that a kerf taper is formed, as approxi-mated and shown in figure 11[44], with the geometry thatincludes thechanneldepth(h),thetop channelwidth(w)and

thechannelwallangle(f).Thesecharacteristicsofthe

machinedfeaturesaswellasmaterialremovalrate(MRR)a reofmajorconcerninpractice.Modelsforestimatingth ese micromachiningperformancemeasuresforgiventarge tmatwhere v_p is the average velocity of particles impacting on thematerial,and$\dot{m}_p$isthemassflowrateofabrasiveparticles throughthenozzlewhichisgivenby

$$\dot{m}_p = C_p r_p v_j \frac{\pi d^2}{4} \quad (4)$$

inwhich$r_p$isthedensityoftheparticle,$d_n$isthenozzlediameter and $C_p$is the percentage particle concentration by mass.Sincetheslurryisconsideredtobeuniformlymixed,theparticlevelocity(v_p)canbe assumedtobeequal totheslurry velocity(v_j)atthenozzleexit,i.e.

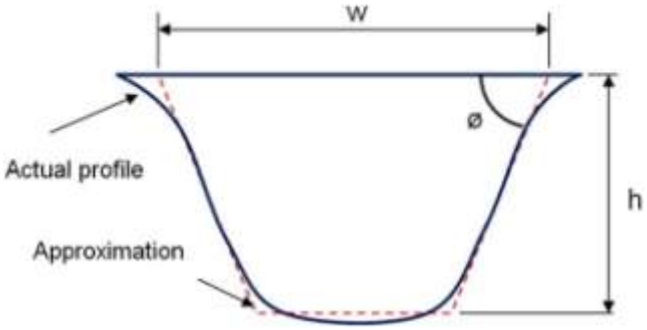

Figure11.Approximationofthechannelcrosssection.Reprintedfrom[44],Copyright(2012),withpermissionfromElsevier.

$$v_p \approx v_j. \quad (5)$$

FromBernoulli'sprinciple,thejetvelocitycanbedeterminedas

$$v_j = k_d \sqrt{\frac{2P}{r_s}}, \quad (6)$$

wherePisthewaterpressure,$r_s$isthedensityoftheslurryand$k_d$isadischargefactortoaccountforvelocitylossduring jetformationduetonozzlewallfriction,andfluidflowdisturbancesoftheslurry.

Properties of the target material and particle.Volumeof the target material removed by an abrasive particle (V) iscomputedusingthemodelproposedbyHutchings[28],i.e.

$$V = C_m d_p^3 \frac{r_p d_p^2}{H_m}, \quad (7)$$

where$C_m$is the coefficient that accounts for the materialproperty in response to the impact of a particle, including thehardness(H_m),fracturetoughness(K_m)andelasticmodulus (E_m) ofmaterial,i.e.

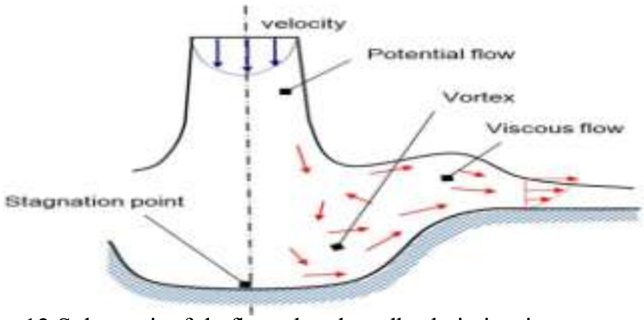

Figure12.Schematicof theflowsdevelopedbythejetimpingement

C=C
(H,K,E).
(8)

inthecreationonachannel.Reprintedfrom[44],Copyright(2012),withpermissionfromElsevier.

