Finiteelementbasedmodellingofthestructuralresponseofweldedmaterialsincomplex

loadingconﬁgurations.PartI:Structuralmodellingconsiderations

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Abstract

Thistwo-partarticlepresentstheresultsofnumericalpredictionandexperimentalstudieswhichaimtodeterminethestructural

responseoffrictionstirweldedaluminium2139-T8subjectedtocomplexloadingconﬁgurations,andinparticular,airblastloading.

Theaimofthisworkistodevelopanumericalmodellingmethodologytoallowdetailedpredictionofthelocalstrainevolution

acrosstheweldzoneasthishassigniﬁcantinﬂuenceinrelationtostructuralresponseandfailure.Inparticular,themethodallows

local material property gradients, which are due to variation in strengthening mechanism arising from microstructural damage

caused by thermal loading during the welding process, to be incorporated into a macro scale structural model. Part I details

themethodologyusedtoimplementlocalmaterialpropertygradientstogetherwithexperimentalevidencetoverifythepredicted

structural response in a range of loading conﬁgurations. Part II provides an insight into the assumptions made in Part I with

respecttohighstrainratematerialsmodellingacrosstheweldzoneandtheassociatedevidenceforthevariationinstrengthening

mechanismsinthealloy. Theworkpresentedhighlightstheimportanceofaccuratedescriptionofthevariationinlocalmaterial

properties,particularlytheworkhardeningrate,indeterminingtheresponseofstructuresunderblastloading.

Keywords: Blastloading,Digitalimagecorrelation,Materialsmodelling,Finiteelementsimulation,Materialscharacterisation

1. Introduction

ofmonolithicstructureshasbecomefavourableasweldsmay

loseintegrityunderblastloading.Localfailureintheweldcan

lead to ingress of the explosive shock front into the vehicle,

whichcanhavecatastrophicconsequencesontheoccupantsof

thevehicle[5].Indeed,itisunsurprisingthatoneareaofcurrent

researchfocusisonpredictivetechniquestoaidtheunderstand-

ingofdeformationandfailuremechanismsinweldedstructures

subjectedtoblastloading[7,8,9].

Ofcourse,inordertomodelthenon-linearbehaviourofa

weldedstructureaccurately,itisnecessarytounderstandthein-

terrelationbetweenmaterialsprocessing,materialmicrostruc-

ture and the subsequent material and mechanical properties.

Furthermore,theapplicationofnumericalmodellingtechniques,

alongsidetheintrinsicerrorsarisingduetothemodellingas-

sumptionsmade,needtobefullyunderstoodifahighﬁdelity

modelofweldbehaviouristobeutilisedandinterpretedcor-

rectly. Thescopeofthispaperlimitsdiscussiontostructures

manufacturedviaFrictionStirWelding(FSW),asdescribedin

§1.2. Furthermore,discussionwillbelimitedtoheattreatable

aluminiumalloys,withparticularreferencetothealloy2139-

T8asdescribedin§1.1,thoughthegeneralconceptsareappli-

cableacrossotheralloys.Finally,considerationisonlygivento

theFiniteElementMethod(FEM),asdescribedin§1.3,since

itiswidelyusedasatooltostudytheresponseofstructures

underawiderangeofloadingconditions.

Thestructuralperformanceofweldedstructuressubjected

to air blast loading is of key interest to engineers and scien-

tistsacrossarangeofindustries.Forcivilianapplications,typ-

ically the risk of air blast is due to gas explosions and is an

importantdesignconsiderationintheconstructionofoﬀshore

oilplatforms[1,2,3].Akeyconsiderationhereisnotnecessar-

ilyjusttheinitialdamagefromtheblastloading,buttheriskof

subsequentinjuryfromcollapseoftheremainingstructure.For

steel framed buildings that are common in civil engineering,

plasticdeformationinthejoints,whichmaybemanufactured

bywelding,canbethelimitingfactorcontrollingstructuralin-

tegrity[4]. Detailedunderstandingofthislocaliseddamageis

extremelyimportantwhenconsideringthepotentialresistance

of a building to blast and, therefore, any required mitigating

engineeringworkstoreinforcethestructure;thismayhavean

impactonthecostordesignlayoutofastructure.

