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Texture of Rotary-Friction-Welded from Dissimilar Medium Carbon Steels

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ABSTRACT
The purpose of the present study was to investigate the texture in dissimilarmediumcarbonsteelsweldedbyrotaryfrictiontechnique.TheElectronBackscatter Diffraction (EBSD)technique was the main technique usedtoinvestigate the effect of welding on grain size and grain crystallographic ori-entationintheweldedjoint.Moreover,theeffectofisothermalheattreat-ment at 600˚C on welded joint has been studied knowing that this annealingallows to decrease the residual stresses. EBSD results revealed different sub-zones in welded joint. The texture in the weld is essentially composed of threecomponents:Goss{110}<001>,RotatedCube{100}<110>,andRotatedGoss {110}<110>orientation.Theheattreatmentsappliedonweldedmaterialhadaslighteffectontexturean dgrainsize.
Keywords: Texture,RotaryFrictionWelding,MediumCarbonSteels

I. INTRODUCTION

This Friction welding is a solid state welding method. This type of welding in-volvestheunionbetweenastationaryandarotatingmember,duetothefrictionheat generated while undergoing high normal forces at the interface, below themelting temperature, the welded joint is achieved [1] [2]. In the case of joiningcircularbars,includingpipes,therotaryfrictionwelding(RFW)methodisused.Thistechnologyhasalotofa dvantagesoverotherweldingprocesses.Thesead-vantagesare;nomelting,highreproducibility,shortproductiontime,lowenergyinput,limitedheataffectedzone,av oidanceofporosityformation,andnograingrowthandtheuseofnon-shieldinggassesduringweldingprocess[3][4][5].

DuringweldingbyRFW,rapidheatingandcoolingtakeplace,whichproduces severe thermal cycle near weld line. Along the axial direction, threemainzonescanbeobservedfromthelinecontact:Weldingzone(WZ),thermalmechanicalaffectedzone(TM AZ)andheataffectedzone(HAZ).TheTMAZisthezonewhereheattransfersfromtheweldmetaltothebasemetal.A saresult,the welded joint obtained by RFW is a structurally inhomogeneous zone, char-acterizedbyawidespectrumofformedstructuresandstresses[6].

Friction welding (FW) is an economical and environmental friendly solidstatejoiningprocesswhichisappliedtojoinsimilaraswellasdissimilarferrousandnonferrousmaterials[7].Lit eratureshowsthatRFWtechniquehasbeenef-fectively applied to join dissimilar steels, such as carbon steel AISI 1020 and duc-tile iron ASTM A536 [8], AISI 304 austenitic stainless steel and AISI D3 toolsteel [9]. In the most published works, the main objective was focused oninvestigation of the effects of process parameters such as rotational speed andfriction time on the microstructure and mechanical properties of the frictionwelded.Forexample,Zdemiraetal.[10]haveinvestigatedtheinfluenceofrota-tional speed on the mechanical and structural properties of the plastically de-formedzoneattheinterfaceoftheweldduringfrictionweldingoftwodifferentsteels(AISI304LtoAISI4340alloyst eel).Itwasfoundthatthetensilestrengthincreaseswithincreasingtherotationalspeed.Radosławetal.[8]studiedthe ef-fect of RFW parameters on tensile strength and microstructural properties ofdissimilarjointsincarbonsteelAISI1020andductileironASTMA536.Itwasfoundthatasthefrictionforceandth efrictiontimeincrease,thetensilestrengthalso increases. Haribabuet al. [9]investigated the weldability in the differentcombinationsofAISI304austeniticstainlesssteelandAISID3toolsteelusingthe RFW welding technique. The results showed that the tensile strength of thejointsincreaseswiththeincreaseoftheupsettingandfrictionforceinitially,anddecreasesafterreachingthemaxi mumvalueof388MPa.

However, crystallographic aspect of the welded joint remains a research ques-tion knowing that limited researches have been reported about the texture dis-tribution in welded dissimilar joints by RFW [11] [12] but no investigation oftexture in welded dissimilar steels joined by RFW process. For example, Gaik-wad et al. [11]studied the texture of friction welded carbon steel (EN24) andnickel basedsuperalloy(IN718).Electron Back Scattered Diffraction (EBSD)analysis showed substantial changes in high angle grain boundaries, low anglegrain boundaries and twin boundaries in TMAZ and HAZ areas. Also significantrefinement in grain size was observed at TMAZ with reference tobasemetals.Ganetal.[12]investigatedbyneutrondiffractionthetexturegradientaroundthe weld line in RFW dissimilar metals of AA7020 Aluminium Alloy with 316Lsteel.Thetextureanalysisshowedaweakrotated Cubenearthebondlineof

AA7020-T6 side which indicated a plastic deformation of AA7020-T6 duringwelding.However,twoveryweakCubeandGosscomponentshavebeenidenti-fiedinthe316Lsteelpolefigures.