Figure 12 presents a schematic of the flows developed uponthe jet impact on a surface. As discussed in [44, 45], the jetkineticenergythatisdirectlytransferredtotheabrasiveparticlesplays a major role in forming the depth of channel, while theformationofthechannelwidthisgovernedbytheviscousflow.

m m m m m

Dynamicpropertiesofthefluid.Theviscousbehaviourof a flow depends on the fluid properties of the slurry, i.e. thedynamicfluidviscosity(μ) andsurfacetension(σ).Theabrasive-waterslurryistreatedasanon-Newtonianfluidwith thedynamicfluidviscosity,μasshown[46]

Theexpansionoftheflowisconstrainedbythecreatedchannelsidewallwherevorticesaregenerated.Suchvorticesforma

$m = K\dot{g}^{n-1}$,
(9)

turbulentflowthatdrivestheparticlesaccumulatedatthebottomofthechannelandcontributestotheformationofchannelwallinclination.Thefeaturesofthechanneltherefore canbeanalysedbased on the main causes, including the jet kinetic energy,propertiesofthetargetmaterialandparticle,dynamicproperties

whereġistheshearrate,andKandnaretheconsistencyand theflowbehaviourindexesoftheslurry,respectively.Kandnare the constitutive properties which for a given fluid, is afunctionoftheparticlecontained(C_p)andthesizeofparticles

(d_p) intheslurry,i.e.

ofthefluid,and dynamicsofthe nozzlemotion.Asemi-ana-lyticalapproachhasbeenusedtodevelopthemodels[2, 37].

4.2.1.Jetkineticenergy.

Astheerosiontakesplacebythe

$K = K(C_p, d_p)$,
$n = n(C_p, d_p)$.
(10)
(11)

motionofabrasiveparticles,thekineticenergycanbeapproximatedas

Foragivencontrolledvolume,theshearratecausedbyagivenslurrycanbeconsideredasafunctionofthejetvelocityattheimpactzone[47],i.e.

$$\frac{dKE}{dt} \approx \frac{1}{2}\dot{m}_p v_p^2, \quad (3)$$

$\dot{g} = \dot{g}(v_j)$.
(12)

Fromequations(9)–(12),
$m = m(C_p, d_p, v_j)$.

(13)

Table2.Operatingparametersformicro-channelmachining.Reprintedfrom[44],Copyright (2012),withpermissionfrom Elsevier.

Waterpressure,P(MPa)	8,10,12and14
Nozzletraversespeed,v_n(mms^{-1})	0.15,0.20,0.25and0.30
Particleconcentration,C_p(%bymass)	15,20,25and30

Accordingtothereportedstudies[48,49],theincreaseofparticleconcentrationcanleadtoanincreaseintheinterfacial

Nozzlestandoffdistance,S_n(mm) 3,4,5,6

surfacesandtheabsorptionofparticlesinslurry,whichin turnresultsinanincreaseinthedynamicsurfacetension of

theslurry.Further,theabsorptionoftheparticlesislimitedbythe size of the particles contained in the slurry. The dynamicsurface tension of slurry therefore can be expressed in theformas
used were 5 mm thick amorphous soda-lime glass sheets, thesamematerialasthatusedintheholedrillingstudyofthispaper.Aluminaabrasiveswiththeaveragediameter d_p= 25µmwereused.Table2showstheoperating

$s=s(C_p,d_p,v_j)$.
(14)
parametersformachining micro-channels. Byregressionanalysisoftheexperimentaldataat95% confidencelevel,equations(17)and(18)become

4.2.4.Dynamicsofthenozzlemotion.
$MRR=f(d_p,r_p,C_p,v_p,v_n,d_n,H_m,E_m,K_m)$.

(15)$h=\frac{w+\sqrt{w^2-(4MRR/v_n)\cos f}}{2\cos f}$
(21)

