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The‘skin effect’of subsurface damage distribution in materials subjected to high-speed machining

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ABSTRACT
This paperproposesthe ‘skineffect’ofthemachining-induceddamageathighstrainrates.Thepaperfirstreviewsthepublishedresearchworkonmachining-induceddamageandthenidentifiesthegoverningfactorsthatdominatedamageformationmechanisms.Amongmanyinfluentialfactors,suchasstress–strainfield,temperaturefield,materialresponsestoloadingand loadingrate,andcrackinitiationandpropagation,strainrateisrecognizedasadominantfactor thatcandirectlyleadtothe‘skineffect’ofmaterialdamageinaloadingprocess.Thepaperelucidatesthatmaterialdeformationathighstrainrates(>10^3 s^{-1}) leadstotheembrittlement,whichinturncontributestothe‘skineffect’ofsubsurfacedamage.Thepaperdiscussesthe‘skineffect’basedontheprinciplesofdislocationkineticsandcrackinitiationandpropagation.Itprovidesguidancetopredictingthe materialdeformationanddamageatahighstrain-ratefor applicationsrangingfromthearmorprotection,quarrying,petroleumdrilling,andhigh-speedmachiningofengineeringmaterials(e.g.ceramicsandSiCreinforcedaluminumalloys).
Keywords:skineffect,strainrate,dislocation,embrittlement,damage

I. INTRODUCTION

The term ‘skin effect’ has been used to describe distributionof the alternating current in a conductor that electric currentmainly flows in the ‘skin’ layer of the conductor. The currentdensityisthehighestatthesurfacelayeroftheconductorandquickly decreases in the inner layers. The ‘skin effect’ isfurther strengthened at a higher frequency of the alternatingcurrent.Similarly,theauthorshavefoundthatthe‘skineffect’ ofsubsurfacedamage(SSD)distributionalsoexistsin materialdeformations.The‘skineffect’ ofSSDdistributioncanbeenhancedatahigherstrainrateinaloadingprocess.

Generally, an increased strain-rate results in embrittlementofthematerialsubjectedtoloading,whichinturnleadstothe‘skin effect’. For example, in armor applications, the brittle-nessofthematerialgreatlyaffectstheballisticperformanceofanarmor.Ceramicsgenerallyhavebetterresistancetothe ballisticimpactthanmetallicmaterials[1,2].Anotherexampleisthehigh-speed machining(HSM)ofengineeringmaterials,such as ceramics and SiC reinforced aluminum alloys. Highspeeds of machining could embrittle the workpiece materialandsuppressSSDdepthbecauseofthe‘skineffect’.

We areliving in a worldthat needssupport fromvarious materials. How these materials may serve our purposes hasbeenasubjectofstudy.Somematerialsareharderandmore

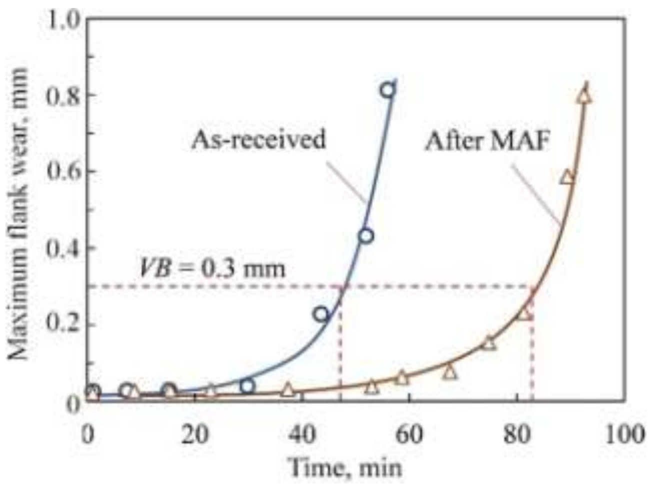

Figure 1.Maximumflankwearofthedifferenttoolinsertsversusmachiningtime(cuttingspeed:100 m min^{-1},feed:75 μm/rev,depthofcut:1.0mm,coolant:5%vol.trimsolution).Reprintedfrom[23],Copyright(2012),withpermissionfro mElsevier.

brittle (e.g. ceramics, semiconductors, cast irons) than others(e.g. most metals). It is necessary to shape the materials intovariousproductswiththehelpofmodernmanufactu ring technologies,suchasmachining,laserbeamcutting,for ming,forgingandwelding.Ontheotherhand,wewantth eproductsto perform the functions as we desire. These functions mayincludestrengthandtoughness,fatiguestrength(e. g.aircraft enginesandbridges),wearresistance(e.g.bearingsand cut- ting tools), etc. To achieve the respective functions, the rightmaterialsmustbechosenfortheappropriateapplic ations.

Titanium, Inconel, and aluminum alloys, for example, arenormallyusedintheaerospaceapplications[3,4].Cr ystallinesilicon is a typical substrate material for the semiconductor[5–7]andphotovoltaicindustries[8,9].Sapphireisusedas thesubstratematerialforLEDs[10–12].Ceramicshavebeen usedinthehigh-precisionbearingsandcuttingtools[13,14]. Glassesareindispensablematerialsforopticsandlightt ransmission [15]. However, the above-mentioned materialscan easily be induced with SSD when they are subjected tomachining.

In machining of titanium, Inconel and aluminum alloys,work hardening and toolwear are notable, resulting in ametamorphic layer on the machined surface [16–19]. Generally,themetamorphic layerdegrades theservice performance ofa part because of the different mechanical properties from thebulkmaterial,such ashardness,toughness,and plasticity[20, 21]. On the other hand, materials, such as SiC, sapphire,and silicon, are hard and brittle, and can easily be introducedwith SSD during a machining process [7, 15, 22], which isdetrimentaltotheperformanceandlifetimeofapart.

As shown in figure 1, an as-received cutting tool insertofferedalifetimeofapproximately49 min.However,whenanother insert of the same batch from the same manufacturerwasfinishedbythemagneticabrasivefini shing(MAF) technique,itslifetimewas86min,almostdoublingthelife-time of the as-received version. Why should this happen?WhatisthefunctionofMAFonthelifetimeofth einsert?

