SHOCK-ASSISTED MATERIALS SYNTHESIS AND PROCESSING: SCIENCE, INNOVATIONS, AND INDUSTRIAL IMPLEMENTATION

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The book is a collection of revised, edited, and formatted abstracts submitted to the IX International Symposium on Explosive Production of New Materials: Science, Technology, Business, and Innovations (EPNM-2008) held in Lisse, the Netherlands, May 6–9, 2008. The contents of the book include recent world-wide accomplishments in basic and applied studies on application of explosives (explosion, shock, and impact) to materials synthesis and processing. The book is addressed to practicing engineers, research workers, and graduate students active in the field.

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Preface

Two years have passed since the previous VIII International EPMN Symposium was held in Moscow, Russia. The volume and scope of the materials submitted to the IX EPMN Symposium in Lisse, the Netherlands, convincingly prove that the research and development (R & D) work on application of explosion energy to materials synthesis and processing is on the up and up. In the classical area of explosive welding, new approaches to mathematical modeling of the process of wavy structure formation have been suggested based on modern methods of numerical mathematics. Increasingly growing is the interest in new high explosives as well as in new applications of explosive welding, including aerospace industry. Ever growing is the number of manufacturers employing explosive welding in different countries of Europe, Asia, and America. New compounds have been prepared by shock-assisted synthesis. Some of these materials seem promising for practical implementation in different areas of modern technology. Great promise has been shown by the data on shock-assisted synthesis and processing of nanomaterials.

A success of EPMN Symposia gives grounds for hope that this branch of modern R&D will be still further developing in the future.

Moscow
February 2008

A. Deribas

Symposium Sponsors

DMC Dynamic Materials CORPORATION

Dynamic Materials Corporation (DMC) is the world's leading provider of explosion-welded clad metal plates. Its Detaclad$^{\mathrm{TM}}$ products are used in a variety of industries, including petrochemicals, refining, hydrometallurgy, aluminum smelting, and shipbuilding.

The Boulder, Colorado, USA, based company began business in 1965 as an explosion forming specialist, producing complex three-dimensional parts for aerospace equipment manufacturers. DMC became a publicly traded company in 1976 under the ticker symbol "BOOM" and shortly thereafter licensed technology from E. I. DuPont de Nemours and Company ("DuPont") to explosively bond, or clad, two or more dissimilar metal plates together. The explosion-bonded clad metal business remains DMC's core business today. The acquisitions of DuPont's Detaclad Division in 1996, Nobelclad Europe in 2001, and DynaEnergetics in 2007 have strengthened the Company's world-wide position in explosion cladding.

Van Campen Exploform

Explosive forming offers a solution for the forming of saddle-shaped panels. This is because this technology has no restrictions with regard to the format or the thickness of the product.

By means of explosion forming, complex and double-curved shapes can be produced in a relatively easy way. Almost all types of metals, such as aluminum, steel, and stainless steel, but also nickel and titanium can be shaped by means of explosion forming.

In comparison with other metal distortion technologies, explosion forming has a number of advantages. For example, large objects can be produced in one go up to 10 m in length, and thick plates, up to even 6-centimeter thick stainless steel, can also be transformed. In addition to this, less aftertreatments are necessary, because of which the metal suffers less stress. It is also possible to transform metal plates that have been lacquered in advance. Explosion forming is preeminently suitable for the creation of prototypes or small ranges, but large ranges can be also easily produced by distorting several plates at the same time.

Exploform is a joint venture of Van Campen Aluminum Productie BV and TNO (Dutch organization for Applied Scientific Research).

Bitrub
international

Bitrub International Ltd. is the leading Russian manufacturer of clad metals by explosive welding

Dimensions of clad plates: 10–200 mm thick, up to 3200 mm wide, and up to 8000 mm long. Base materials are: carbon steels, low-alloy steels, high-alloy steels, nonferrous metals, and alloys shaped as plates, slabs, forged pieces, etc. Cladding layer is 1–15 mm thick.

Cladding materials are: stainless steel, high-alloy corrosion-resistant steels, titanium and its alloys, copper, brass, bronze, aluminum and its alloys, nickel, iron–nickel alloys, tool steels, etc.

Products quality meets the requirements of GOST 10885-85 and other national standards or agreed specifications.

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Science, Innovations, and Industrial Implementation

DEFENSE RESEARCH AND EXPLOSIVE PROCESSING OF MATERIALS

E. P. Carton

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Practically all defense research organizations in the world have a department that is equipped for research on explosives, their handling, transport, storage, and their performance. The special equipment needed — like special computer codes, detonation chambers, high-speed cameras, and x-ray flashers — normally is considered too expensive for the limited use by the R&D department of an industrial company.