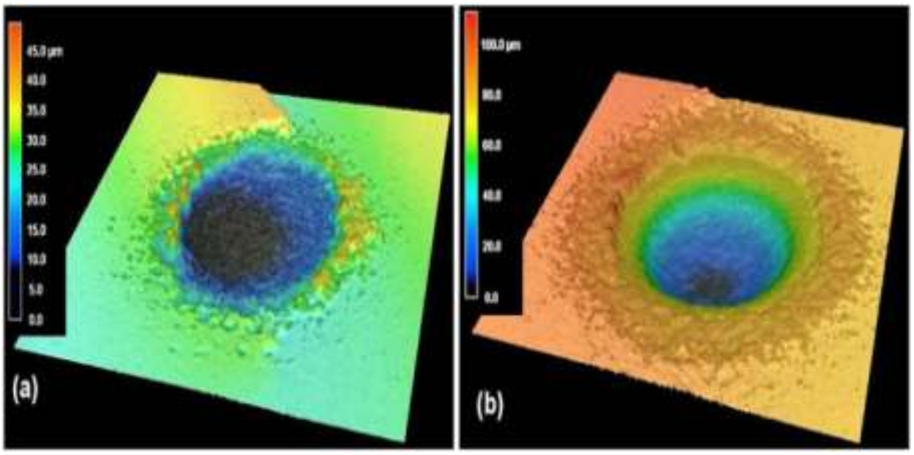

Figure13.HolefeaturesobtainedonSiCsurfaceafter30sofprocessingbya120ms^{-1}slurryjetof125µmindiametercontaining25µmSiCabrasivesat15%concentration:(a)withoutvibrationand(b)withvibration.

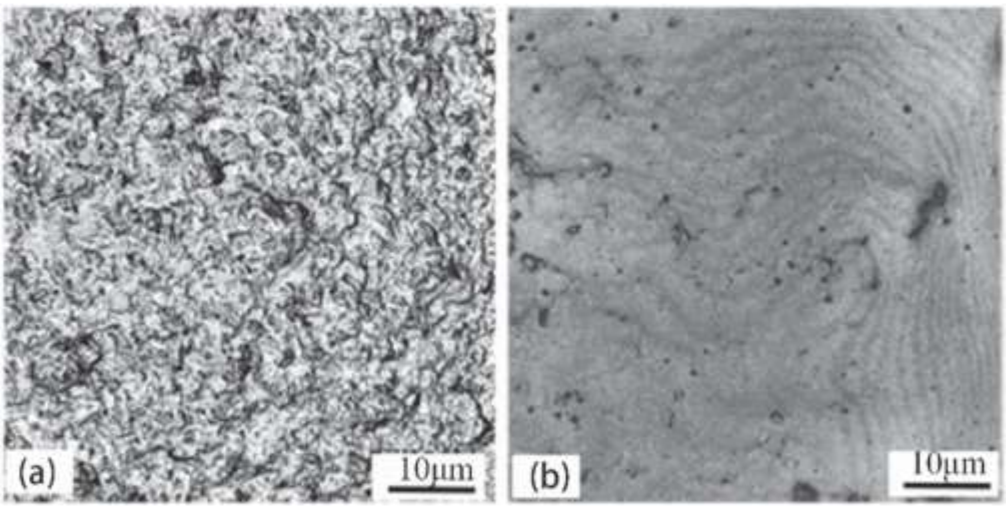

Figure14.SurfacetopologyofSiCafter30sofprocessingbyaslurryjetdescribedinfigure13:(a)withoutvibrationand(b)withvibration.

performancemaybedifferentfromthoseintraditional machiningwheresolidtoolsareused[52,53].Inarecent studyattheauthors' laboratory,ultrasonicvibrationof20kHzwasappliedperpendicularlyonthetargetmaterial surface with the amplitude in an order of ten micrometres.The target materialwas single crystal 4H-SiC thin film of350 μm in thickness. This type of material is considered to beextremelyhardandbrittle,rankedasthirdinthehardness
scale after diamond and cubic boron nitride (CBN) [1].
Theworkuseda125μmdiameternozzleandSiCabrasives with
the concentration varying up to 15%. The jet velocity
wascharacterisedasfullyturbulentwiththevelocityabove120ms^{-1}.
Figure 13shows the typical hole features obtained frommicrojetmachiningwithoutandwithvibrationassistance.Itwasfound that vibration assistance could enhance the MRR. Theholeprocessedwiththevibrationassistancehadthedepthof18timesgreaterthanthatobtainedwiththesamemachiningcon-ditionbutwithouttheassistanceofvibration.Itwasinterestingtofindthatnotonlythe MRR,butalsothesurfacefinishthat
wassignificantlyimproved,asshowninfigure14.Itisnoticedthat in spite of the material's brittleness and the tendency ofbrittlefailure,ductiledeformationwasfoundtobedominantonthe SiC surface processed with vibration assisted
microjet.Detailsofthisfindingwillbereportedseparately.