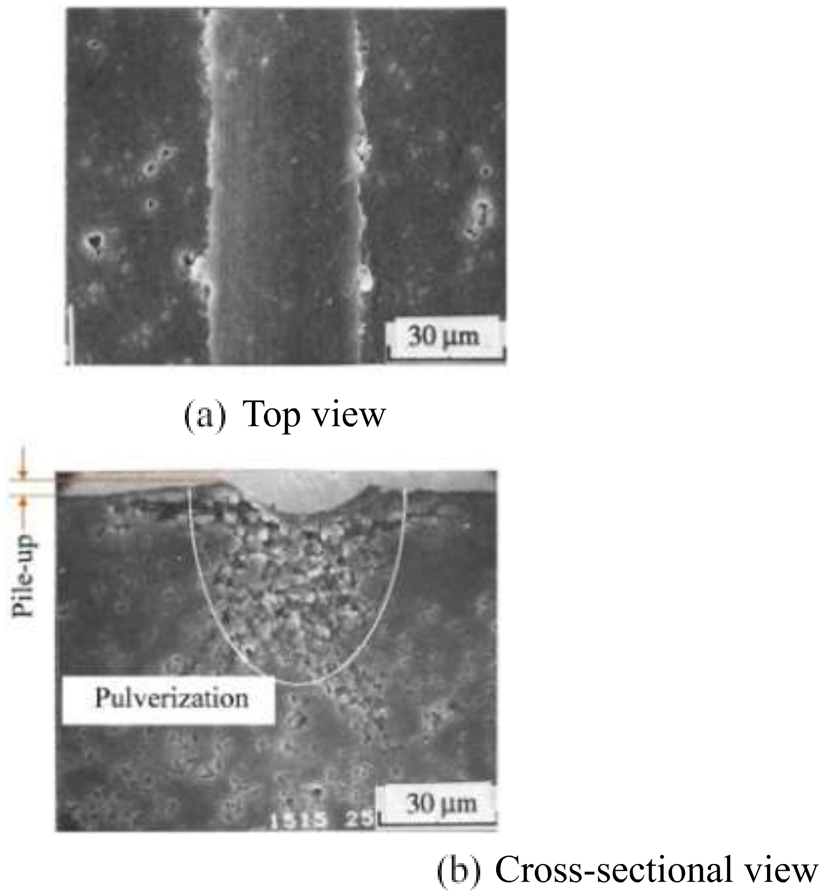

Figure 2. SEM imagesof(a) top view and (b) cross-sectionalview ofa smooth groove generated by grinding in an alumina sample. [24](1988)©ChapmanandHallLtd.WithpermissionofSpringer.

To answer these questions, an early work conducted byZhangetal[24,25]shouldbereferredto.Intheirwork, Zhanget al produced a smooth groove in a hot-pressed alumina samplein the single-point grinding process at a speed of 1800 m min^{-1}.Figure2showstheimagesofthegroovetakenfromthetopand cross-sectional views by a scanning electron microscope (SEM).Figure 2(a) presents the top view of the groove with a smoothsurface. Although the groove did not show any observabledamage (e.g. cracking, chipping), its subsurface was severelydamagedwithalayerofpulverization,asshown infigure2(b).Moreover,thecross-sectionalviewrevealsthatmaterialpile-up occurredtothetwosidesofthegroove.Thepile-upwasclearlybecauseofthesideflowofthepulverizedmaterial.Therefore,pile-up does not have to be plastic deformation in the machiningofthehardandbrittlematerials.

Based on the understanding of figure 2, it is suggestedthat the cutting edge of the as-received insert in figure 1shouldhavebeenleftwiththegrinding-inducedSSDwhichisresponsible for the compromised tool life. Upon the removalofSSDbytheMAFtechnique,toollifewaslargelyextended,asdepictedinfigure1.Therefore,theremovalofthemachining-induced damage is beneficial to the improvementoftheperformanceandlifetimeofacuttingtool.

Over the years, continuous efforts have been made inmachiningofhardandbrittlematerials.Bifanoetal[26]were

thefirsttoproposethe‘ductile-regime’machiningtechniqueforbrittlematerialstoach
Although‘ductile-regime’ machininghasreceivedmuchattention, it is still controversial as it lacks both theoreticalandexperimentalsupport.Thistechniqueis mainlyconcerned
de_=

withsurfacefinishwithnoconsiderationofSSDofamachined workpiece. It has not solved the machining pro-blemsofthehardandbrittlematerials.

In order to solve these problems, Zhang et al [25] used adifferentapproach.Theynotonlyinvestigatedthesurfacebutalsothesubsurfacecharacteristicsofamachined workpiece.
wheretheelementalchipthicknessisrelatedtothedepth
Theywerethefirsttoreportthematerialpulverizationmechanismtogetherwiththeotherformsofmachining-inducedSSDinceramics[24,25,27–30].Theirfindingshave beenappliedinindustryforhighefficiencyandlowdamage machiningofceramicmaterials.

Ultrasonically-assisted machining (UAM) has success-fully been used in reducing machining force and improvingsurface integrity for the hard and brittle materials [31–35]. Infact,UAMhelpssuppressmachining-induceddamage, enhancethecriticaldepthofcut[31],reducemachiningforces[32,36],andaltermaterialproperties[37].UAMhasagreatpotentialformachiningofthehardandbrittlematerials,however, there are still critical issues to be resolved. TheissuesincludehowUAMsuppressesthemachining damageandimprovesworkpiecesurfaceintegrity.

HSMhasattractedmuchattentionbecauseofitsimprovementinmachiningefficiency,reductionintoolwear,

$$d = k \cdot \left(\frac{de}{dt} \right)^{-0.34}, \quad (3)$$

ievehigh-qualitygrinding.
presentedinequation(1)[46,47],

$$\frac{de}{dt} = \frac{V\cos g}{D\cos(j-g)}, \quad (1)$$

of cut. However, equation (1) cannot be used to calculate thestrainrateinthemachiningofhardand brittlematerialsbecausethesematerials do notnormallyshownotable plastic deformation before fracturing. Wang et al proposed a simpleformulaforcalculatingstrainrate,shownasequation(2)[48],

$$\frac{de}{dt} = \frac{V}{a_c}, \quad (2)$$

-induced

where $a_c$represents depth of cut. Equation (2) describes strainrate in the region of a material compressed by a cutting tool.In this study, equation (2) is adopted to calculate strain ratebasedonthepreviousstudies.Asshowninfigure3,theSSD depthinthehard andbrittlematerialsdecreaseswithanincrease in strain rate of machining, which well depicts the‘skin effect’ of damage formation in terms of strain rate. Thebestfittinglinein figure3showsthattheSSDdepthismathematicallyproportionaltothenegativeexponentofstrainrate,aspresentedinequation(3), and suppression in workpiece damage as compared to theconventionalmachining[38–40].HSMcanbeappliedtomanydifferentmaterialswithnospecificrequirementsontheworkpiece properties. Most of all, HSM leads to a high strainratewhichresultsintheso-called'skineffect',namely,the machining-inducedSSDtendstodistributeinthesuperficial layer of a workpiece machined at a high strain rate [41–45].Therefore, HSM presents a huge potential in high-efficiencymachiningoftheabove-mentionedmaterials.However,the underlying mechanisms of the 'skin effect' of SSD distribu-tionremainunrevealedandneedinvestigations.