Inthepresentstudy,investigationofRFWofthetwodissimilarsteels32-2Mnand 40-Cr-Ni is important, because these two steels were used for the produc-tion of geological exploration drill pipes [13]. In previous investigations [13][14],analysiswasfocusedonthepost-weldtemperingeffectonthemechanismof fracture of welded joints of these medium alloy steels [13], and the residualstress distribution [14]. Stress distribution in welded joint is characterized byhighcompressivestressesinthermomechanicalaffectedzone,duetothemicro-structural changes present in the cross-section of the welds. However, the postheattreatmentscausedarelaxationphenomenoninweldregionwhichisduetotherecoveryandrecrystallizationreactions[14].

However, investigation of the texture in rotary friction welded joints fromthese dissimilar materials has never been reported up-to-date. Furthermore,studyandcontrollingtexturearenecessarybecauseitaffectsmechanicalproper-ties.Thenatureofthetexturedevelopedinaparticularspecimendependsonthematerialandonthemechanicalandthermaltreatments[15].

Inthiscontext,themainobjectiveofthisresearchistoinvestigatethetextureindissimilarsteelsweldedjointmadebyrotaryfrictionweldingandalsotoun-derstand the heat treatment effect on the crystallographic texture which has notbeenstudiedbefore.

II. EXPERIMENTAL PROCEDURE

1.1. MaterialsandWeldingProcess

Tow medium carbon steels were chosen to be welded by rotary friction tech-nique,32-2Mnand40-Cr-Ni.Thechemicalcompositionoftheweldedmaterialsisshownin**Table1**.

Rotaryfrictionweldingwasperformedonpipebilletswithadiameterof63.5 mm and a wall thickness of 4.5 mm. Experimental samples were welded on aThompson-60 friction welding machine in several stages. A rotary tube with aconstant speed is pressed onto a stationary tube and the relative movementcreates heat by friction. When the temperature necessary for formation ofweldedjointisreachedattheinterface,thetwotubesstarttodeformplastically.Afteracertainshorttime,theforgingphasebegins,wherethemotionisstoppedrapidlyandtheaxialpressureisincreaseduntiltheplasticdeformationceases.

In this investigation, the welding parameters were as follows: friction force 50kN,forgingforce130kN,frictiontime5.86s,androtationspeed800rpmwhich

Table1. Thechemicalcompositionoftheweldedmaterials.

Material	C	Mn	Si	S	P	Cr	Ni	Cu	Mo
32-2Mn	0.32	1.07	0.18	0.002	0.006	0.09	0.10	0.17	0.02
40-Cr-Ni	0.31	0.53	0.32	0.006	0.004	0.51	1.06	-	0.09

are chosen according to the previous works [13] [14]. As the melting tempera-tureisnotreached,thisweldingtechniquedoesnotproducetypicalweldingde-fectsknownfromfusionwelding[16].

1.2. MicrostructureandTextureAnalysis

The purpose of the EBSD experiments was to determine the texture before andafter heat treatment at 600˚C for 1 min of the welded joint. Specimens werepreparedforEBSDanalysisinastandardmanner(mechanicalpolishingwithSiC paper and electro polishing with the A2 Struers solution during 12 s in 40 Vflux 12). A Zeiss Sigma HD FEG-SEM operating at 20 kV coupled with the auto-maticOIM^{TM}(OrientationImagingMicroscopy)softwarefromTSL-EDAXCompany was used for the sample cross section EBSD analyses. **Figure 1** presentsthe schematic illustration of the studied area. The pole figures were calculated, us-ing the harmonic series expansion method (series rank L = 34), from the orienta-tionsmeasured by EBSD. Each orientation was modeled by a gaussian functionwitha5˚halfwidth.TheEBSD mapsare measuredin the (A1,A2)plane.