II. CONCLUSIONS

A micro scale of the ultrahigh pressure AWJ is capable ofmachining micro part geometrical features. While it earns thevariousadvantagesofAWJ,itcanprovideaductile-likematerialremoval on the processed surface regardless of the material'sbrittleness.Thecharacteristicsofthemachinedsurfaceand
featuresarearesultofdifferentwearprocessesassociatedwiththechangeofflowregimesdevelopedonthesurface.Thevis-cous flow generated upon the jet impact induces a shearingactionwhichisakeymechanismthatpromotestheductile-likeremovalmode.Relevantmodelshavebeendevelopedforesti-matingthejetandprocessperformance.Withtheassistanceof vibration,it isfeasibletoextendthetechnologytoprocessingextremelyhardandbrittlematerials,inwhichthevibrationdoesnotonlyenhancethe MRR,butalsothesurfacefinish.Furtherworkisbeingundertakentooptimisetheoperatingparametersforabalancebetweentheproductivityandthehighdemandformachinedsurfaceintegrity.

REFERENCES

[1] Saurav G 2014 The current understanding on the diamondmachining of silicon carbide J. Phys. D: Appl. Phys. 47243001
[2] ChenY,NguyenTandZhangLC2009Polishing ofpolycrystallinediamondbythetechniqueofdynamicfriction—Part5:quantitativeanalysisofmaterialremovalInt.J.Mach.ToolsManuf.49515–20
[3] PattenJ,GaoWandYasutoK2004Ductileregimenanomachiningofsingle-crystalsiliconcarbideJ.Manuf.Sci.Eng.127522–32
[4] ShinjiM,Sin'yaM,ToshiyaY,HiroakiAandSusumuN1981Reactiveion-beametchingofsiliconcarbideJapan.J.Appl.Phys.20L38
[5] ZhaoY,KuniedaMandAbeK2016ChallengetoEDMslicingofsinglecrystalSiCwithbladeelectrodeutilizingareciprocatingworktableProcediaCIRP42185–90
[6] BorowiecAandHaugenHK2004FemtosecondlasermicromachiningofgroovesinindiumphosphideAppl.Phys.A79521
[7] NguyenT,ZarudiIandZhangLC2007Grinding-hardeningwithliquidnitrogen:mechanismsandtechnologyInt.J.Mach.ToolsManuf.4797–106
[8] KeK, JoglekarAP,Hsiao-huaL,MeyhoferE, HasselbrinkE,MourouGandHuntAJ2005Thephysicsandlimitsoffemtosecondlasermicromachining(CLEO) Conf.on LasersandElectro-Optics
[9] WangJ2003AbrasiveWaterjetMachiningofEngineeringMaterials(Zurich:TransTech)
[10] SummersD1984WaterjettingTechnology.(London:ChapmanandHall)
[11] NguyenT,LiuD,ThongkaewK,LiH,QiHandWangJ2018The wear mechanisms of reaction bonded silicon carbideunder abrasive polishing and slurry jet impact conditionsWear410–411156–64
[12] LiuHT2010WaterjettechnologyformachiningfinefeaturespertainingtomicromachiningJ.Manuf.Process.128–18
[13] NouraeiH,WodoslawskyA,PapiniMandSpeltJK2013Characteristicsofabrasiveslurryjetmicro-machining:acomparisonwithabrasiveairjetmicro-

machiningJ.Mater.Process.Technol.2131711–24

[14] McCarthyMJandMolloyNA1974ReviewofstabilityofliquidjetsandtheinfluenceofnozzledesignChem.Eng.J.77–20

[15] HumphreyJAC1990FundamentalsoffluidmotioninerosionbysolidparticleimpactInt.J.HeatFluidFlow11170–95

[16] MomberAWandKovacevicR1998PrinciplesofAbrasiveWaterJetMachining(Berlin:Springer)

[17] NguyenT,PangKandWangJ2009Apreliminarystudyoftheerosionprocessinmicro-machiningofglasseswithalowpressureslurryjetKeyEng.Mater.389–90375–80

