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Deformation Nano-Mechanisms Occurring on the Interface of Dissimilar Materials Joined in Solid Phase by Means of High Temperature Rolling

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Abstract

Nano-mechanisms of crystal lattice deformation on the interface of dissimilar materials (Cu-Nb), joined by vacuum rolling in solid phase under high temperature (950˚C) were studied by means of high resolution electron microscopy. Input of carriers of rotation modes—nano-dipoles of partial disclinations and nano-twist disclinations in the form of double spirals in deformation mechanisms were analyzed. The role of these mechanisms in decrease of shear stability of the interface areas and in production of high-quality rolled metal is discussed.

Keywords

Vacuum Hot Rolling, Solid Phase, Interface, Cupper-Niobium, Microscopy, Disclinations

1. Introduction

Development of present-day technology, especially its new directions, provides more rigid requirements to the welds of the construction materials. Most works conducted in this field are devoted to the welding procedures under melting of the material. However, when welding by melting is used for joining of metals a number of difficulties takes place, especially when joining the heterogeneous in properties materials. They are connected with

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impossibility to limit the processes of mutual diffusion, resulting in development of chemical heterogeneity and appearance of fragile intermediate phases and compounds.

Other technological processes of joining the materials in solid phase have been successfully developing within several decades, for example, pressure welding in solid phase, which decreases significantly the negative high-temperature influence on the materials. Besides this usage of pressure welding opens the possibility for purposeful formation of the needed structures and properties of the materials in the joined area.

Priority in creation of industrial equipment and development of method of metal treatment by pressure in vacuum belongs to NSC KIPT NAS of Ukraine. Early in 1952-1953 under supervision of K. D. Sinelnikov and V. E. Ivanov vacuum rolling machines were constructed and research of beryllium, zirconium, uranium and other metals rolling was conducted for the first time in international practice [1].

Despite the fact that a number of multi-layered materials, combining all positive properties of the components of the pack, were obtained by method of vacuum rolling, many problems connected with processes taking place on the interface of the composites remain unsolved.

Among them determination of the mechanism of structuring, taking place near to the interface of the metals—elements of the composite on the nano- and micro-level. Taking into account that under conditions of developed plastic deformation not only translation shears take place in the materials but also plastic rotations (rotations modes), which are beard by disclinations of different types [2], research of their input into the deformation processes close to composite interface was of special interest.

2. Materials and Methods

Bimetal Cu-Nb was selected for research, whose components are almost insoluble between each other. Selection of the materials is stipulated by the fact that these pair of materials is used as transition layers when creating the compounds steel-titanium, which are promising for use in nuclear energy.

Joining in solid phase was conducted in common pack St. steel-Cu-Nb-Ti under temperature 950˚C in vacuum $p = 10^{-2}$ - 10^{-3} Pa on rolling machine DUO-170. Rolling deformation was about 27% - 30%. Plate with thickness 0.15 mm was cut from the welded pack on the electro-spark discharge machine, from which samples for electron-microscopy research were produced. Thinning (cross-section) from two sides was conducted by ion etching on the interface of the Cu-Nb solid phase joining.

High-resolution electron microscopy (microscope JEM-2100F) was used for analyses of the processes taking place on the bimetal interface, joined by high-temperature vacuum rolling. Analyses of components distribution on the interface was conducted by X-ray micro-analyzer INCA (Oxford Instruments).

3. Results and Discussions

Earlier [3] the first nano-structural research of interface of solid-phase joining of niobium-copper was conducted. Effect of formation of deformation structure in near-boundary areas, called by authors as quasi-periodic "wave-front" of the crystal lattice deformation, indicating the hydrodynamic flow of the material in the transition area (**Figure 1(a)**) was discovered on the nano-level. The work also shows that processes of dynamic nano-crystallization take place in the rolled composites (stainless-steel-copper, Nb-Cu) on the interface copper-niobium which ends with the creation of grains with sizes of several nm, having strongly disoriented boundaries, which can be the result of rotation plasticity processes flow.

Use of IFFT method (method of image cleaning by means of Fourier transform) allowed determining the nature of "wave front" (**Figure 1(b)**). It was determined that this area consists from a set of quasi-periodic nano-strips (sometimes with width less than nm), created by the system of high density shears (up to $10^6 \ldots 10^7$ cm^{-1}). Their front boundaries-combs are created by collective shears, as complete and partial dislocations. Most of these strips create defects which can be called *re-orientation nano-strips* as they represent rotation plasticity on the lowest level of deformation.

On the meso-structural level they can be compared with front of Chernov-Luders lines. On that level the plastic deformation under development of reorientation strips can be described within the disclination approach [2].

Collective effects based on long-distance interactions between each other appear in disclination assemblies and in their dipoles. The so called dipoles of partial disclinations are most preferable from the energy point of view and are observed more often. Their movement apart from the reorientation of crystal lattice on the angle φ (dipole power) results also in shears.