This paper is to explore the mechanisms of the 'skineffect'ofSSD at highstrain rates anditsapplicationto HSM.AmongthedifferencesbetweenHSMandthelow-speed machining, the strain rate is the primary factor. This paperpresents the 'skin effect' of SSD distribution at high strainrates (>10^3 s^{-1}) with section 2 dealing with the 'skin effect'ofmachining-induceddamage.Section3discussestheunderlying mechanisms of the 'skin effect' at high strainrates; section 4discusses the 'skin effect' in terms of dis-locationandenergytheories;section5concludesthepaper andpresentsanoutlook.

1. 'Skin-effect'ofdamageathighstrainrates

In machining, the plastic strain rate dε/dt is regarded as afunction of rake angle γ of a cutting tool, shear angle j,cuttingspeedV,andtheelementalchipthicknessΔy,as

wherekisaconstant(k=1531infigure3).

In addition, the 'skin effect' can also be found in themetallicmaterials.The 'skin effect' was identified in theearlyworksconductedonIN-718byPawadeetal[60],on the nickel-based FGH95 superalloys by Jin et al [42, 43], onthe D2 tool steels by Kishawy and Elbestawi [61], and on thenickel-basedME16superalloysbyVeldhuisetal[62].Therefore, the 'skin effect' exists not only in the hard andbrittlematerials,suchasceramics,semiconductor materials, andglasses,butalsointhemetallicmaterials,suchassuperalloysandtoolsteels.

The 'skin effect' is an intrinsic property that governs thedamagebehavioroftheengineeringmaterials.The'skineffect' can be interpreted as 'material damage (e.g. cracking,dislocation, phase transformation) is localized if the materialis loaded at a high strain rate'. In the case of machining, forexample, SSD depth decreases at an increased machiningspeed(strainrate),andviceversa.

2. Mechanisms of the 'skin-effect'of damageathighstrainrates

Materialembrittlement

Generally,amaterialsubjectedtomachiningundergoesplastic deformation before it fractures. The plastic deforma-tionisgovernedbydislocationmotionwhichisdependentonstrainandstrainrate.Therelationshipbetweenthedislocationmotionandstrainrateisinferredbasedonthe Orowantheory

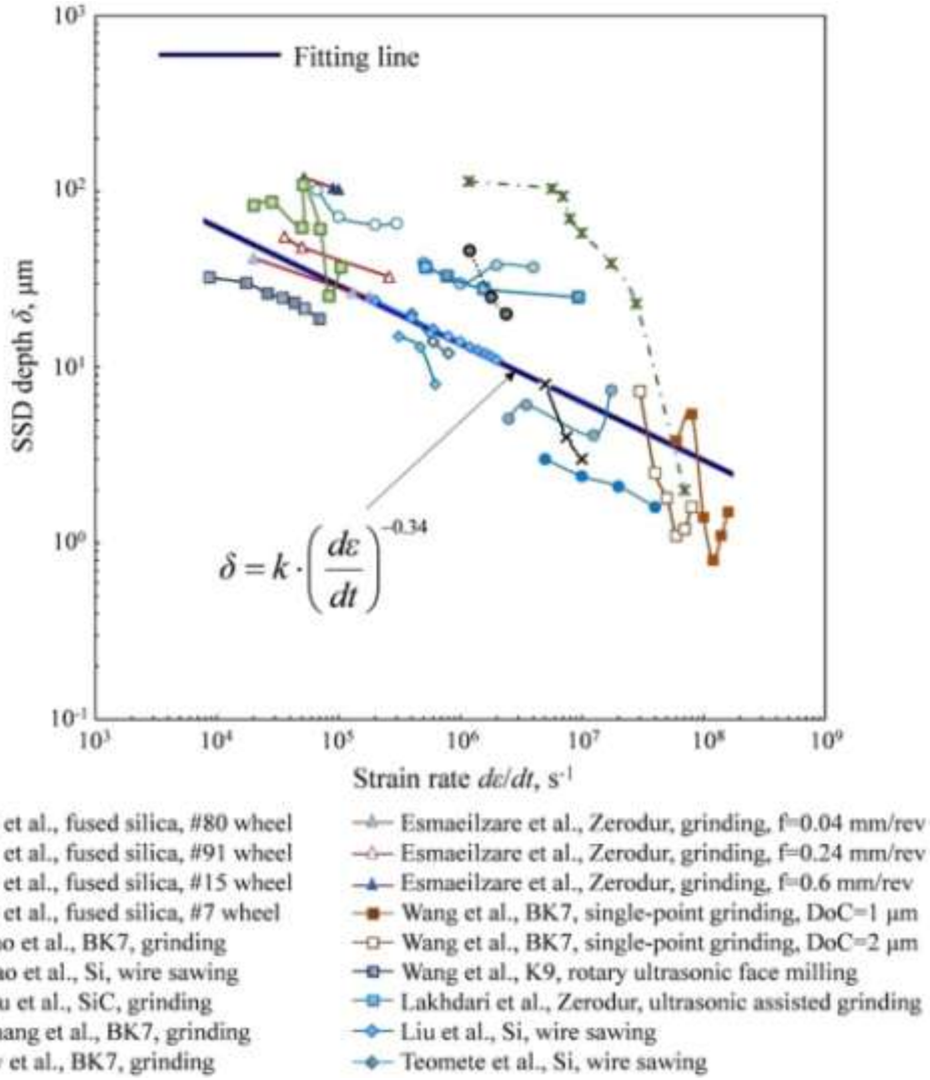

Figure3.SSDdepthofthehardandbrittlematerialsatdifferentstrainratesinmachining[22,49–59].Otherconditionsareprovidedinthe

figurelegends.

