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UTILITY OF STRESS-TEXTURE CHARACTERISTICS OF STRUCTURAL MATERIALS BY X-RAY TECHNIQUE

PRZYDATNOŚĆ CHARAKTERYSTYKI NAPRĘŻENIE-TEKSTURA MATERIAŁÓW STRUKTURALNYCH WYZNACZONEJ METODĄ RENTGENOWSKĄ

The work is dedicated to Professor Bogusław Major
for the occasion of his 70 anniversary

The article presents the results of residual stress analysis in selected metal-metal joints manufactured by conventional welding and explosive merging. The X-ray diffraction technique applied for advanced stress-texture measurements and data processing revealed directions and values of the principal stresses and their configuration on the surface of the examined structural elements. The obtained stress topography of the joint intersections indicates a possible path of potential cracking formed during the exploitation process and thus it becomes a very useful tool in the diagnostics of structural elements.

Keywords: residual stresses, crystallographic texture, state of microstructure

W pracy opisano badania i uzyskane wyniki analizy naprężeń własnych przeprowadzone dla wybranych połączeń metal-metal wytworzonych przez konwencjonalne spawanie oraz łączenie wybuchowe. Pomiary naprężeń oraz tekstury dokonane techniką dyfrakcji rentgenowskiej, jak i zastosowane odpowiednie procedury obliczeniowe pozwoliły zidentyfikować kierunki i wartości naprężeń głównych oraz ich konfigurację w badanych elementach konstrukcyjnych. Topografia naprężeń w wybranych obszarach badanych połączeń wskazuje możliwą drogę potencjalnej destrukcji złączy w procesie ich eksploatacji. Charakterystyki naprężeniowo-teksturowe uzyskane w oparciu o technikę dyfrakcji rentgenowskiej okazują się bardzo przydatnym narzędziem w diagnostyce elementów konstrukcyjnych, szczególnie takich jak przedmiotowe złącza.

1. Introduction

Lifetime of most machine parts is determined by the wear-resistant properties of their surface layers and functional coatings. Such structural elements as punching dies, spray nozzles, gear wheels, which can be found in many different devices, represent a system of surface layers working together or in contact with a gas/liquid medium. The parameters of those surface layers have an essential influence on the dynamics of the wearing process. The state of the near-surface area of the working elements – referred to as the technological surface layer (TSL) – is the result of the technological treatment applied in the production process [1].

As a rule, TSL is characterized by a significant crystallographic texture [2,3]. From the viewpoint of the tribological processes occurring on the surface, it is desirable to induce a compressive stress state in the TSL, acting as a counterbalance for the tensile stresses caused by friction. Under mechanical or thermo-mechanical loading, the TSL transforms it dynamically into the exploitation surface layer (ESL), in which the actual stress state plays an active role, contributing to the importance of such technological parameters as lubrication or motion mode. The evolution from TSL into ESL employs changes in the distribution of the structural defects such as shear bands, modifications in crystallographic texture and the state of the residual stresses. The intensity of these changes depends on the stage of the fatigue pro-

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cess progress. The texture analysis itself provides non-destructive methods of monitoring fairly subtle modifications in the preferred crystallographic orientation of grains in thin near-surface layers [2,3] and it can be combined with different types of measurements for the stress-texture investigation of the working surface. Since TSL is characterised by the definite stress-texture conditions of its microstructure, the identification of that state reveals a possible path of potential cracking formed during exploitation. Regardless of the identification, monitoring the stress levels and the crystallographic texture during the fatigue process allows for the detection and observation of the developing destruction of the working surface. Changes in the appropriately selected texture component are an early signal for the building-up of microstructure damage [1] and a similar use can have a stress state analysis [4].

In addition to the surface layers and the functional coatings, equally important from the technological and exploitation point of view is the bulk of the structural element. A well-known technological process such as cold rolling generates a special field of stresses, which is a driven force of the emerging of the crystallographic texture [5]. The texture, in turn, generates elastic anisotropy of the material, which has to be taken into account in the stress analysis by means of diffraction techniques. Beside the mentioned cold rolling, many other common technologies, such as casting, drawing, extrusion or electrodeposition of coatings, generate the preferred orientation of crystallites and thus their products demand a suitable, often combined or multi-scale, methodology of the microstructure analysis.