III. RESULTS AND DISCUSSION

Figure 2 shows EBSD map of welded of 32-2Mn steel to 40-Cr-Ni steel by RFWprocess,before(**Figure2(a)**)andafterpost-weldheattreatmentat600˚C(**Figure 2(b)**). The welded joint obtained by RFW is a structurally inhomoge-neous zone. From this general view, weldment can be divided broadly into twozones,(1)Weldinterface(WI)and/or thermomechanically affectedzone(TMAZ) on both sides. However, the HAZ cannot be distinguished from theBM.Basedonthescalein**Figure2(a)**,thethicknessofWIislessthan500µm.The microstructure in this region consists of fine grains with. The TMAZ ischaracterized by spiral lines. It has been reported that in RFW, the rotation andthe axial force govern the plastic material flow that results in shear as well ascompressivedeformation.Therefore,theflowlineshaveaspiralshape[17]. Asmentionedinourpreviouspaper[14],themicrostructureobservationsre-vealedtheintensivedevelopmentofdynamicrecrystallizationprocessesinthe

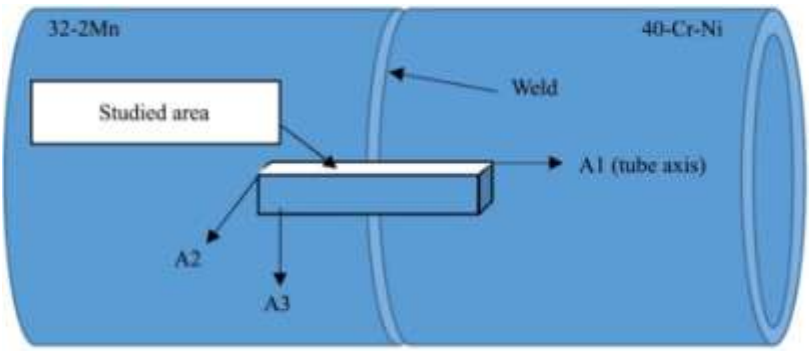

Figure 1. SchematicillustrationoftheEBSDstudiedarea(A1-A2planeinwhite)ofsam-pleswiththecoordinatesystem.

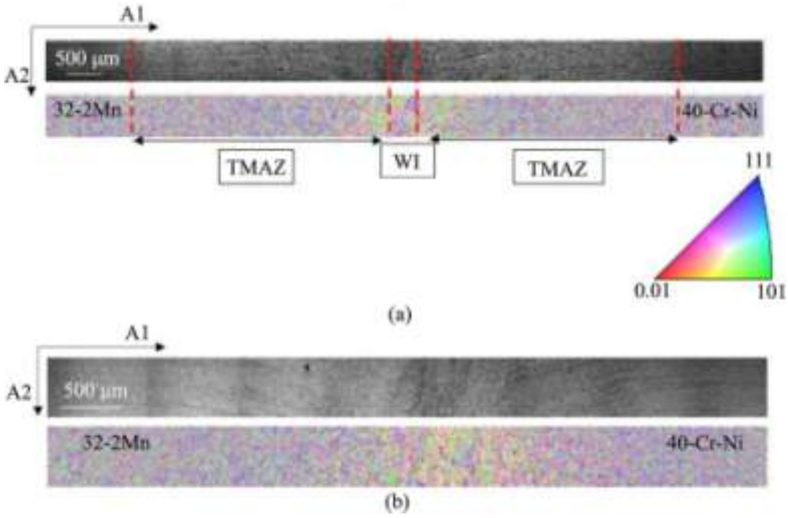

Figure 2.EBSD maps (QI and A3-IPF) of welded of 32-2Mn steel to 40-Cr-Ni steel byRFWprocess,(a)beforeand(b)afterpost-weldheattreatmentat600˚C.Thecolorcodeis given on the standard triangle. (QI: The image quality parameter or IQ describes thequalityofanelectronbackscatterdiffractionpattern).