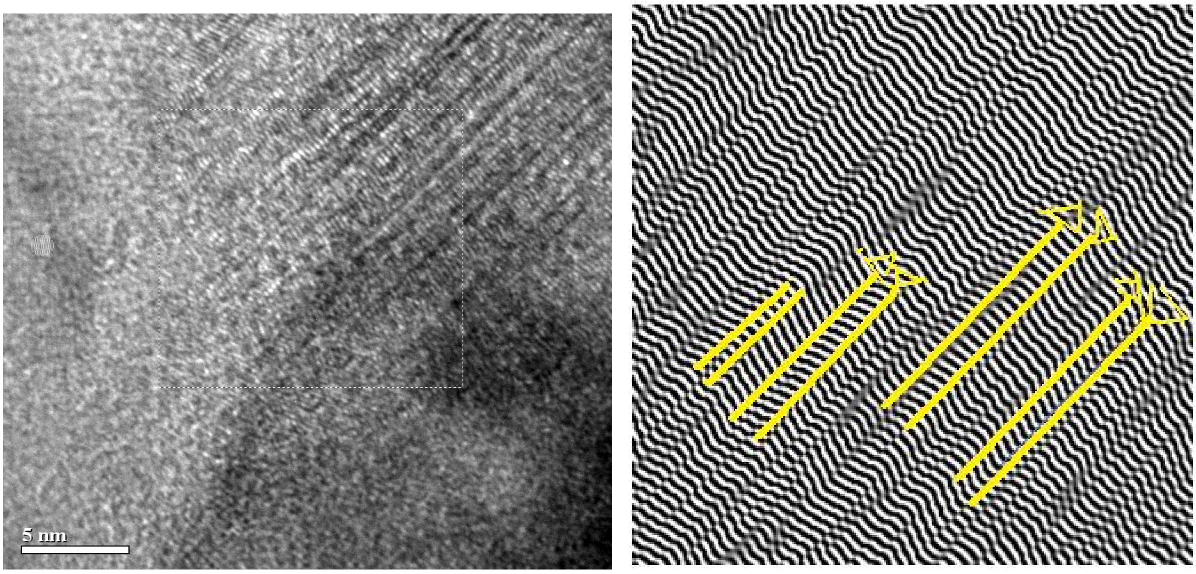

Figure 1. "Wave front" on the Cu-Nb interface. (a) Area of "wave front" investigated by means of high-resolution microscopy; (b) Area is marked with square. Defects in shear nano strips of the area of "wave front", which can be interpreted as "dipoles of partial nano-disclocations" (marked in lines). Method of image cleaning by means of Fourier transform (IFFT).

In order to characterize the dipoles, the same authors introduced the concept of super dislocations with effective Burgers vectors $\mathbf{B} = \varphi \times L$ (L dipole lever) [2]. Namely with use of these defects, formation of reorientation strips and non-crystallographic shear in the wide range of materials is described. In accordance with the same work, the dipole lever cannot be more than 1 μm and less than 0.1 μm. However as the recent research showed [4], under specific conditions of deformation by rotation on Bridgman anvils, formation of nano-dipoles of partial disclinations with sizes of several nanometers is possible in molybdenum and vanadium alloys under high values of logarithmic deformations (e = 5). In this research we see formation of such specific defects under high-temperature rolling of bimetals under deformation values not exceeding 30% that is several orders lower.

Examples of structures which can be interpreted as nano-dipoles of partial disclinations are shown of **Figure 1(b)**. These defects are shown on the ends of the moving nano-strips. Similar to mezzo-dipoles they are terminated, stopped in the crystal volume. In contrast to "classic" dipoles of partial dislocations, nano-dipoles have lever about 1 nm. At this effective Burgers vector of the nano dipole **B** is several time less than normal Burgers vector in ($\mathbf{B} \sim \varphi \times L \sim$ **0.04 nm**). It means that the energy of such "defect" essentially less than the energy of normal dislocations and disclinations. The necessity of formation of such structures in dissipative nonequilibrium system becomes clear—they provide the most effective relaxation of deformation energy on the nano-structural level.

Use of method of Fourier-cleaning (IFFT) allowed determining absolutely new, nowhere discovered earlier in the volume materials, type of defects, which can be called "nano-twist disclinations" (**Figure 2(b)**).

Indeed in the monograph which became classic [2], direct-line disclinations with Frank vector, parallel to the defect line are called wedge and disclinations with Frank vector perpendicular to the line are called twist disclinations.

However, all that defects were the defects of meso-structural level. Thus Panin with co-authors observed similar meso-defects in the form of "cords" on the interface of the coatings with metallic substrate [5].