[63],asgiveninequation(4),
de=rbv,

(4)
Therefore, the strain rate in machining is obtainedas
de=drbL+rbv,

(7)
dt dt dt

where ρ is dislocation density; b is the magnitude of theBurger's vector; and v is dislocation velocity [64, 65]. How-ever,equation (4)only describesaninstantaneousmotionofadislocationexcludingthe dynamic behaviors, such asnuclea- tion, immobilization, recovery, and annihilation. Therefore, amoreadequate modelisneeded. Strain can becalculatedby wheredρ/dtisthechangerateofdislocationdensity.Therightside of equation (7) has two terms, the first term representingthenucleationandannihilationofdislocationsandthesecond termrepresentingdislocationmovement[67].Thedislocationvelocityvcanberesolvedbytheappliedshearstress[67]

equation (5)[66],
Cv=bt,
(8)

e=rbL,
(5)
whereCisthedragcoefficientduetolatticeviscosityand τis

whereListheaveragedisplacementofadislocation.Then,therelationship between the dynamic behaviors of dislocationsand strain rate can be inferred by differentiating both sides ofequation(5),
the applied shear stress. As shown in figure 4, the dislocationvelocity increases with the applied shear stress, but by anupperlimit.Thedislocationvelocityisboundedbythe phonon ddrageffects[67–70]withthetimebetweenobstacles[71],thedislocation velocitydoesnotexceedthesoundvelocityinthe

de = d(rbL) = dr bL+rb dL,
(6)
material[72,73].Atastrainratehighenoughtotheextent

dtdt dt dt
thatthemovingdislocations cannoteffectivelyaccommodate

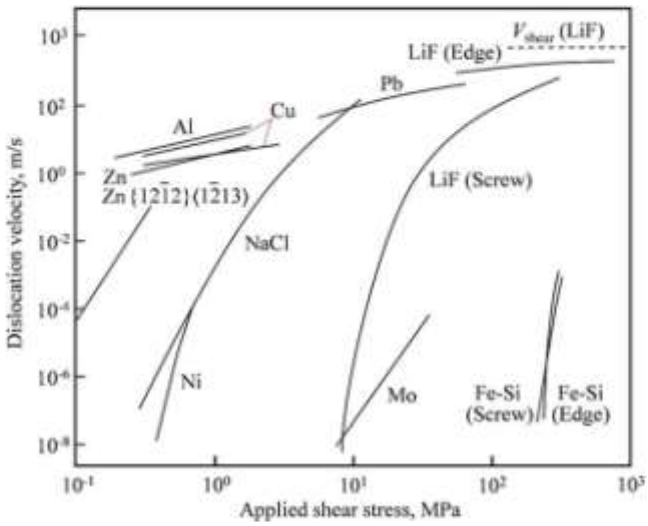

Figure 4. Relationshipbetweendislocation velocityand appliedshearstressfordifferentmaterials.[74]JohnWiley&Sons.©1994WILEY-VCHVerlagGmbH&Co.KGaA,Weinheim.

yield-to-tensileratioσ_s/σ_bincreases.At a high strain rate(>$10^4 s^{-1}$),theyield strength approachesthe tensilestrength.As a limit, the yield strength can be the same as but neversurpass the tensile strength [76]. In this case, the materialfracturesprior toyielding,whichis a typical characteristicof abrittlematerial.Materialembrittlementduetothestrainrateeffectisthusrealized.

As shown in equation (2), strain rate is determined basedoncuttingspeedanddepthofcutinthecaseofmachining.

Therefore, the strain-rate evoked embrittlement can be acquiredby increasing cutting speed and decreasing depth of cut. Asshown in figure 6 (a), at a cutting speed of 1000 m min^{-1}, the cuttingchipexhibitedatypicalcontinuousmorphology fora ductile material, such as an aluminum alloy. However, as thecutting speed increased to 5000 m min^{-1}, the chip morphologyturnedtobefragmental,asshowninfigure6 (b),whichmeansthatthematerialhasbeenembrittledunderthiscondition.

For brittle materials, Lawn and Marshall first proposedthattheratioofhardnesst shouldbeusedto estimate the brittleness of a material [80]. Boccaccini studiedthemachinabilityofaglass-ceramicsintermsofthe materialbrittlenessrepresentedinequation(9)

$$B=\frac{H}{K_C}, \quad (9)$$

whereHand$K_c$arethehardnessandfracturetoughnessofthematerial,respectively.

Itshouldbepointedoutthatmaterialhardness$H$isstrain-rate sensitive and generally increases with strain rate[16, 45, 81–85] due to the strain-rate hardening effect.

Acorrelationbetweenhardnessandstrainrateisexpressedin equation(10)[86]

$$H \propto \left(\frac{d\varepsilon}{dt}\right)^m, \quad (10)$$

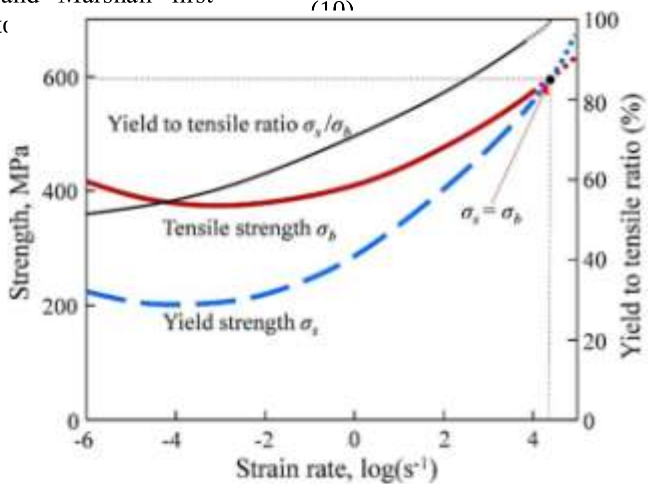

Figure 5.Strainratedependencyofmaterialstrengths[77,78].

loading,moredislocationsnucleate,emittingatthesoundvelocity,andresultinginadislocationavalanche.

Dislocations can be classified into two types, mobile andimmobile. The mobiledislocationsmaybe trapped by eachotherandturnedintoimmobileonesbecauseoftheirinter-actions,includingentanglement,attraction,obstruction,etc.Therefore,materialdeformationenhancesnotonlydisloca-tionnucleationandmotion,butalsodislocationimmobiliza-tion.Theaccumulationoftheimmobiledislocationsincreasestheresistancetoplasticdeformationandleadsto materialhardening[75].Atahighstrainrate,dislocation avalanchemaydramaticallyincreasethedensityoftheimmobiledis-locationswhichareresponsibleformaterialhardening. Consequently,theplasticdeformationofamaterialissup-pressedbeforefracturing,namely,thematerialisembrittled.Intermsofthestrengthenhancement,bothtensilestrength$\sigma_b$andyieldstrength$\sigma_s$increasewithstrainrate,as showninfigure5.However,asstrainrateincreases,they ieldstressincreasesmore rapidly than thetensilestrength andthe