Formilitaryapplications,theuseofweldedjointsiscom-

moninpersonneltransportvehicles. Withanincreaseinthe

threatfromImprovisedExplosiveDevices(IEDs),theperfor-

manceofweldedstructureshascomeunderscrutiny[5].There

hasbeenaglobaltrendtowardstheuseofvehicles,suchasthe

Mastiﬀ,whicharedesignedtobemineresistant[6]. Incriti-

calareasofatypicalvehicle, suchastheunderbelly, theuse

1.1. Aluminium2139-T8

Originallydevelopedforaerospaceapplicationsdemanding

high fracture toughness and fatigue life at elevated tempera-

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tures,thealloydemonstratessuperiorperformanceatelevated

temperaturesandstrainratesincomparisontoexistingalloys

[10,11].Thealloyhasalsobeenfoundtodemonstratesuperior

ballisticperformanceincomparisontoexistingarmouralloys

[11,12].Asaresult,thereisinterestinusingthisalloyformil-

itaryvehicleapplicationsasanalternativearmouralloy. 2139-

T8isanAl-Cu-Mg-Agbasedalloywhosecompositionleadsto

thepreferentialformationofthestableΩphase[13,14,15]:

Zone(TMAZ),andacentralregionknownastheNuggetwhich

isapproximatelyenvelopedbythedimensionsofthetoolitself

[18]. Withineachregionthereexistsstrongmaterialproperty

gradients;thesegradientsarelinkedtotheinducedchangesin

microstructure,whichcanlocallyalterthestrengtheningmech-

anismsfromthatwhichcontrolstheparentmaterial[19,20].

Forheattreatablealuminiumalloys, inadditiontothein-

trinsic strength, mechanisms such as precipitation hardening

fromsecondphaseparticles,solutehardening,grainsizehard-

ening,andworkhardeningallcontributetotheoverallstrength

of a material. In the HAZ, softening is due to thermal load-

ing arising during the welding process alone; softening pro-

cessesincludecoarseninganddissolutionofstrengtheningpre-

cipitates.IntheTMAZ,thereareadditionalmechanismswhich

ariseduetotheinteractionofmechanicalprocesses.Forexam-

ple,largedeformationmaybeinducedinthealloywhichmay

aﬀectthecontributionfromgrainsize.Inthenuggetregion,the

largeamountofheatandplasticstrainisenoughtoinducedy-

namicrecrystallisationinthealloy.Inthisregion,grainsizeand

distributionareanimportantcontributingfactortotheproper-

tiesofthematerial.Sincethelocalmaterialpropertiesarecon-

trolledbythesechangesinstrengtheningmechanisms[16],it

isnecessarytodevelopanunderstandingofhowtheydevelop

duringweldinginorderforthemtobeincorporatedintoany

structuralmodeltostudyweldperformance.