TMAZ of the both sides of the welded joint. This dynamic recrystallization reac-tion is due to heating and deformation during friction process. The color of in-dividual grains in EBSD maps describes the {hkl} crystallographic plane parallelto the observation plane (**Figure 2(a)** and **Figure 2(b)**). These EBSD maps give ageneral idea about the grain morphology and orientation along the welded joint.From the EBSD maps of **Figure 2**, the microstructure of the center of the weldedjoint is characterized by coarse grains and the other zones (HAZ, BM) are com-posed of finer equiaxed-grains. The colored inverse pole figure (IPF) map of thewelded joint is also presented in **Figure 2**. The color of each grain indicates itscrystallographic direction parallel to A3 (red for {001}, blue for {111}, and greenfor{101}),asshowninthestereographictriangle. Forclarity,sevendistinctsub-zoneswereconsideredinallweldedjoint(sub-zonesa,b,c,d,e,f,andg)(**Figure3**).Thesub-zones(a)and(g)corres-pondtothetwobasemetalswhicharenotaffectedbytheRFWprocess.Thesub-zone(d)isthecommonzone(WI)ofthedissimilarsteels,anditisamix-turezoneasshowninEDSprofileoftheweldedjoint(**Figure4**),thechemicalprofilesofthetwoselectedelements(Cr andMn)changealongthissub-zoneWI.Thesub-zones(c)and(e)aretheadjacentzonestothemixturezone(d).FromtheEBSDmaps,thesesub-zonesaredifferentfromthebasemetalsandmixturezone.Besides,the(b)and(f)sub-zonesarecharacterizedbyspirallines.**Figure 5** presents the grain size distribution along welded joint before and af-terheattreatmentat600˚C.Grainsizeincreasesinthetwosub-zones(c)and(e)andintheweld(sub-zoned).Thisisprobablyduetoadynamicrecrystallizationeffect during welding. As observed in other materials welded by RFW, such asmolybdenum[16].Itiswellestablishedintheliteraturethatdynamicrecrystal-lizationoccursduringFW[11][18][19].Inaddition,thereisaslightdifference

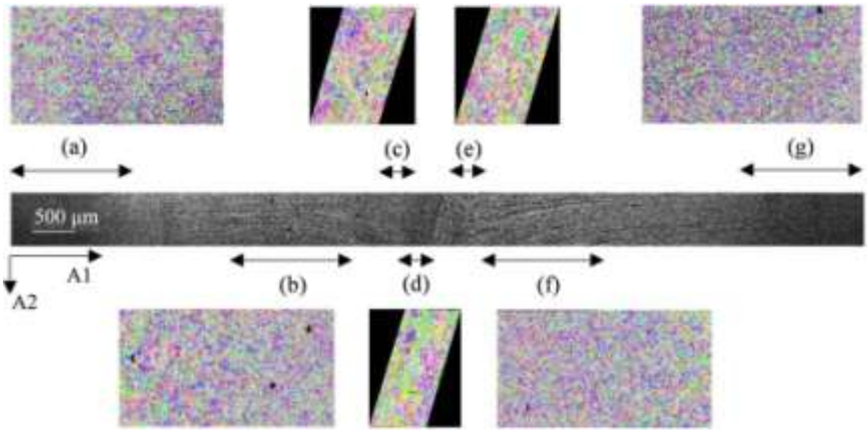

Figure3.EBSDmapofdifferentsub-zonesweldedof32-2Mnsteelto40-Cr-NisteelbyRFWprocess.

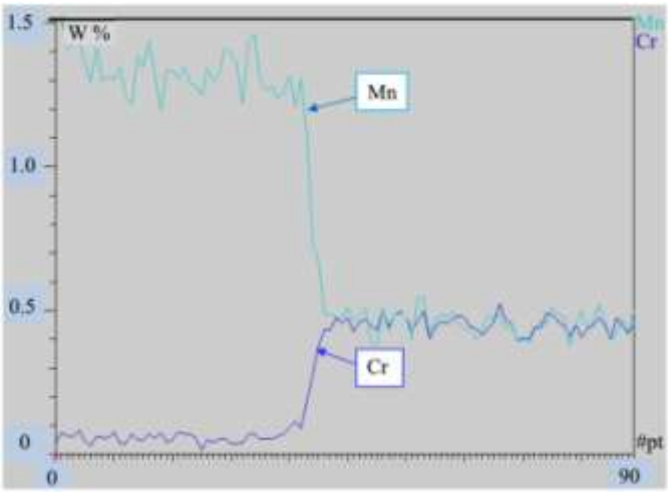

Figure4.EDSprofilealongthecommonzone(WI)oftheweldedjoint32-2Mnsteel/40-Cr-NisteelbyRFWprocess.