[18] WangJ,NguyenTandPangK2009MechanismsofmicroholeformationonglassesbyanabrasiveslurryjetJ.Appl.Phys.105044906

[19] PangKL2011Astudyoftheabrasivewaterjetmicro-machiningforamorphousglassesPhDThesisSchoolofMechanicalandManufacturingEngineering,TheUniversityofNewSouthWales

[20] McLeanRH1964CrossflowandimpactunderjetbitsJ.PetroliumTechnol.161299–306

[21] YanaidaK1974Flowcharacteristicsofwaterjet2ndInt.Symp.onJetCuttingTechnologyBHRAFluidEngineering(Cranfield,Bedford)

[22] BhuniaSKandLienhardVJH1994SurfacedisturbanceevolutionandthesplatteringofturbulentliquidjetsJ.FluidsEng.116721–7

[23] Wensink H and Elwenspoek M C 2002 A closer look at theductile–brittle transition in solid particle erosion Wear 2531035–43

[24] WangJandLiWY2016AnewlookintothelooseparticleimpactprocessforductilematerialsMater.Sci.Forum874213–8

[25] ZengJandKimTJ1996AnerosionmodelforabrasivewaterjetmillingofpolycrystallineceramicsWear199275–82

[26] BitterJGA1963Astudyoferosionphenomena: PartII Wear6169–90

[27] GerhartPM1992FundamentalsofFluidMechanics(Harlow:Addison-Wesley)

[28] HutchingsIM1992Tribology:FrictionandWearofEngineeringMaterials(London:EdwardArnold)

[29] PaikU,ParkHC,ChoiSC,HaCG,KimJWandJungYG2002Effectofparticledispersiononmicrostructureandstrengthofreaction-bondedsilicon carbide Mater.Sci. Eng.334267–74

[30] ToulemontY,BreysseJ,PiepotDandMiuraS2004The3.5-mall-SiCtelescopeforSPICAProc.SPIE54871001–12

[31] YoshidaM,OnoderaA,UenoM,TakemuraKandShimomuraO1993Pressure-inducedphasetransitioninSiCPhys.Rev.B4810587–90

[32] AgarwalSandRaoPV2008Experimentalinvestigationofsurface/subsurface damage formation and material removalmechanismsinSiCgrindingInt.J.Mach.ToolsManuf.48698–710

[33] ZarudiI,NguyenTand ZhangLC2005 EffectoftemperatureandstressonplasticdeformationinmonocrystallinesiliconinducedbyscratchingAppl.Phys.Lett.86011922

[34] JangJ,LanceMJ,WenS,TsuiTYandPharrGM2005Indentation-inducedphasetransformationsinsilicon:influencesofload,rateandindenterangleonthetransformationbehaviorActaMater.531759–70

[35] BudnitzkiMandKunaM2016StressinducedphasetransitionsinsiliconJ.Mech.Phys.Solids9564–91

[36] NguyenT,ShanmugamDK andWangJ2008 EffectofliquidpropertiesonthestabilityofanabrasivewaterjetInt.J.Mach.ToolsManuf.481138–47

[37] NguyenTandZhangLC2005ModellingofthemistformationinasegmentedgrindingwheelsystemInt.J.Mach.ToolsManuf.4521–8

[38] LefebvreAH1989AtomizationandSpray(WashingtonDC:TaylorandFrancis)

[39] GrantRPandMiddlemanS1966NewtonianjetstabilityAIChEJ.12669–78

[40] KitamuraYandTakahashiT1976StabilityofaliquidjetinairflownormaltothejetaxisJ.Chem.Eng.Japan9282–6

[41] DombrowskiNandJohnsWR1963TheaerodynamicinstabilityanddisintegrationofviscousliquidsheetsChem.Eng.Sci.18203–14

[42] ZhangJandPeltonR1999Thesurfacetensionofaqueouspoly(N-isopropylacrylamide-co-acrylamide)J.Polym.Sci.A372137–43

[43] BayvelLandOrzechowskiZ1993LiquidatomizationCombustion(AnInternationalSeries)(London:TaylorandFrancis)