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Residual Stresses, Thermomechanical Behavior and Interfaces in the Weld Joint of Ni-based Superalloys**

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In welds, in Ni based superalloys complex interactions between different physical processes are expected to occur.[1] On heating to a temperature close to the solidus temperature, the eutectic phases will dissolve (Fig. 1(a)). Regions heated below solidus, but above the γ' solvus temperature will lead to complete dissolution of γ' precipitates. On cooling, re-precipitation of γ' phase results in a wide range of sizes of γ' precipitation. Due to thermal stresses, the dislocation activity occurs in different regions of the weld. The focus of the current research was to evaluate the structural changes that occur in the weld of Ni-based single crystal alloys.

Results and Discussion: During heating and cooling the alloy passes through the single phase γ region (Fig. 1(a)). This creates complicated thermal mechanical conditions in the weld joint.[2,3] Two single crystal alloys, Rene N5 and CMSX-4, were investigated. Alloy compositions are shown in the Table 1.

Positions of the alloys on the phase diagram are shown by a dashed line in Figure 1. Equilibrium temperatures for the alloys are shown in the Table 2. The very early stages of the weld process together with the base metal (BM) structure determine the properties of the weld. BM in both alloys had a dendrite structure (Fig. 1(b)). Each dendrite contained Ni_3Al based cuboidal γ'-phase particles with their (001) plane aligned with matrix (001) plane (Fig. 1(c)). SEM and OIM analysis shows that BM in both alloys had quasi single crystalline structure. Large angle boundaries were not observed (Fig. 1(d)). Orientation of the BM was relatively homogeneious (Fig. 1(e)) with surface normal in the [013] direction in RENE N5 and the [001] direction in CMSX superalloy.

During welding the weld pool moves through the sample creating a complicated thermal mechanical field accompanying this movement. Formation of the quasi single crystalline structure of the weld joint at early stages of weld joint appearance is shown in Figures 2(a,b). Continuous nucleation of dendrites in the melted weld pool starts upon cooling at the fusion line (FL) separating BM within the heat affected zone (HAZ) (Fig. 2(c,d)). Therefore the BM structure together with the direction of temperature gradient G, determine the morphology of the FL (Fig. 2(e,f)) and the orientation of the nucleating dendrites.

During dendrite formation the angle between the temperature gradient at the solidification front and the dendrite direction continuously increases. When the angle reaches 45° a change of the growth direction to the perpendicular one takes place ([100] ⇒ [010]) (Fig. 3(c)). This results in the formation of regions with different dendrites growth directions in the weld such as ([100],[100],[010]). Regions with the first two dendrite orientation are located in the left and the right sides of the FZ, and the third one with [010] dendrite direction is located in the central part of the joint as observed experimentally (Figs. 3(a,b)).

According to OIM analysis the overall orientation change is much smaller in CMSX 4 than in RENE N5 alloy (Figs. 1(e), 2(f), 3(d–g)). Dominating red color at Figure 3(f) according to color scheme to the right of the figure demonstrates that mainly small angle (up to 3°) boundaries are present in the weld. However OIM provides information about the orientation only in the thin near-surface region. The next structural level of plastic deformation is probed with higher special resolution synchrotron radiation PXM analysis. Although local orientation according to OIM analysis remains the same in different regions of the weld PXM reveals strong plastic deformation both in the FZ and HAZ. A typical PXM image obtained from the HAZ of a CMSX4 alloy weld shows strong plastic deformation (Fig. 4(b)). PXM images of the nondeformed material usually consists of very sharp Laue spots (Fig. 4(a)). Strong lattice rotations within the probed region results in the "streaking" of the Laue spots.[2–4] The direction and the FWHM of the streak are related to the orientation of the resulting rotation axes caused by geometrically necessary dislocations (GNDs) within each probed region. To check for homogeneity of plastic deformation several linescans across the weld were performed with a step size of 0.25 μm along the line and 1μm step between the lines. Strong oscillations of