The above mentioned aspects impose strong requirements on the proper selection of the representative samples of the investigated material, the necessity of a suitable preparation of those samples and adequate registering the diffraction data, which later should be carefully analysed. A broad range of computer and machine aided methods is now available for the automation of sample preparation and the measurement procedures, but computerization is more important in the field of data processing and the calculations related to the particular methodology in the diffraction experiment. A single stress-texture measurement combines approaches and methods from different areas of physics and material sciences, but the results are most valuable if such a stress-texture characteristic concerns the surface of the sample as a whole, which means that hundreds of single examinations are brought to the new dimension of stress-texture maps for structural elements.

The study contains a stress-texture analysis of selected welded joints carried out with the methodological and automation solutions developed at the research laboratory of the Institute of Metallurgy and Materials Science of the Polish Academy of Sciences in Krakow. The practical implementation of the modern laboratory diffractometer to combine the advanced texture and stress measurements for a single stress-texture characteristic at a given point on the material's surface and extending this further to a new dimension of stress-texture mapping is an exciting and unique opportunity to study the exploitation behaviour related to the state of the microstructure of present-day materials.

2. Materials and methods

The reported investigations were performed on various joints manufactured by conventional welding (steel-steel)[1] and explosive merging (steel-Ti)[2], see (Figs. 1 and 2). The residual stresses were measured by the X-ray diffraction technique on a cross-section of the joints prepared by grazing and mechanical or electrochemical polishing.

The stress investigation was carried out with the basic assumptions known from the traditional $\sin^2\psi$ method [6] with the use of the *D8 Discover* Bruker diffractometer equipped with a parallel-beam primary optics *PolyCap* system completed a pinhole collimator (1.0 mm aperture) for CoK_α radiation ($\lambda = 1.790300$ Å) and a linear position-sensitive detector *Lynx-Eye* (range 2.6° on 2θ), capable to work in a parallel secondary beam configuration with the use of Soller collimators. The *211* for steel (α-Fe, ferritic phase) and *101* for Ti (α-Ti phase) diffraction profiles were registered. The mapping of the stress state was performed by way of many three-directional stress measurements along the x,y grid on the sample surface. The pole figures for the obtaining of complete texture data were measured in several key points of the same grid. The analysis of the experimental data was carried out with the use of the TARSIuS (*Texture-Aided Residual Stress Identification System*) package, developed at the home Laboratory and it employed the modern refinement approach to the stress tensor calculation and the uncertainty estimation.

The diffraction experiments yielded to series of peaks fitted with a semi-phenomenological continuous function (modified Person VII profile, taking into account the $CoK_{\alpha 1}$ and $CoK_{\alpha 2}$ radiation components), from which the peaks center positions $2\theta_{hkl}$ were obtained. With Bragg's Law, those peak center positions were used to calculate the distance between the crystallographic planes d_{hkl} and each interplanar distance measured for a different position of the diffraction vector according to the sample surface can be transformed to the crystal lattice deformation ε_{hkl}. The diffraction vector is traditionally described by the tilting angle ψ for the azimuth direction φ, and the lattice deformation observed in this way is the function of those two angles in the laboratory coordinate system. With the generalized Hooke's law, the set of the observed lattice deformations ε_{hkl} can be used to calculate the stress tensor, which, on the basis of mechanics, is responsible for the observed deformation of a material with known elastic properties. Any type of three-dimensional elastic behavior of the investigated substance could be described by the tensor quantity F, known as the *stress factor* (eg. [7]), allowing us to write:

$$\varepsilon^L(\varphi,\psi,hkl) = \sum_{i,j=1}^{3} F_{ij}(\varphi,\psi,hkl)\sigma_{ij} \qquad (1)$$

where: L denotes the lattice strain e measured with respect to the laboratory frame of reference. The stress factor for a polycrystalline material incorporates the grain interaction model for the

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crystallites in the stress field – it can be as simple as the Voigt or Reuss models, or much more complex, based, for example, on plastic deformation modelling, leading to the present state of the investigated material. Nevertheless, the stress factor is always associated with the real material's texture and the elastic properties of its basic components, such as the single crystal elasticity parameters.