Despite the works presented above, **Figure 2(b)** shows series of specific representatives of rotation modes, which can be called "nano-twist disclinations". Most of the presented on the figure twist nano-disclinations have power of "Frank vector" from π to 2π. Another peculiarity of these defects should be noted—they have appearance of double spirals.

Thus, one of the mechanisms of plastic flow in the area of interface of the joined by rolling, dissimilar materials is the distribution in the direction, perpendicular to the direction of shearing nano strips distribution—strips of the localized deformation in the form of double spirals. It can be assumed that exactly due to this mechanism,

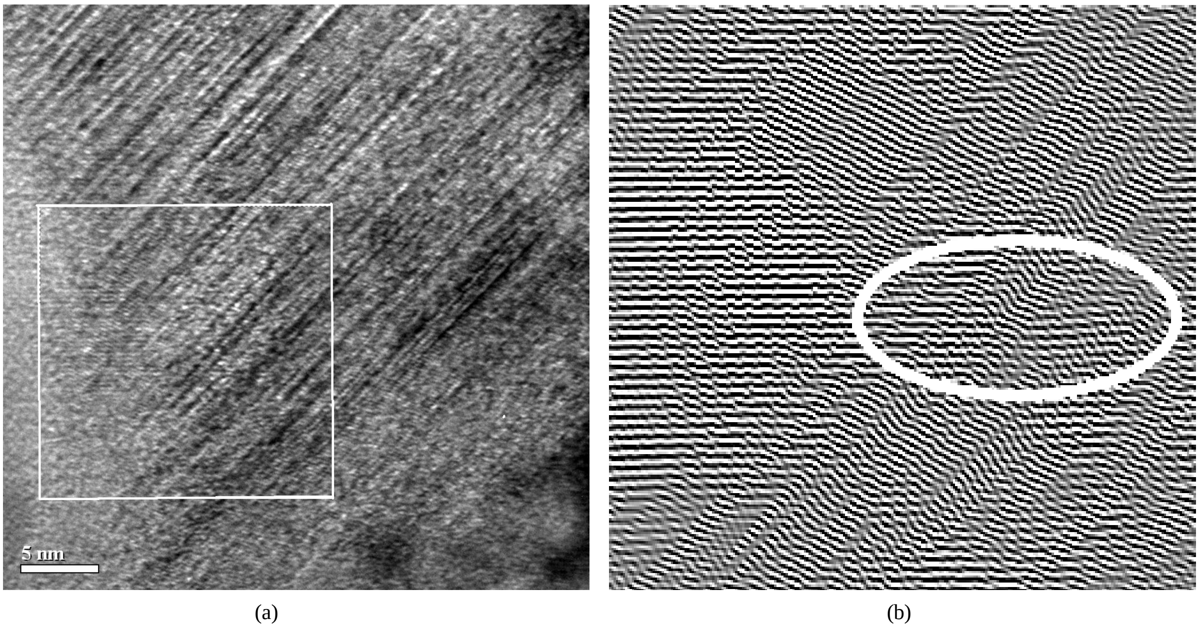

Figure 2. "Wave front" on the Cu-Nb interface. (a) Area of "wave front" investigated by means of high-resolution microscopy; (b) Specific representatives of rotation deformation modes—"nano-twist disclinations" in the form of double spirals (marked with oval), observed in the area of "wave front".

which decreases the shear value in the strip, achievement of critical shear value, resulting in appearance of cracks embryo, does not take place in it. **Figure 2** shows the shear is not distributed further in the area where double spirals appeared.

Again returning back to meso-level of plastic deformation, we will mention the results of work [5], which in some range can be the confirmation of the mentioned above. Double spirals of meso-strips were not destroyed but just stretched like springs under formation of embryo of cross cracks in deformed titanium film.

Expressed considerations on the different nature and behavior of these two types of nano-disclinations can be summarized in the way that they play the contrary role in the processes of development of shear-rotation instability. Dipoles of partial nano-disclinations stimulate this process and nano-dipoles of rotation on the contrary—make it difficult, providing the increase of crack resistance of the interface area.

It is interesting to note that defects of such type, connected with formation of "cords", curling of atomic chains were observed on atomic level in the polymers and some amorphous materials [2]. Taking into account the fact that twisted double spiral DNA is also a polimer, unintentionally there appears a temptation to spread these idea on the animate nature.

Thus, one of the conditions to eliminate the cracking and conduct qualitative rolling of dissimilar bimetallic composite materials is the creation of conditions of decreasing the shear resistance in the interface areas. In turn, on the lowest possible nano-structural level, this condition is provided by appearance of high density of strips, limited with nano-disclinations, as bearers of shear-rotation instability.