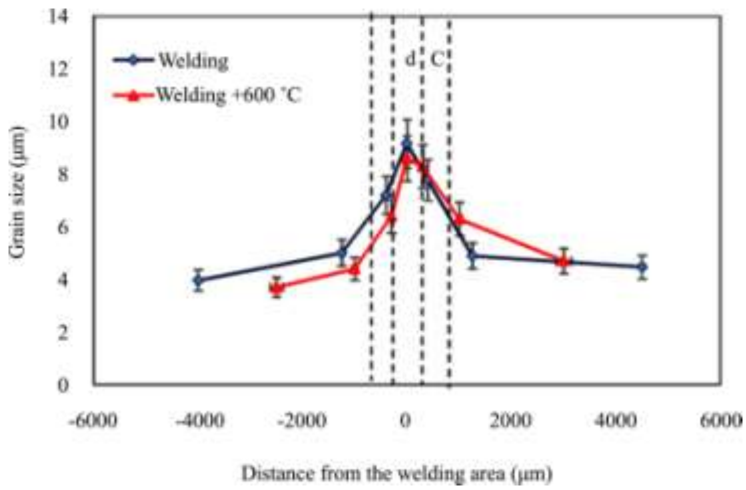

Figure5. Grainsizedistributionalongweldedjointbeforeandafterheattreatmentat600˚C.

between the welded dissimilar steels before and after heat treatment at 600˚C,because the remaining time at 600˚C is very short (60 s). From mechanical as-pect, this result is important, because this treatment did not cause any graingrowth but it reduced the residual stresses as mentioned in our previous pub-lished work [14]. The stresses are less relaxed in the different zones (in the centeroftheweldedandtheTMAZ).

Besides, the fraction of high angle grainboundaries(HAGB)(>15˚) decreasesinthetwosub-zones(c)and(e)andintheweld(sub-zoned)(**Figure6**)downto 75%. It is to be linked with the texture that shows up more grains in the sameorientation (**Figure3**) and therefore themisorientation between thesegrains islow.Incomparison,witharandomtexturedistributionofMacKenzie,theHAGB percentage is approximately 98%.More, Stützetal.[16],found that dueto the higher strain rates achieved in the contact zone, the production of disloca-tionswashigherthaninallotherzones.Consequently,themagnitudeofdy-namic recrystallization was alsohigher andthe formationoflowangle grainboundarieswasenhanced.Forthisreason,thepercentageofHAGBinthecon-tactzone(thecenteroftheweld)islowerthaninotherzonesoftheweldedjoint.

Intheweldedzone,thegrainsizeandpercentageofHAGBaresimilarbeforeandafterheattreatment.Onthecontrary,thepercentageofHAGBinbasemetalwasobservedtobe88%beforeheattreatmentand96%afterheattreatment.

Figure 7presents the pole figures of welded joint before heat treatment. It isnecessarytomentionthatthemaximumintensityofthepolefigureswasmeas-ured in the two sub-zones (c) and (e) and in the weld (sub-zone d) which con-firmsthecrystallographicdifferencebetweenthecenteroftheweldedjointandtheotherzones.Thedevelopmentofdifferenttexturein theweldedjointisduetothemicrostructuralheterogeneityoftheweldedjoint.Thisheterogeneitycanbeexplainedbytheweldingofdissimilarsteelsandalsobytheformationofdif-ferentsub-zonesfromthecontactzonewhichishighlyrecrystallizedtothebasemetal.

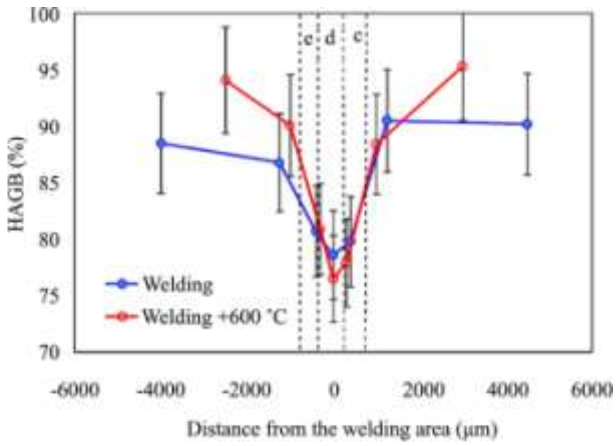

Figure 6. Fraction of HAGB distribution along welded joint before and after heat treat-mentat600˚C.