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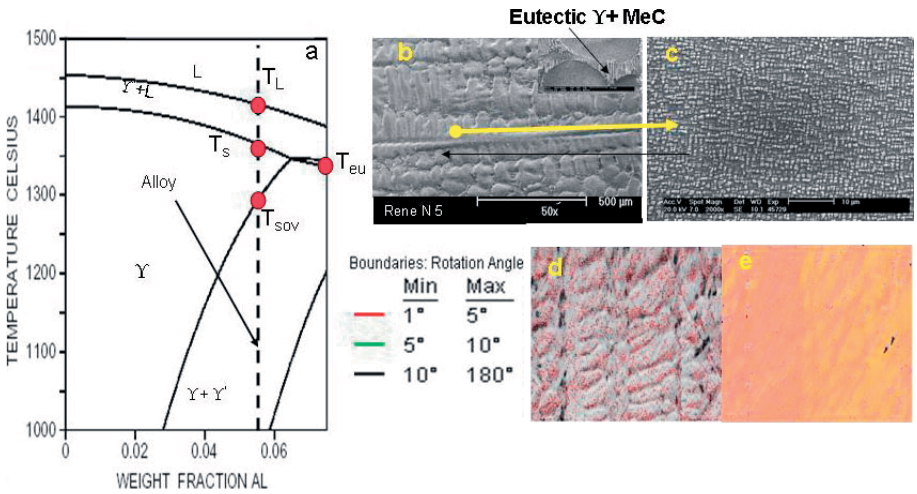

Fig. 1.(a) Section of the phase diagram with the alloy position (dashed line) showing the change in Al solubility in the matrix with temperature; (b) dendrite structure of RENE N5 in BM; (c) γ′-phase particles within the dendrite; (d) boundaries distribution in the BM; (e) homogeneous orientation of the BM according to OIM analysis.

Table 1. Alloy composition.

Alloy	Cr	Ti	Mo	W	Re	Ta	Al	Co	Hf	B	C	Σ
Rene N5	7.0	1.0	2.0	5.0	3.0	7.0	6.2	8.0	.15	.004	.05	17.0
CMSX-4	6.5	1.0	0.6	6.0	3.0	6.5	5.6	9.0	.1	–	–	16.4

Table 2. Equilibrium temperatures for superalloys in (°C).

Alloy	T_{sov}	T_{eu}	T_S	T_L	ΔT ($T_L - T_S$)	ΔT^2 (T_{eu}-T_{sov}')	Vol Y′
Rene N5	1304	1317	1336	1387	51	13	74.2
CMSX-4	1282	1317	1339	1404	65	35	71.7

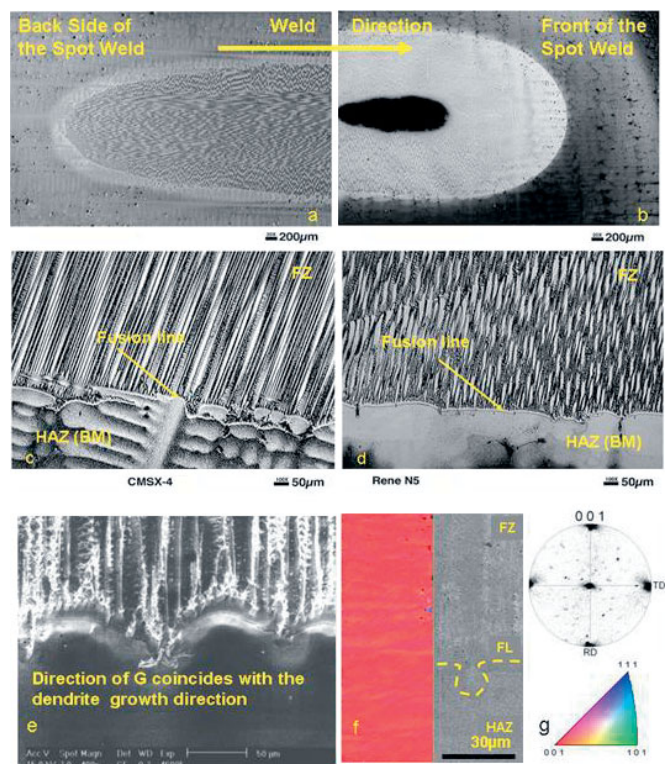

Fig. 2. Shape of the back (a) and front (b) side of the weld pool; Nucleation of dendrites at the fusion line in CMSX-4 (c) and RENE N5 (d) superalloys. Weld direction is from left to right. Evolution of solidification front near the fusion zone (e) and local orientation distribution near the FL from OIM analysis (f).