The special facilities, equipment, and knowledge present in the defense research organizations could very well be used for industrial research issues that may exist at explosive manufacturers and users like companies active in mining, demolition, oil and gas exploration, and explosive processing of materials.

TNO Defense, Security, and Safety, as an independent contract research organization, is open for industrial research. Examples will be shown of our in the field measurements and imaging of blast waves and detonation velocity measurements at large scale open air explosions.

Last but not least, a lot of experience and specialized computer programs for highly dynamic events are available which can and have been used for several questions and investigations on explosive materials processing technologies like explosive forming, welding, cladding, and powder compaction. Examples of numerous possibilities will be presented.

CONCENTRIC EXPLOSION WELDED PRODUCTS

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The explosion welding process can be used to concentrically weld cylindrical components. The basic welding considerations are similar to that of flat-plate cladding. However, energy containment concerns present unique considerations, particularly when hollow cylinders are being joined to each other. Tooling, or explosive systems, must be designed to prevent destruction of the product by the explosive energy. A broad range of examples and commercial applications are addressed.

ROLE OF GAS IN THE GAP DURING EXPLOSIVE CLADDING

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Explosive cladding is normally performed using a parallel plate setup with a (constant) gap between the two plates. During the plate collision process, any gas present inside the gap is expelled. This occurs with a mass velocity equal to the collision point (line) velocity, which equals the detonation velocity (D = 1–4 km/s) in this setup. Such high mass velocities will generate a strong shock wave inside the gas (Mach 4–15 for air at normal conditions). Due to their large compressibility, shock waves heat up gasses tremendously and a temperature of several thousand degrees are easily obtained. Although there is only a small time for heat exchange during the cladding process (several milliseconds for large plate cladding), a surface layer of the two metal plates in contact with the hot gas is heated. Although only a surface layer is heated (no bulk metal heating), it is the same layer that will shortly after participate in the deformation (flow) process inside the collision region (jet formation, laminar or turbulent flow, interface morphology). We investigated the role of the gas type and initial pressure on the heating of the metal surface layers both theoretically and experimentally. Using a computer simulation, the temperature profiles of several metal plates could be calculated for different gas types, initial gas pressure, and detonation velocities. Also, some experimentally obtained results will be presented.

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COMPARATIVE TENSILE STRENGTH AND SHEAR STRENGTH OF DETACLAD EXPLOSION CLAD PRODUCTS

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The tensile strength of an explosion clad interface can be an important consideration when structural components are to be welded to the clad surface of equipment and for tube sheets in certain shell and tube heat exchanger designs. A considerable amount of data has been published on the bond shear strength features of explosion clad plates. In contrast, minimal data has been presented on the tensile strength of explosion welded interfaces (tested in the through-thickness direction). In general, it is relatively easy to perform shear strength tests on clad plates; however, since cladding layers are typically thin, it is relatively difficult to perform through-thickness tensile tests. It would be beneficial if a reliable relationship could be established between shear strength and tensile strength. A testing program has been undertaken to establish statistically significant data on the interface tensile strength properties of explosion clad plates and to compare the results with the interface shear strengths and the bulk mechanical properties of the cladding and base metal components. Results and indicative relationships are presented and discussed.

(HOT) EXPLOSIVE CLADDING OF TUNGSTEN ON COPPER AND STAINLESS STEEL SUBSTRATES

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Explosive cladding of tungsten is a major challenge because of brittle nature of this refractory material. Thin foils (0.3 mm) were clad on copper at room temperature but thicker W layers could not be bonded without cracks running perpendicular to the (well) bonded interface.

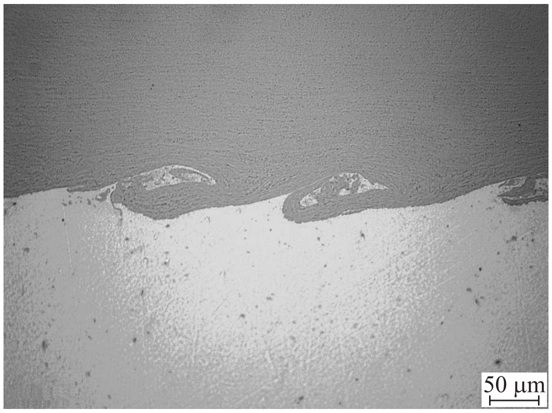

Figure 1 Microstructure of W clad (1 mm) onto Cu (5 mm)

A solution was found by raising the temperature of the tungsten layer above the ductile to brittle transition temperature. This required the use of special experimental arrangements. With hot cladding, sound W clads were the result: up to 2 mm of W could be bonded to CuCrZr, pure Cu, and SS 316 using W as a base plate, but also the cladding of a 1-millimeter W layer onto Cu, using W as a flyer resulted in a metallurgical bond (Fig. 1). Specimens with sizes in the order of 60 × 100 mm were tested ultrasonically and no delaminations were found, apart from small edge effects.