The general relation between the observed lattice deformation and the estimated stress tensor was used in the presented investigations to connect the data from three separate traditional stress measurements conducted in $\sin^2\psi$ methodology and to estimate the uncertainties of the results in a more general and reliable way. If the standard measurements expressed good linearity, for the principal stress calculations, the approach of Barret and Massalski was applied [8], where at least three independent directional stress measurements can be used to find the base of the principal stresses. When the registered data exposed significant oscillations on the $d_{hkl}(\sin^2\psi)$ plots, a general strain-stress relation was applied with the use of the Reuss model. Simultaneously, the single crystals data [9] in calculating the stress factors and general stress refinement procedure was used to find the principal stresses.

2. Results and discussion

The stress analysis was preceded by X-ray phase and crystallographic texture analyses. The phase analysis allowed for the selection of the appropriate acquisition parameters; reflection, its nominal angular position $2\theta_{hkl}$, the scan range and the scan step $\Delta2\theta_{hkl}$ of the diffraction spectrum to maximize the experiment efficiency.

The texture of the examined explosively joined materials was analyzed on the basis of the experimental data registered by the X-ray diffraction technique (Figs. 1 and 2). The pole figures revealed a relatively weak texture in the case of the steel-steel joint (figures registered in the dominating α-Fe phase in the Heat Affected Zone) and an essentially stronger one in both α-Fe and α-Ti in the case of the steel-Ti composite (figures registered in the near-interface areas of both materials). Moreover, the texture of Ti presents a distinct asymmetry which reflects the nature of the joining process. In the case of the steel-Ti composite, the texture was considered in procedure of calculating the diffraction constant in the stress analysis [7].

The identified topography of stresses in the selected areas of the examined joints is shown in (Figs. 3-5). The circles on the map indicate the location of the measurement points, and their radius depicts the direction of the stresses with the ascribed value. With the increasing result uncertainty for a given measurement point, the circle becomes more transparent and the radius direction – less defined (larger spread on the picture).

As it can be seen in (Fig. 3), the topography of the stresses reflects the weld material and the joined steel sheets, as well as the heat affected zone.

The stresses identified in Ti have a tensile-compressive character, with a global predominance of the first one, and their extreme values are 350 and 500 MPa, respectively. The configu-
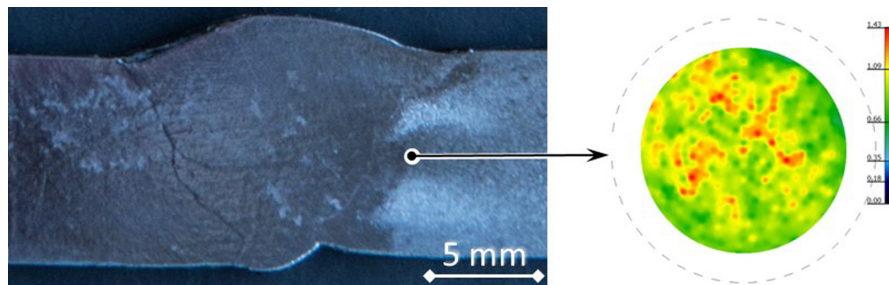

Fig. 1. View of conventional steel-steel welded joint and incomplete (110)-pole figure of dominating α-Fe phase registered in Heat Affected Zone
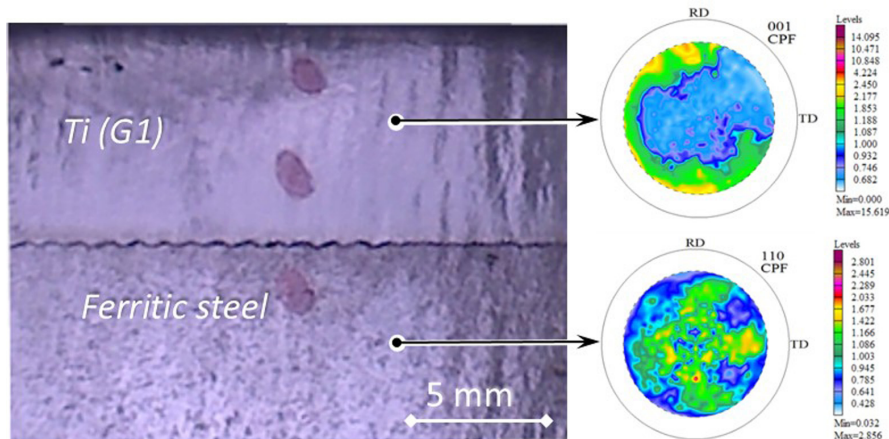