where m represents strain-rate exponent, and m = 0 for arigid-perfectly plastic material and m = 1 for a linear viscoussolid,respectively[87,88].Hardnesshasapowerlawdependenceonstrainrate. Thevariationinfracturetoughnessiscomplicated.Machado et al found that the fracture toughness of CFRPdecreased as strain rate increased [89, 90]. Anton et al foundthat the dynamic fracture toughness of the Pyrex glass wasgreater than the static fracture toughness. However, for themagnesiapartially-stabilizedzirconiaandyttria-tetragonalzirconia polycrystals, the dynamic fracture toughness wassmaller than the static fracture toughness [91]. Generally, thefracture toughness of a material is larger at a high strain ratethan under the static or quasi-static condition. Suresh et alfoundthattheratioofthedynamictostaticfracturetoughness wasintherangeof1.1–1.6for brittleceramics [92].Liuetal studiedthehigh-speedgrindingofsiliconcarbideceramics andconcludedthatthedynamicfracturetoughnesswasrelated to strain rate [93]. Even if both the hardness andfracturetoughnessincreasewithstrainrate,theformerdemonstrates a higher rate of increase than the latter. There-fore, as the strain rate increases, the brittleness of a materialincreasesaccordingly.

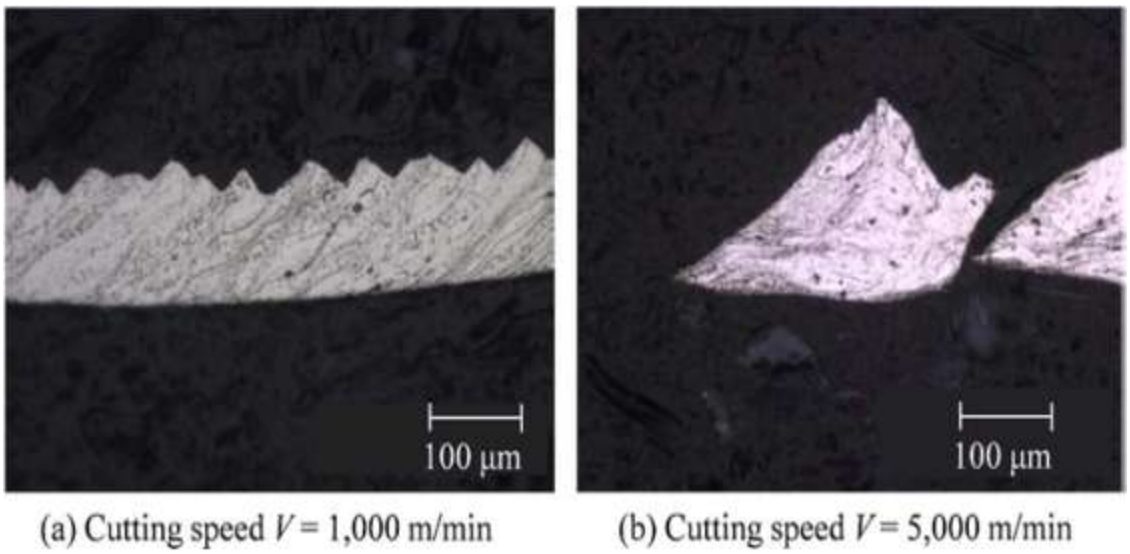

Figure6. Chipmorphologiesof7050-T7451aluminumalloywiththeuncutchipthicknessof0.1mmandthecuttingspeeds (a)V=1000mmin^{-1}and(b)V=5000mmin^{-1},respectively.Reproducedwithpermissionfrom[79].

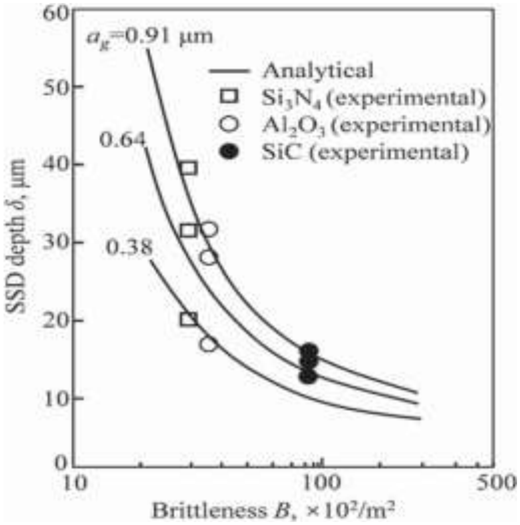

Figure 7. Variation of SSD depth with material brittleness.
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Zhangetalstudiedtheeffectofbrittlenessofceramicsin grindingonSSDdepthandfoundthattheSSDdepthdecreased as brittleness of ceramics increased [94], which isexplainedinfigure7.Theypresentedananalyticalequation forSSDdepthδinequation(11),

Dislocationkinetics

Dislocations can be responsible for the formation of grainboundariesandcracks.Themovementofdislocationsisessentialtotheevolutionofdamage.Underanexternalloading condition, dislocation nucleation, multiplication, andmotionaretodissipatetheloadingenergy.Thedislocationsinamaterialmaybeattractedtothefreesurfacebytheimage force [95–98]. As a result, the dislocation density in the skinlayerofthematerialishigherthanthatinthedeeperlayers.In addition,dislocationdensityshouldhavealargergradientatahigher strain rate, and vice versa. If the dislocation density isnot high enough to accommodate the loading from machin-ing, for example, the dislocation entanglement should firsttake place in the skin layer, followed by grain refinement andcracking.Therefore,atahighstrainrate,thedistributionof SSDfollowsthe‘skineffect’.

Stresswaveeffect

At high strain rates, the contribution of stress waves to the‘skin effect’ of SSD distribution should be taken into con-sideration.Asshowninfigure8,thecompressivestress wavesareproducedduetothehigh-speedsqueezingbyacuttingtool.

The stress waves propagate along the cutting direction andthey are partially reflected by the free surface because of theshortest propagation distance. The compressive stress wavescan be converted to tensile stress waves from the free surfacereflection, which wasalso describedbyHopkinson[99]. Fol-

$$d=k\cdot a_g^{1/\log(\mathbf{1}\cdot B)}, \quad (11)$$

lowingthislineofreasoning,thereflectionwavesnearthefreesurfacemayproducetensilestressthatisunbearableforan

whereand λ are constants; $a_g$is the grit depth of cut.Equation (11) depicts that in grinding of ceramics, SSD depthcanbesuppressedbyincreasingbrittlenessofceramics,whichisobtainedwithanincreasedstrainrateinhigh-speed grinding.Inotherwords,the‘skineffect’ofSSDdistributionexistsinmachiningofmaterialsatanincreasedspeed.

embrittledmaterial.Consequently,cracksmushroomnearthefreesurface.Thismaybethereasonfortheresultsthattherearportion (with stress wave reflection) were with more damagethanthefrontportionofthesamplesubjectedtoimpactloadinginthestudyconductedbyJiangetal[100]. Theimpact energyisrapidlydissipatedbythemushroomingofthecracks.