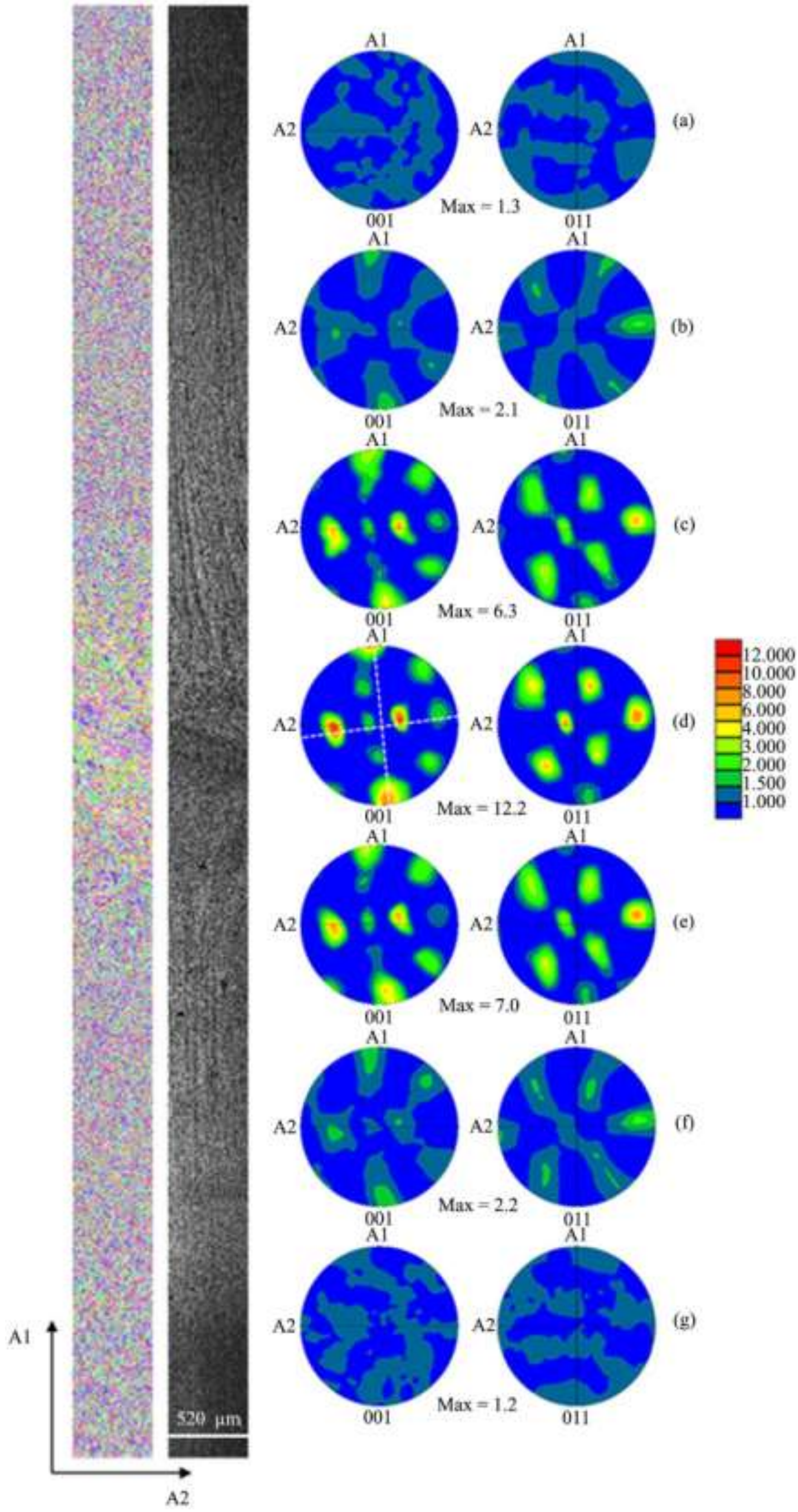

Figure7.{001},{011}and{111}polefiguresindifferentsub-zones((a)-(g))ofthedissi-milarweldedjoint.

ThepolefiguresarerotatedwithrespecttobothA1andA3axes.TherotationwithrespecttoA1isconstantforallsub-zoneswhichsuggeststhatthisrotationislinkedtoanexperimentalproblem.TherotationrelativetoA3increasesfro mthe base metal (about 0˚ or a few degrees) to the center of the welded joint(about10˚).Thisrotationisrelatedtotheproductionofspirallinesobservedin**Figure4**whichindicatestheplastic materialflowduringRFWprocess[17].

CalculationoftheODF(**Figure8**)hasneededrotationsrelativetoA1andA3 in order to force texture symmetry and consequently to be able to identify thethree main texture components. The texture is essentially composed of thecomponents:Goss{110}<001>,RotatedCube{100}<110>andRotatedGoss {110} <110>. We consider that the first component (Rotated Cube {100} <110>)is related to the plastic deformation during RFW, because it has been reportedthat the rotated Cube orientation is important for the development of shear tex-ture components [20]. It has been reported that Rotated cube is stable orienta-tionaftercoldrolling[21].