Fig. 2. View of steel-Ti explosive joint and incomplete (001)- and (110)-pole figures of α-Ti (top) and α-Fe (bottom) of coupled materials
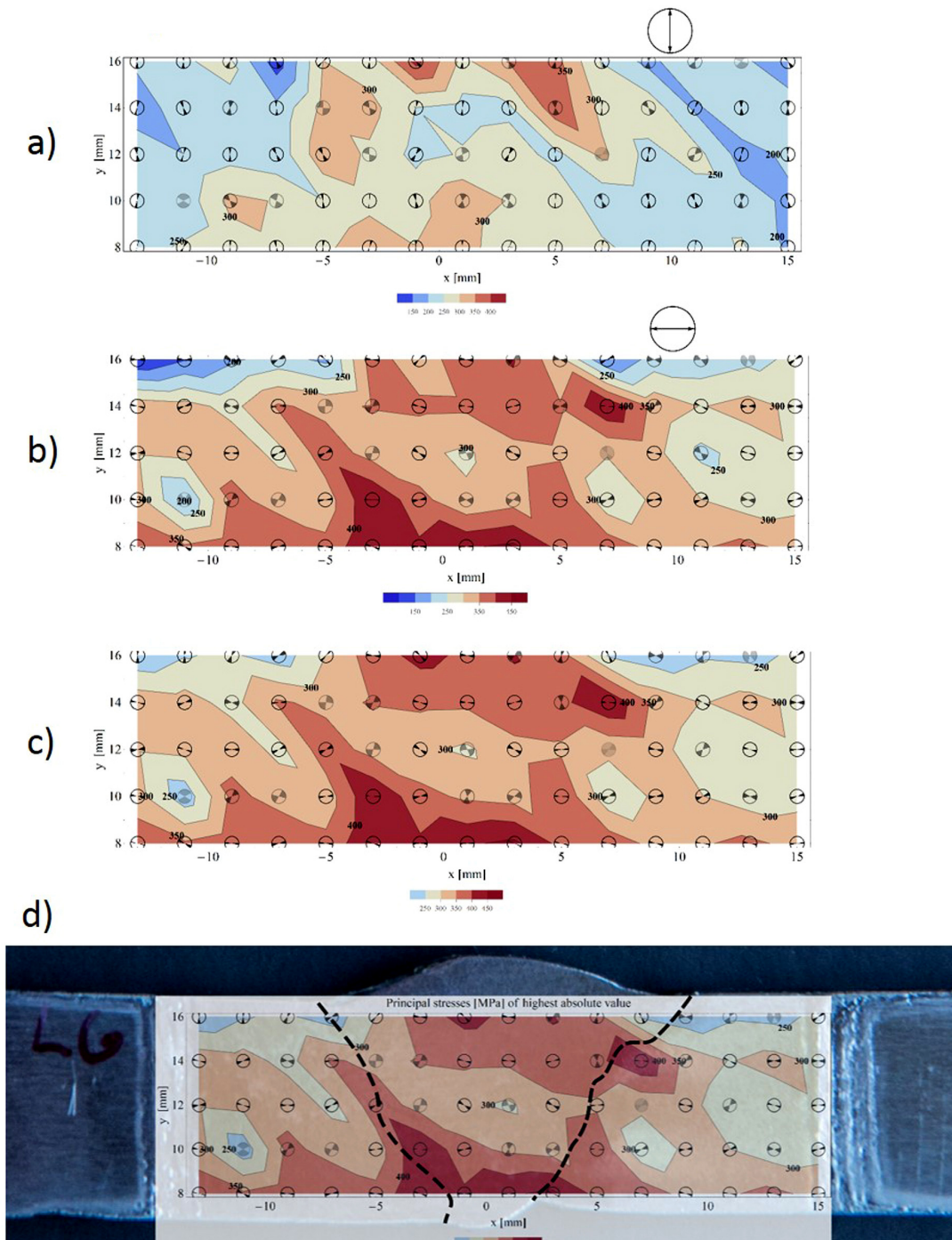
Fig. 3. 2D distributions of principal stresses in cross-section of examined traditional steel-steel welding sorted by their proximity to vertical – (a) and horizontal – (b) direction on samples, map of principal stresses with highest absolute value (c) and superposition of stress topography and picture of the examined element with marked boundaries of weld material