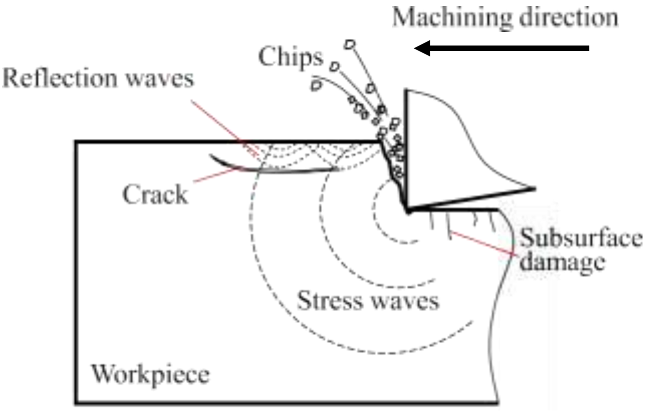


Figure 8. Schematic of stress waves propagating in the workpiece inhigh-speedmachining.

Correspondingly, the cracks are more concentrated in thanawayfromthesurfacelayeroftheworkpiece.

Cracking

Generally, SSD is dependent on stress distribution. Based onthe Boussinesqelastic-fieldtheory[101], asillustratedinfigure9,thereisanelasticallystressed(strained) regionbeneaththeloadingpoint.Foranindenterwithasharptip,thestresslevelapproachesinfinityaroundthetipanddecreases away from the tip. However, the stress cannot approach in-finity since a material should yield or fracture as the stressexceedsthematerialstrength.Theregionissubjectedtohydrodynamic stress and shear stress which may result ingrainrefinementorpulverization.

Material damage is due to the consequence of loadingduringwhichenergyisconsumedbythematerialsubjectedtoloading. Damage is dependent not only on the intensity ofloading stress but also on the process of loading. In otherwords, it is also dependent on the strain rate during loading.Atanincreasedstrainrate,thedamageincreasescorre-spondingly[100,102].Pingetalfoundthattheenergydensity in breaking a rock increased with the power law ofstrain rate [103]. At a high strain rate, the number of smallcracksrapidlyincreasestoeffectivelyabsorbtheimpactenergy, the intersection of the small cracks results in thecomminutionofamaterial.Therefore,materialfragmentationincreaseswithstrainrate,asshowninfigure10.

Gradyproposedamodeltopredictfragmentsized,basedon the balance between the kinetic energy and the newlycreatedsurfaceenergy,asshowninequation(12) [104],

$$\left(20^{12} K_C \right)^{23}$$

silicon, and finally the intact monocrystalline silicon [106],sequentiallyinthedepthdirection.

Figure 11 shows a schematic diagram of SSD in a brittlematerial subjected to machining. At the top surface is theamorphous layer below which is the pulverization layer. Thepulverizedmaterialissqueezedbythecuttingedgetothetwosidesofthegroove,formingpile-up.Medianandradialcracksform around the pulverization layer. If a radial crack extendstothesurface,surfacechippingoccurs.

Stress gradient may also be responsible for the ‘skineffect’ of SSD. At an increased strain rate, the stress gradientincreases,whichmayresultinaconcentratedSSDlayerbeneath the surface. As described in figure 12(a), at a lowstrainrateinmachining,SSDdepthislargeandsoisthechip size. On the other hand, as the strain rate increases, the stressgradientincreases,whichresultsinmoreconcentratedSSDinthe skin layer of the material. As shown in figure 12(b), thethicknesses of the respective amorphous and pulverizationlayersdecrease,andsodoesthechipsize.Inaddition,the stressleveldecaysfasterduetoahigherstressgradient,whichresultsinareducedSSDdepth.

Based on the above analysis, figure 13 describes the dis-tribution of SSD at different strain rates in machining.

Thematerialatthefrontofthecuttingtoolissubjectedto boththedeviatoric and hydrostatic stresses. In such a case, the combi-nation of the two stresses tends to form a pulverization zonedescribedbyZhangetal[25].Thepulverizationzoneconsists of microscopic cracks and an amorphous layer (or a grain-refined layer). Macro-cracks initiate and propagate from theboundaryofthepulverizationlayer.Thefreesurface ofthe workpiece has the least resistance to crack propagation com-paredtothebulkmaterialdownbelowthesurface.Therefore,basedontheprincipleoftheminimummaterialresistance,thecrackstendtopropagatetowardsthefreesurface, whichleadsto thedamageconcentrationinthesurfacelayertocausethe‘skineffect’. At an increased strain rate, as schematically shown infigure13(b),thechipsizeisdecreasedandthethicknesses ofthepulverizationandamorphouslayersarereducedacrates,theformationanddistributionofdislocationsfollowthe ‘skineffect’andsodoesSSD.Dislocationsmovetowardsthe cordingly. Morechippingisexpectedinthemachinedsurfacebecauseofthematerial embrittlement attheincreasedstrain rate.

3. Discussion

Based on physics, SSD may be caused by lattice mismatch(e.g. dislocations and stacking faults) and bond rupture of amaterial. Generally, cracking can be a consequence of dis-locations.Forexample,itmayresultfromtheaccumulation andentanglementofdislocations.Therefore,athighstrain

whereversusisthesonicvelocity.Thefragmentsizedecreases at an increased strain rate [105]. The limit to thegrain refinement is likely to be amorphization, as reported byZhao et al who discovered that the microstructural change inthemonocrystallinesiliconunderalaser-inducedshockloading.Thesurfacelayerofthesiliconwasleftwithlayersofmicrometer-sizedgrains, nanometer-sizedgrains,amorphous
free surface under the image force, creating 'skin effect',whichleadstothedislocationsaswellasSSDaccumulation nearthefreesurface.Ontheotherhand,highstrainratestendtopromotedislocationmultiplication,whichinturn obstructsmaterialdeformationand causes the embrittlementto thematerial.Basedon an early grindingstudy conductedbyZhangandHowes[94]onceramicmaterials,SSDdepth