the GNDs slip systems and density were observed across the weld (Fig. 4(c)). Interestingly, strong plastic deformation was observed in the HAZ at relatively large distances (~ 1–2 mm) from the weld for both alloys. In contrast to the near surface orientation distribution, which is more homogeneous in the CMSX4 weld than in RENE N5, plastic deformation is much stronger in CMSX4 than in RENE N5. This is consistent with the model that residual stresses relax in the CMSX4 resulting in a stronger plastic deformation while the weld in RENE N5 keeps a higher level of residual stress. GNDs densities are almost twice as high in the weld joint of CMSX4 than in RENE N5 weld joint. Zones of the most intense plastic deformation are neigboring the FL in both superalloys (Fig. 4(d)) and the line of the dendrite orientation change within the FZ (dashed line DD in Figs. 4(d) and 3(c)).

GNDs density oscillations are observed at different length scales (Figs. 4(d,e)). At the microscale, oscillation of the GNDs density are found between different dendrites in the FZ. Sometimes twinning is observed resulting in the splitting of the Laue spots (Fig. 4(c)).

Numerical analysis of the thermal field around the weld pool (distribution of temperature and it's first and second derivatives) during welding of thin sheets of Ni-based superalloys demonstrates structure in the distribution of these thermal parameters around the melted zone. The welding process was simulated with the finite element method (FEM) using ABAQUSPP®.[5] To simplify the calculations, the specimen was modeled as a plane, axisymmetric 70 × 50 × 0.8 mm specimen. Eight-node quadratic, rectangular elements were

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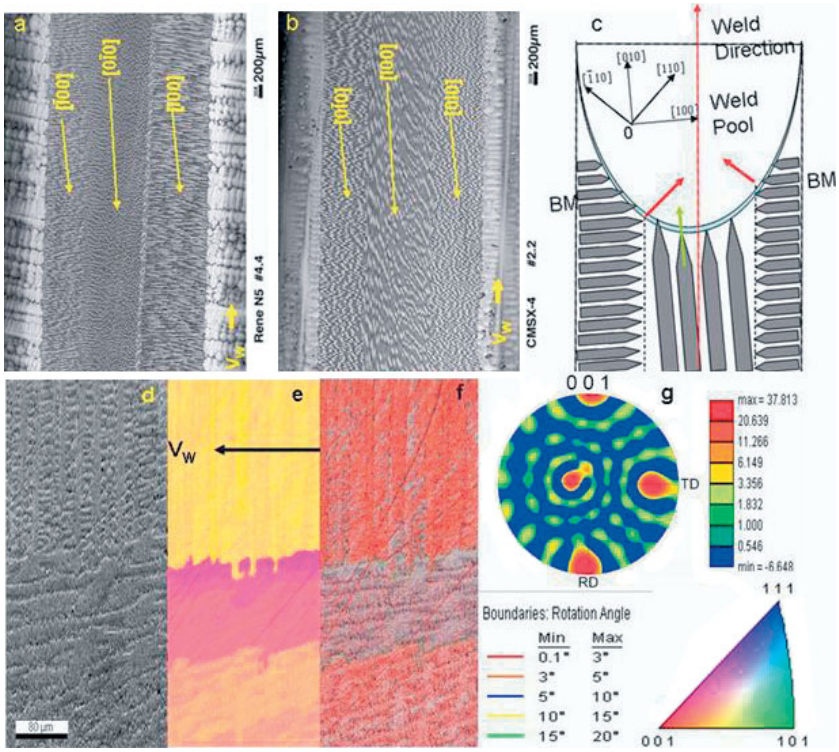

Fig. 3. Three regions of dendrites with different cubic orientation of the dendrite growth axis in RENE N5 (a) and CMSX 4 (b), a scheme of the dendrite formation in the weld (c). OIM characterization of the central part of the weld demonstrates three possible cubic growth directions: d) microstructure of the weld; e) OIM image of the weld; f) distribution of boundaries across the weld; g) pole figure of the weld.