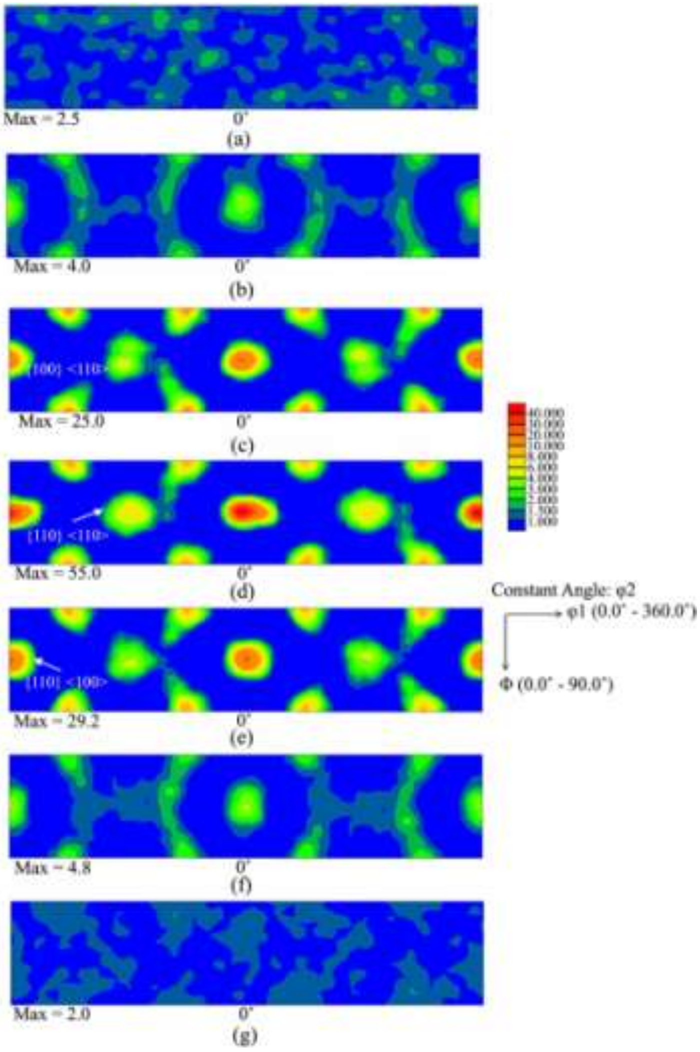

Figure8.ODFintheweldedjointofdissimilarsteels(afterrotation).

It has been indicted that during subsequent plastic deformation, the crystalsrotate toward certain stable orientations. However, Goss {110} <001> and Ro-tated Goss {110} <110> components are the components of recrystallization. Inbccmetalsoralloys,therecrystallizationtexturesarelargelysimilar,althoughthe relative prominence of the various texture components may differ to someextent,becauseofmaterialorprocessingvariations[15].Ourresultsareinagreement with the finding of Rahimiet al. [22]. They found shear deformationwith textures ferritic steel side of the two investigated in friction stir weldedmicroalloyed steel. For these reasons cited above, two types of textures were de-veloped in welded joint by FRW; shear (Rotated Cube {100} <110>) and recrys-tallizationtextures(Goss{110}<001>andRotatedGoss{110}<110>).

Therelativestrengthofthecrystallographictexturewasquantifiedastextureindex,ascalarparameterindicatingrelativeanisotropyEngler[23],withahigh-ervalueofitsignifyingstrongtextureandlowervaluesignifyingarandomtex-ture.

Figure9presentsthetextureindexalongtheweldedjointofdissimilarsteelsbefore and after heat treatment at 600˚C (after rotation).The main point is thattexture index is higher in the central zone of the welded joint than in the basematerials. It is known that the texture gets strengthened when recrystallizationoccurs.Besides,thereisnotasignificantdifferenceintermsoftextureindexbe-foreandaftertheheattreatment(**Figure10**).

Figure10presentsthetexturecomponentfractionsintheweldedjointofdis-similar steels before after heat treatment at 600˚C (after symmetry correction)withdispersionof15˚ontheEulerangles.AsitispresentedinFigure10,thereisanincreaseinthefraction ofthecomponentsinthetwosub-zones(c)and(e)and in the weld (sub-zone d). The Goss fraction is greater than that of the Ro-tated Cube which is itself greater than that of the Rotated Goss {110} <110>component,whiletheyhavesimilarfractionsinthebasematerials.