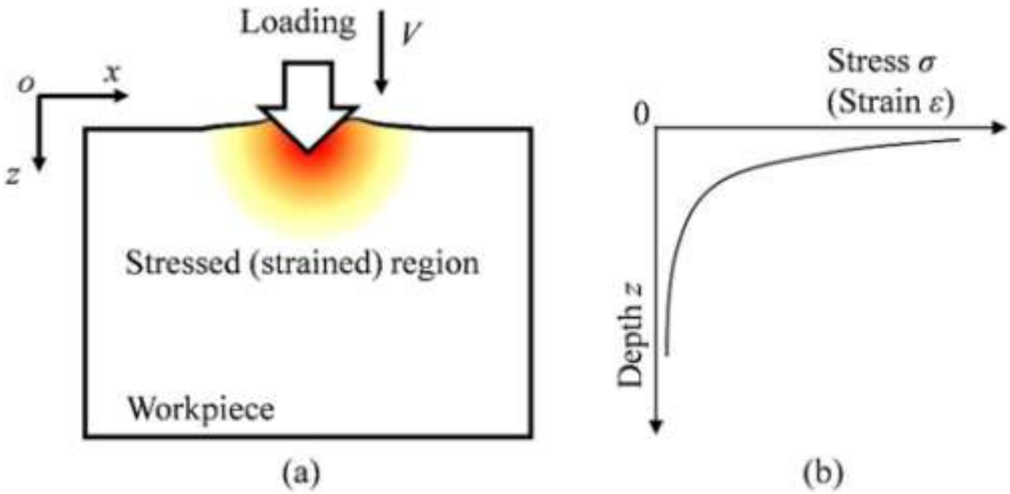


Figure9.Schematicsof(a)astressed(strained)regionaroundtheloadingpoint;(b)stress(strain)distributioninthedepthdirection.

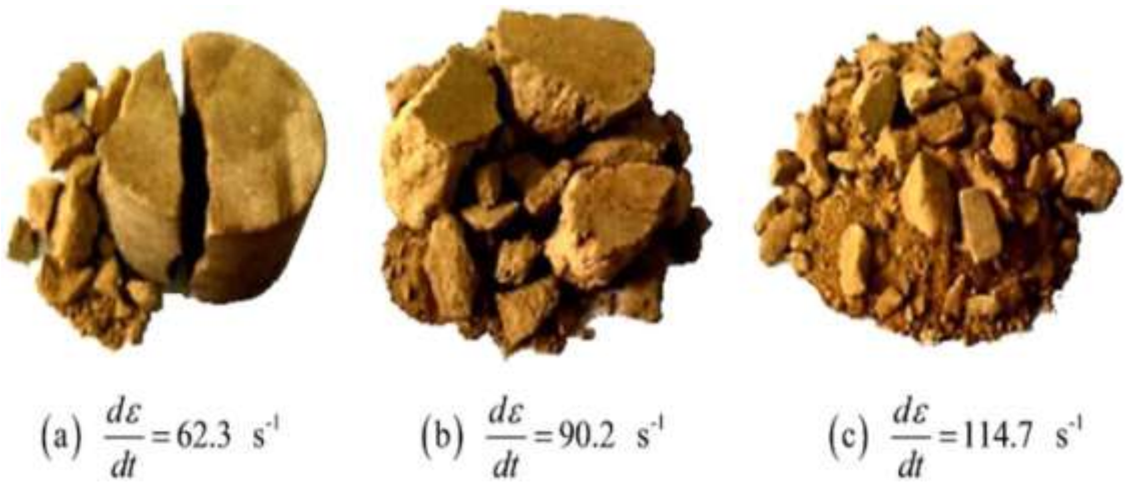


Figure10.Fragmentsofsandstoneimpactedatdifferentstrainrates.Reproducedwithpermissionfrom[102].

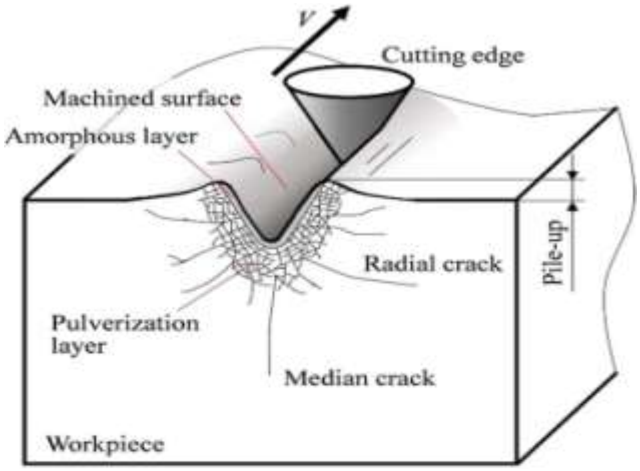
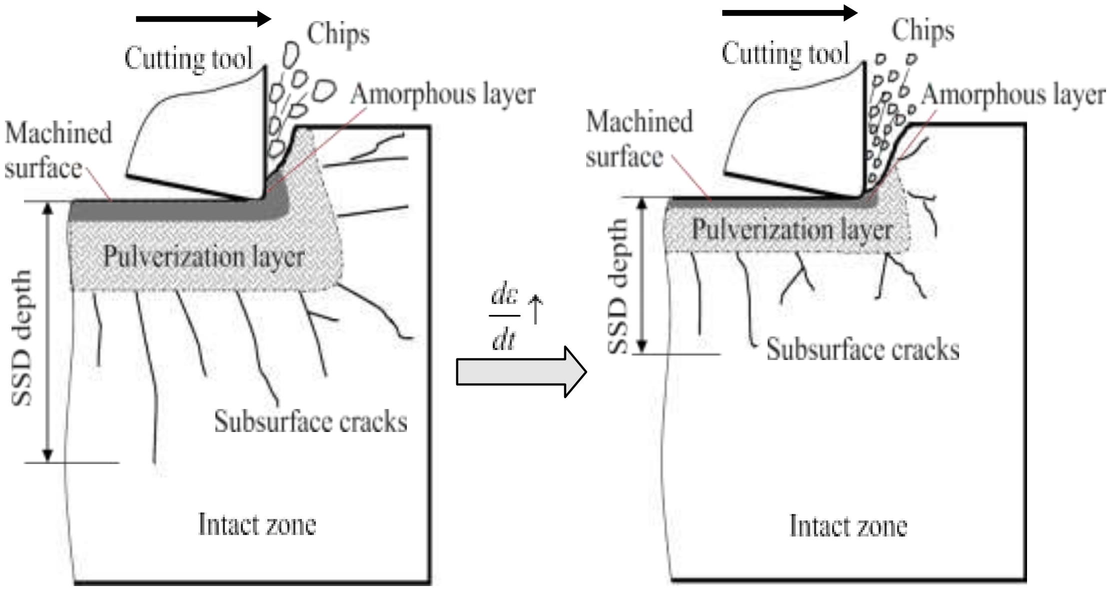