Alloying of materials with poorly soluble, horophilic elements, decreasing the shear resistance of their grain borders, can also serve for this purpose. Thus alloying of refractory metals of the 6 group (Cr, Mo, W) with poorly soluble elements of the 8 makes them more plastic and eliminates cracking of metal under rolling [6]. In turn, decrease of high shear resistance of the 6 group metals lattice while alloying is connected with the decrease of covalent component of metal d-bond and influence of high density of electronic states on the level Fermi metals of the 8 group.

4. Conclusions

1) Interface area of the joined by rolling dissimilar materials constitutes a separate, strongly different on behavior and deformation mechanisms volume of material, which stays in condition of share-rotation instability already under comparatively small level of deformation.

2) It is determined that bearers of plastic deformation in the interface area of the joined by high-temperature rolling materials can be not only the shear modes but also representatives of rotation mode—nano dipoles of partial disclinations (or dislocation of non-crystallographic shear) either of usual, dipole type or the nano-dipoles of torsion in the form of two spirals, whose movement can be controlled by fluxes of point defects vacancies, staying in great quantity in non-equilibrium, deformed under high temperature material. These nano-defects provide opposite influence on the deformation localization and as a result–"optimize" the development of rotation-shear instability, which is one of the conditions for creation of qualitative joining of dissimilar materials.

3) One of the conditions to eliminate cracking and conducting of qualitative joining in solid phase of dissimilar materials, is the creation of conditions to decrease the shear resistance of interface areas. On nano-structural level, this condition is prided by appearance of high density of strips, limited with nano-dipoles of partial disclinations as bearers of shear-rotation instability.

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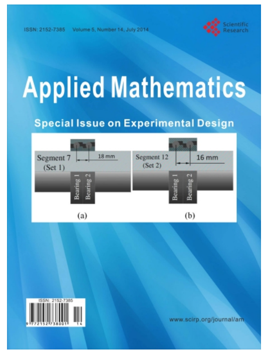
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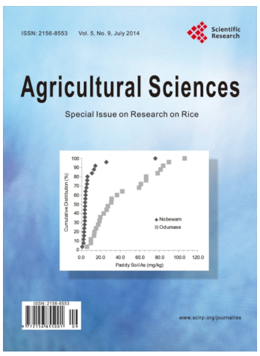
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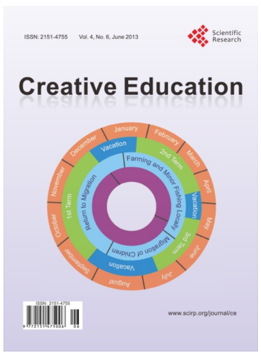
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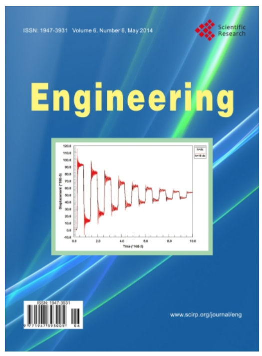
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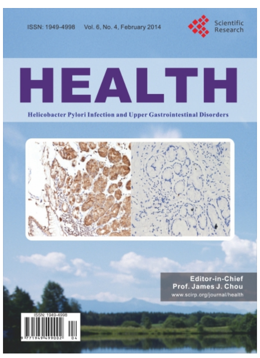
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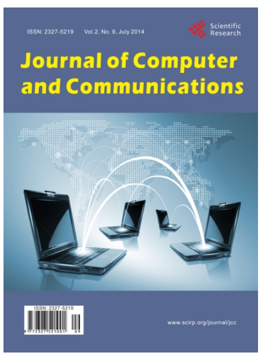
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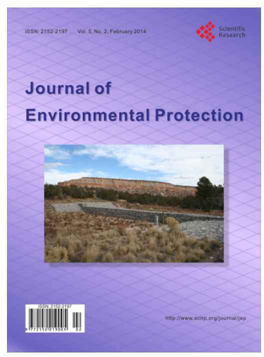
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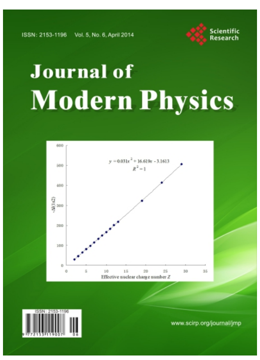
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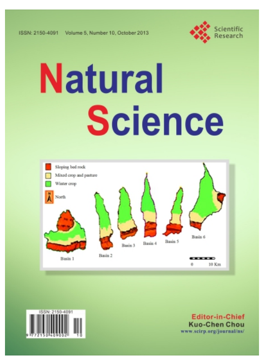
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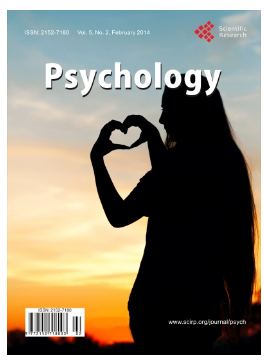
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