SSSS→GPZ→θ00→θ0

→Ω

TheΩphaseformsasextremelyﬁne,hexagonalplate-likepre-

cipitatesorientedalongthenaturalslipplanesofthealuminium

crystalstructure, {111} ; precipitatespacingintheT8condi-

α

tionisoftheorder101nm.Whilstthisalloydoescontainother

secondaryphases,suchasmanganeseandzirconiumcontain-

ingparticles,itiswidelyacceptedthatΩisthedominantphase

intheT8conditionand,therefore,precipitationhardeningdue

to the Ω phase is the major strengthening mechanism to the

alloy. Hence, the mechanical properties of 2139-T8 are sen-

sitive to variation, in terms of size and distribution, of the Ω

phase. InPartII,TransmissionElectronMicroscopy(TEM)is

usedtogainanunderstandingofthevariationinstrengthening

mechanisminFSW2139-T8byobservingtheeﬀectsofFSW

ontheΩphaseandamoreindepthdiscussionshallbegiven

there. Brieﬂy, the Ω phase responds to thelocal thermal cy-

cleexperiencedduringFSW.Heatinputduringprocessingmay

causetheΩphasetooverageandcoarsen;iftemperaturesare

highenoughtheΩphasemaygointosolution.Therefore,FSW

maycausesigniﬁcantlocalchangestothestrengtheningmech-

anismsin2139-T8. Thisprocessisrelativelywellunderstood

andcanbepredictedusingexistingmethodsintheliterature.

1.3. WeldModelling

Thetypicalmethodtostudystructuralresponsetoloadingis

tousetheFEMandtherearemanyinstancesofitsusetostudy

theresponseofweldedstructures[21,7,22,23].However,suc-

cessfulmacroscalemodellingofweldbehaviourundergeneral

loadingconditionsisextremelychallengingastherearemany

factorswhichcontributetotheoverallstructuralbehaviour. In

addition to the variation in strengthening mechanisms across

§

1.2. FrictionStirWelding

theweldzone( 1.2),phenomenasuchasgeometrymisalign-

mentfromtheweldingprocess,theformationofwelddefects,

and residual stresses are all complexities which contribute to

structuralperformance[24,8]. Forexample,residualstresses

areknowntoadverselyaﬀectthefatiguelifeofweldedstruc-

tures. Moreover, correct application of modelling technique,

suchasdeﬁnitionofloadingandboundaryconditionsisperti-

nenttomodelquality. Whilsttherehasbeenalotofworkto

improveFEbasedmodellingmethodswithrespecttosomeof

theaforementionedphenomena[25,7,21,12],asystematicap-

proachtoimplementinglocalmaterialpropertyvariationwhich

ariseduetoweldingprocess,whichprovidesclosequantitative

correlationbetweenprediction,hasnotemergedinthepublic

domain.

In FEM based modelling, meso-scale complexity is typi-

callydealtwithbypartitioningthemeshintodistinctregions,

whicharerepresentativeoftheweldregions(i.e.Nugget,TMAZ,

HAZ and parent material) [7, 21]. Elements are assigned to

thesepartitionsandarecollectivelyassignedhomogeneousisotropic

properties;theseareusuallydeﬁnedbyaJohnson-Cookmate-

rialmodel:

Firstdescribedin1991byTWI,FSWisasolidstatejoining

process which enables the manufacture of high quality joints

inmaterialsthatarediﬃculttomanufactureviatraditionalfu-

sionbasedtechniques,suchas2xxxand7xxxaluminiumalloys

[16,17]. FSWhastheadvantageofreducingboththethermal

degradationtotheparentmaterialmicrostructureandtheresid-

ualstressgeneratedduringmanufactureincomparisontofusion

basedjoiningmethods[18]. Theseadvantagesmakethetech-

nologysuitableforthemanufactureofweldedstructuresfrom

alloyssuchas2139-T8.InFSW,thetool,whichiscomprisedof

arotatingpinandshoulder,isusedtogeneratefrictionalheatin

thework-piece.Thissourceofheatsoftensthemateriallocally

aroundthetoolwhichcanthenbemechanicallymixedabout

the tool as it rotates and traverses the joint line of the work-

piece.Sincetheprocessinducesatemperaturerisethatisbelow

themeltingtemperatureofthealloy,theweldingoccursinthe

solidstate.Whilstthereisnophysicalstatetransformation,dif-

fusionaltransformationprocessescanoccurwhichsigniﬁcantly

aﬀectthepropertiesacrosstheweldzone. Theseprocessesare

alloyspeciﬁcbutgenerallytheyinducecertainmeso-scalefea-

turesintheweldzone. Thesefeaturesincludetheformationof

aHeatAﬀectedZone(HAZ);aThermo-MechanicallyAﬀected