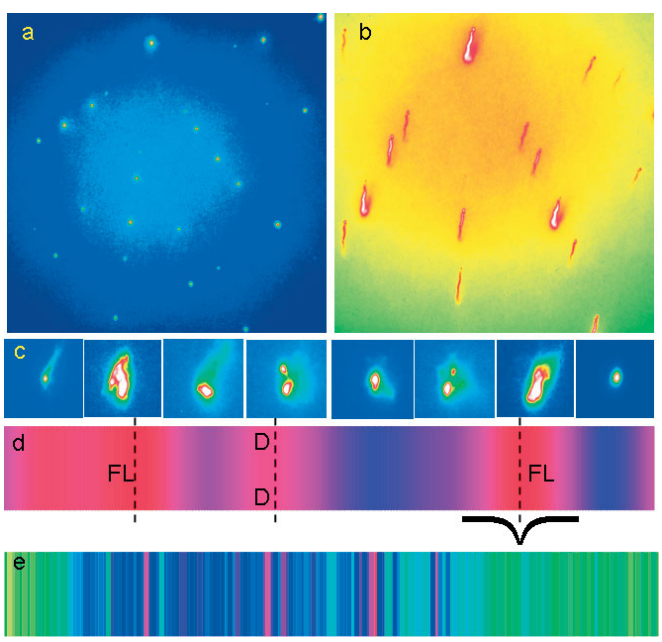

Fig. 4. Typical Laue image from the BM far from weld (a); streaked image (b) from the location with strong plastic deformation in the HAZ of CMSX4 superalloy; Oscillating intensity distribution of the (001) Laue spot at different probing locations across the weld (c); GNDs density oscillations across the weld (d); GNDs density oscillations in the region near the FL marked with an arrow in Figure 4(d) (red color corresponds to maximal GNDs density value in the region).

used in a mesh. The left boundary of the mesh was the edge of symmetry. The mesh was refined closer to the top surface and near the edge of symmetry because the largest temperature gradients occur in these regions.

The Gaussian heat source function by Goldak[6] was used. Temperature-dependent material properties were used, and heat loss on the surface by convection and radiation was considered. The thermal modeling results were calibrated by weld cross-section shape fit[7] corresponding to the weld geometry.

Although temperature gradually decreases with the distance from the pool center, its derivatives first increases, reaches maximal values close to FL. Their maximal values are located close to the solidification front, within the region of crystallized metal. Absolute maximums of temperature and its derivatives are found in the HAZ in the close vicinity of the FL (Fig. 5). It is worth noting that Laue images show maximal streaking in these regions.

Concluding Remarks: It is possible to retain quasi single crystalline structure of the Ni-based single crystal superalloys under certain conditions of welding. Residual stresses in the weld joints of Ni-based superalloys partially relax via the formation of dislocations and dislocation boundaries. The thermal field in the vicinity of the moving weld pool in the Ni- based superalloys is not homogeneous. Maximal values of temperature gradient are located close to the FL. Oscillations in the dislocation structure are observed at different length scales supported by Fourier transformation methods. Plastic deformation is most intensive in the regions with maximal temperature gradient. Densities of GNDs are almost twice as high in the weld joint of CMSX4 than in RENE N5 weld joint. The typical length scale of GNDs density oscillations in the fusion zone region is related to the dendrite size.

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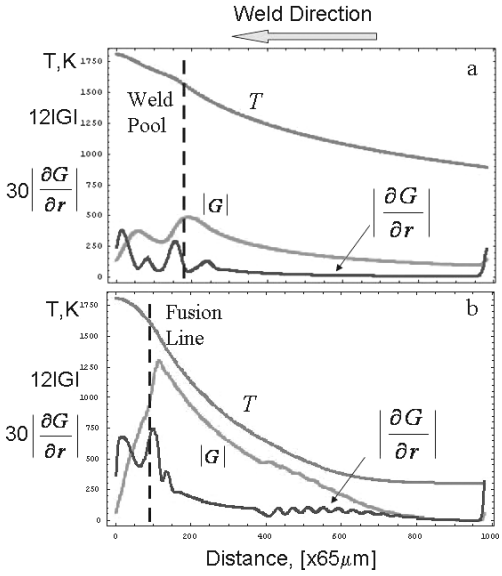

Fig. 5. Distribution of temperature (T), it's gradient (G) and second derivative along (a) and across (b) the weld.