ration of the stress field has the nature of bands, which reflects the process of explosive joining (the explosive material was located on the side of the Ti sheet and pushed in the horizontal direction). That band structure is slightly inclined in relation to the line of the material's interface, which may indicate a directional force that acted during the joining process in the wave of the migrating material. This effect is visible in all the stress maps presented in (Fig. 4). The extreme residual stresses were identified on the cross-section of Ti in the direction inclined by 60°-90° to the normal to the junction surface (0°-40° in respect of direction of

propagation of the detonation). A similar band structure of the stress field is observed in the near-interface area of the steel component of the steel-Ti composite (Fig. 5).

The presented method of nondestructive material investigation allows to observe the evolution of the stress state in relation to the junction proximity and the detonation direction. Moreover, the results obtained by the advanced X-ray technique correspond well in terms of the values and directions of the calculated principal stresses with the results obtained in the hole-drilling method for the same material [10]. This correspondence of both results
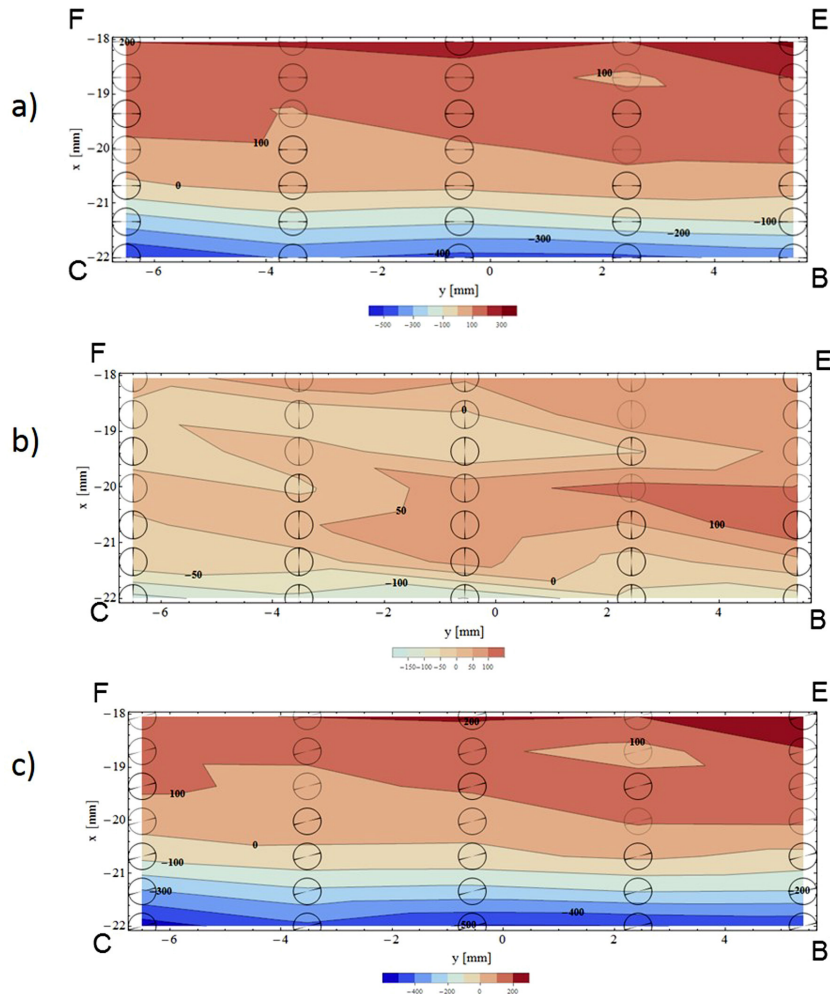
Fig. 4. 2D distributions of stresses in cross-section of explosively joined steel-Ti sheet, observed in α-Ti on direction parallel – (a), perpendicular (b) as well tilted by 75° to both materials' interface (CB-side) (c)
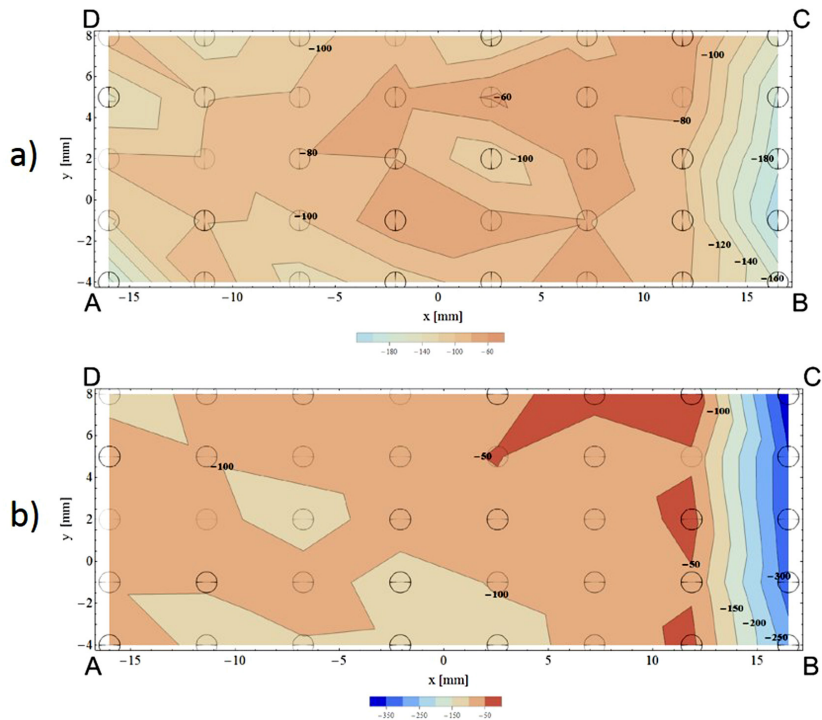