Figure11.Subsurfacedamageofbrittlematerials.

decreases with an increase in the material brittleness. There-fore, the 'skin effect' of the dislocations and the materialembrittlement due to dislocation multiplication lead to the'skineffect'ofSSDathighstrainrates.
Practically,numerousfactors,suchasstrainandstrain rate, dislocation movement, crack initiation and propagation,materialphasetransformation,stressdistribution,andstress wave propagation, as well as the changes in the materialproperties,arecollectivelyresponsibleforthe 'skineffect'ofSSD. It is difficult to analyze the 'skin effect' from one factoralone.However,theeffectcanbecomprehendedfromthe aspectofenergydissipation.
From the energy point of view, machining is recognizedas an energy rebalance process. A system with the minimumenergy level is the most stable. A material in machining isactivatedwithanelevatedenergythathasa tendencytotransform into the most stable state of the minimum energy.The material damage, including dislocations and cracking, isa way of energy relaxation. Based on the minimum energyprinciple,thedamagetendstomovetowardswherethe



(a) Low strain rate(b) High strain rate
Figure12.Subsurfacedamageevolutionwithstrainrate.

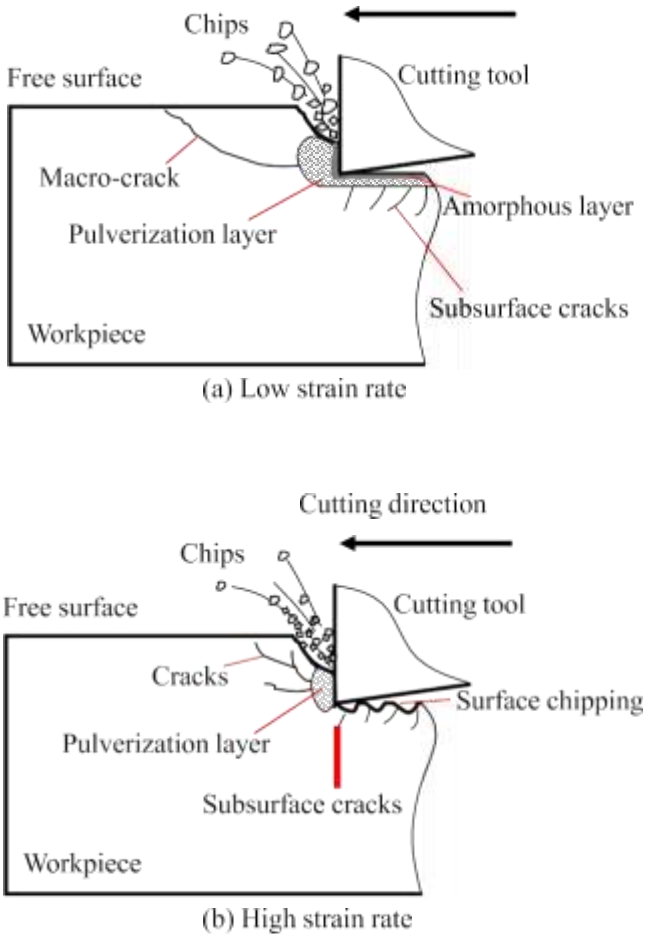


Figure13. Propagationofmacro-cracksatdifferentstrainrates.

energyrequirementisthelowestfordamageformation. Sincethe free surface has the lowest energy for damage formationcomparedtootherlocationswithinthemateri al,damagetendstopropagatetowardsthefreesurface.

In this paper, the effect of temperature rise on damageformationinmachiningistemporarilyputaside tosimplifythediscussion. The temperature in machining indeed affects themechanical behavior of a material, such as dislocation kinetics[107, 108], stress wave propagation, and eventually surfaceintegrity of a machined part. Specifically, in the conventionalmachiningofductilematerials,temperatur ehasanotableeffectonthegenerationofthesurfacemetam orphiclayer[17,20,109].Whereasatthehighstrain-ratemachining,thetemperatureeffectcanbeneglected.T hereasonisexpatiatedinthefollowing.

Temperature rise is a reflection of the heat generation inmachining. The heat in machining of a ductile material ismainly generated from material shear and friction. However,at a high strain rate, the material is embrittled, which directlycontributestotheheatreductionfromthedecrea sedshearandfrictionandthustothetemperaturereducti onaccordingly.

The ‘skin effect’ of damage at high strain rates provides aguidance for many industrial applications. In machining, the‘skin effect’ allows to acquire the desired surface quality of amachined part by increasingstrain rate inmachining,such as ultrasonicassistedmachiningandpeening.

II. CONCLUDING REMARKS AND OUTLOOK

This paper proposes the ‘skin effect’ of material damage athighstrainratesforthefirsttime.The‘skineffect’ isapplicablenotonlytothehardandbrittlematerials,but also to most other engineering materials, such as metallic materi-als.Thepaperdrawsthefollowingconcludingremarks.

(a) The‘skineffect’ofdamageisobtainedatahigh strainrateinaloadingprocess.
(b) Highstrainrateresultsinanincreaseinmaterialbrittleness.
(c) Brittlenessisamaterialpropertythatcontributestothe ‘skineffect’ofdamageinaloadingprocess;

The ‘skin effect’ of damage can have numerous industrialapplications.OnedirectapplicationistheHSMofthediffi-cult-to-machine materials, such as ceramics, high strengthmetals, and composite materials. Nevertheless, many issuesremain unresolved, such as how high the stain rate should bein order to suppress SSD in machining. Other issues mayinclude dislocation nucleation and motion, interactions amongdislocationsduringloadingatahighstrainrate. With a rapid development of the modern testing equip-ment and techniques, to have well-controlled testing condi-tionscomestoreality.High-speedandhighprecisionmachinetools are readily available. In addition, the state-of-the-artcharacterizationfacilities,suchasthefocusedionbeamdeviceincombinationwithhigh-resolutiontransmission electron microscopes (HRTEM), the cathode luminescencedeviceincombinationwithSEM, arealso readilyaccessible. Withtheaforementionedmoderntestingequipmentandtechniques,theunresolvedissuesareexpectedtoberesolved,and the underlying physical mechanisms of the ‘skin effect’ ofdamagecanfurtherbeexploredinthenearfuture.

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