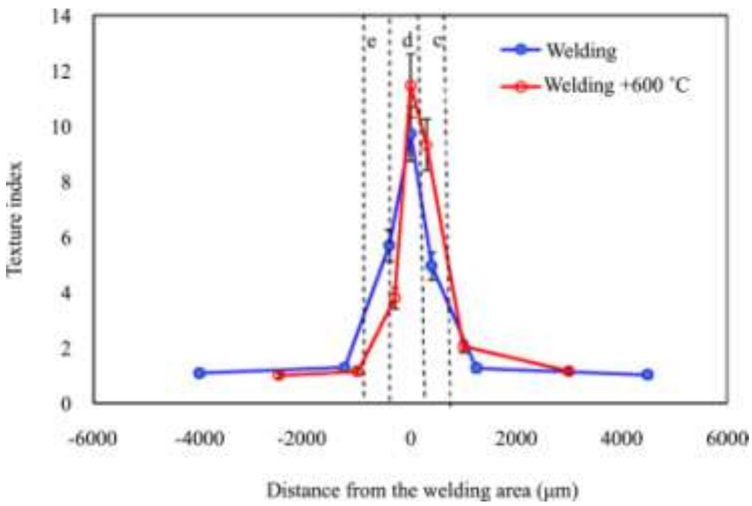

Figure9. Textureindexintheweldedjointofdissimilarsteelsbeforeafterheattreatmentat600˚C(afterrotation).

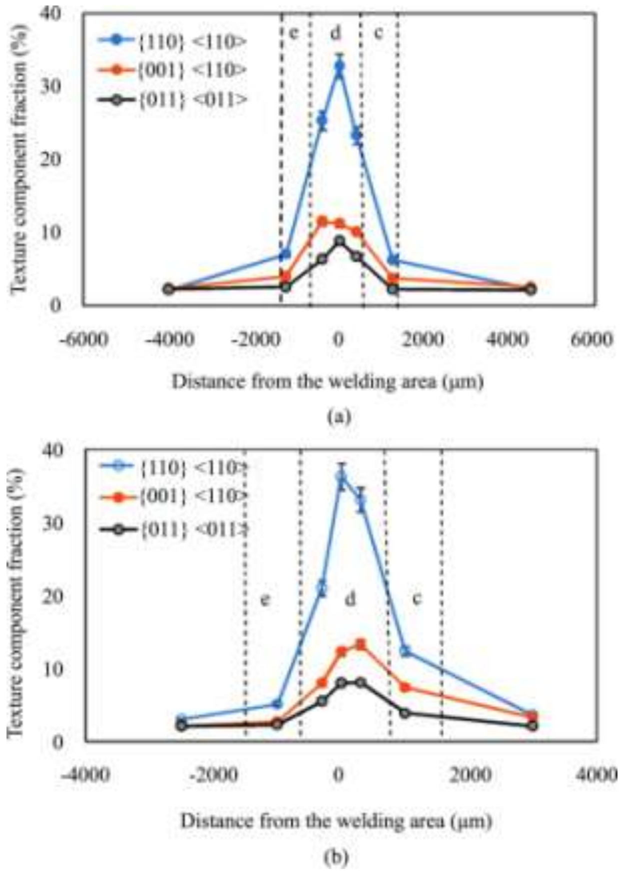

Figure 10. Texture component fraction in the welded joint of dissimilar steels: (a) beforeand (b) afterheat treatment at 600˚C (after rotation).

IV. CONCLUSIONS

Following conclusions can be drawn from the present work of dissimilar me-diumcarbonsteelsweldedbyrotaryfrictiontechnique.

- The welded joint obtained by RFW is not homogeneous from the micro-structuralaspect.
- EBSDresultsrevealedthatseventhsubzonesinweldedjointandthecentralzone are different to other zones in terms of texture. The texture in the weldis essentially composed of three components: Goss {110}<001>, RotatedCube{100}<110>,andRotatedGoss{110}<110>orientation.RotatedCube {100} <110> is a sheartexture; however, Goss {110} <001> andRotated Goss {110}<110>arerecrystallizationtextures.
- Thereisnotasignificantdifferencebetweenbeforeandafterheattreatmentat 600˚C in terms of microstructure, texture intensity and texture compo-nentswhatevertheweldedzoneisstudied.

ConflictsofInterest

The authors declare no conflicts of interest regarding the publication of thispaper.

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