Experimental

Residual stress distributions and their relaxation via plastic deformation and the formation of dislocations was characterized with Polychromatic X-ray microdiffraction (PXM). PXM was performed with the 3D X-ray crystal microscope using a modified Laue diffraction method based on polychromatic radiation.[4,8] This approach allows for true 3D mapping of crystalline phase, orientation, elastic strain and plastic deformation with unprecedented spatial resolution. The differential-aperture microbeam technique[8] allows mapping of the crystal structure orientation and distortions with sub-micron spatial resolution in three dimensions. This method allows a micrometre-scale resolution with depth (along the path of the incident beam). At each depth the data are obtained by computer reconstruction for each pixel of the CCD. Details on the experimental setting and data collection can be found elsewhere.[4,8] Data collection has been carried out using microbeam Laue diffraction on beamline 34ID at the APS.

Scanning electron microscopy (SEM) and orientation imaging microscopy (OIM) was performed using Philips XL30.

Autogenous welds of thin superalloy sheets with the size of 50 × 70 × 0.8 mm were prepared at 1.5 kw with continuous wave Nd-YAG laser in two different crystallographic direction, parallel and perpendicular to the dendrite orientation in the plane of the sheet. Different processing conditions were used: power was varied in the interval of 300-850 w; welding velocity in the interval of -2.1-21.2 mm/sec.

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[1] S. A. David, S. S. Babu, J. M. Vitek, Welding, In: *Encycl. of Mater. Sci. and Technol. Updates*, Elsevier, Oxford **2003**, 1–9.

[2] O. M. Barabash, S. S. Babu, S. A. David, J. M. Vitek, R. I. Barabash, *J. Appl. Phys.* **2003**, *93*, 738.

[3] O. M. Barabash, J. A. Horton, J. S. Park, S. S. Babu, J. M. Vitek, S. A. David, G. E. Ice, R. I. Barabash, *J. Appl. Phys.* **2004**, *96*, 3673.

[4] R. Barabash, G. Ice, F. Walker, *J. Appl. Phys.* **2003**, *93*, 1457.

[5] ABAQUS, ver.6.3-1, HKS. **2003**.

[6] J. Goldak, A. Chakravarti, M. Bibby, *Metall. Trans. B-Process Metall.* **1984**, *15*, 299.

[7] D. dye, O. Hunziker, S. M. Roberts, R. C. Reed, *Metal. Mater. Trans. A* **2001**, *32*, 1713.

[8] G. E. Ice, B. C. Larson, *MRS Bull.* **2004**, *29*, 170.

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Tensile Deformation Behaviour of the Titanium Alloy with Hard Elastic Coating

By *Waldemar Ziaja*, and *Jan Sieniawski**

The increasing demands for higher performance and more severe application conditions have been the main driving forces for wider use of titanium alloys for engineering components. The main reason for that is a favourable combination of properties like high specific strength, corrosion resistance and biocompatibility. However low resistance to oxidation at high temperature and poor tribological behaviour are the main reasons that very often surface treatment is applied for elements made of titanium alloys in order to obtain surface layer having favourable properties. PVD methods lead to formation of intermetallic or compound layers (e.g. TiN, TiC, Ti_3Al, TiAl, Al_2O_3) with thickness of the order of several μm. As the result of thermochemical treatment (e.g. nitriding, carbonitriding) hardened diffusion layer is formed, at the top of which intermetallic or compound layer can also be present (e.g. TiN). These phases have high Young's modulus and can be treated as perfectly elastic. Because of high value of elastic modulus and very low plastic deformability of the layer, when large tensile stresses are present, microcracks appear in the layer. They induce stress concentration that leads to local plastic deformation of the substrate at the macroscopic tensile stress value below its yield strength.[1,2] Plastic deformation of the substrate is additional factor decreasing durability of the layer because of delamination and flaking.[2,3] This phenomenon was most frequently studied for indentation and friction

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