Fig. 5. 2D distributions of vertical and horizontal directional stresses on steel cross-section in examined steel-Ti joint, with material's interface parallel to CB line

proofs high quality of the separately conducted investigations, as it is not an easy task to estimate the residual stress with satisfying repeatability across different laboratories, especially if different measurement methods are applied for materials with a significant planar and a possible (conclusions for hole drilling method) depth variability of the stress state. Consistent with the hole-drilling experiment results, a picture of the stress evolution in context of the detonation direction and the distance from the junction in the Ti part of the steel-Ti composite is shown in (Fig. 6).

3. Concluding remarks

Exemplary 2D stress maps based on many single stress tensor refinements and principal stress calculations for the points on the sample surfaces were presented in the article. The usefulness of such stress state topography in the diagnosis of the structural elements during the progression of the fatigue damage or in the following effects of different technological treatments in the production process is unquestionable. The maps also provide information on the physical properties of the samples related to the stress-texture state of their microstructure and can be used to predict a possible elasto-plastic behavior of the examined parts under working conditions. The knowledge of the crystallographic texture is necessary in the advance methodology of the stress investigation because the texture-related anisotropy has a significant impact on the elastic properties of the materials and, in some cases, the grain interaction models utilizing the texture information are the only valuable way of interpreting the results of the x-ray diffraction experiments.
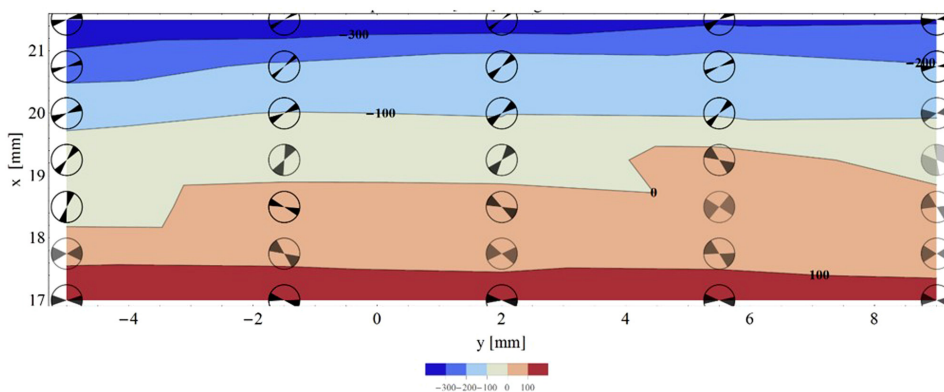

Fig. 6. 2D distribution of principal stresses in cross-section of explosively joined steel-Ti sheet, observed in α-Ti. The interface of the both components is located along a bottom line of the map

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