This research is aimed at the use of W clad on copper and stainless steel heat exchangers for the plasma facing components of the future International Thermonuclear Experimental Reactor (ITER). For that purpose, high heat flux testing of a 2-millimeter thick W clad layer onto a copper heat exchanger is foreseen this year.

SOME ASPECTS OF JOIN FORMATION DURING EXPLOSIVE WELDING

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In this communication, we are going to discuss the following three aspects of explobond formation that are still open to arguing:

(1) Is the collision of plates askew?

(2) If occurrence of the cumulation process is questionable, what is the mechanism for cleansing the metal surface from contaminations (oxides, etc.) and its activation?

(3) What is the mechanism of joining in the absence of oblique collision and cumulation process?

In order to get answers to the above questions, we carried out experiments on explosive welding of large-sized plates (8–10 m^2, gap 8 mm) using the methods of witness marks and traps. Witness marks (indents) were made on the clad plate and the side edge of base plate at a pitch of 50 mm. After explosive welding, separation between the marks on the clad plate remained intact, except for its end where it somewhat increased. Significant deformation (change in intermark distances) was also observed at the far end of base sheet. Experiments with traps installed at the far end of large-size sheets (steel – stainless steel, steel–titanium under argon) failed to detect a flux of metal particles from the gap. No flux was found in experiments with intentionally added contaminations (rust, dross, oil): these were almost completely buried in the weld join. Analysis of our and published data leads to a conclusion that a explobond is formed behind the contact point upon collision of metal surfaces thermally activated by shock-compressed gas and sliding the projectile material over the base one.

TUNGSTEN CARBIDE–ALUMINUM MULTILAYER COMPOSITES BY UNDERWATER EXPLOSIVE WELDING

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An explosive welding technique which uses underwater shock wave to weld thin aluminum sheets has been explored, and the technical advantages were determined. Using this technique, a thin metal plate is uniformly accelerated by underwater shock waves. The initial angle of inclination of the explosive pack is important in high-explosive welding systems. The angle is varied to allow welding and to minimize the negative effects of high horizontal collision velocity. It is possible to make a welded thin multilayered product by using the technique. This research attempts at using not only thin metal plates but also hard powder placed between the plates for making a composite material. The recovered welded multilayered composite including hard powder in the boundary was examined using optical microscope, electron probe microanalyzer, and friction measurement machine for searching a possibility of practical use. The results obtained will be reported at the symposium.

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EXPLOSIVE WELDING: DEFORMATION–TIME RELATIONSHIP

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This work is aimed at establishing the deformation–time relationship for explosive welding under varied conditions. The time of plastic deformation of metal in the heat-effected zone was determined by comparing the parameters of the wave profile in the welds obtained by plane-parallel and simultaneous symmetrical schemes of cladding upon variation in the thickness of base plate and impact velocity V_p. Our data imply that the time of metal deformation behind the contact point and the time of welding τ_w depend on V_p. It has been found that τ_w changes within the range 1.5–2.5 μs.

It is suggested that a key parameter that defines the feasibility of plastic deformation of metal behind the collision point is the magnitude of deforming pressure pulse I_d which depends on pressure p and pulse duration τ. This magnitude can be regarded as a measure of the energy spent on plastic deformation of metal in the heat-effected zone and as a useful tool for controlling the structure/properties of joints. For explosive welding of steel composites, a full-strength joint is achieved for $I_d \geq 3.5$–3.7 kN·s/m^2 (critical value for steel–steel pairs).

CUMULATIVE METAL LOSSES DURING EXPLOSIVE WELDING OF MODEL Al-BASED COMPOSITES

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A distinctive feature of explosive welding is formation of a cloud of dispersed particles (or a cumulative jet) ahead of the collision line. The amount of metal expelled form the heat-affected zone due to cumulative phenomena can be evaluated in experiments with model feeds of rolled aluminum foil, 25 μm thick, oriented along the direction of wave propagation. The metallographic data for the samples welded near the lower boundary for their weldability (contact point speed $V_c = 700$–2800 m/s, collision speed $V_l = 200$ m/s) show that the thickness of the metal layer expelled from the surface of the immovable plate due to cumulative effect attains a value of 0.025–0.05 mm. With increasing V_l (from 200 to 700 m/s), the latter grows up to 0.15–0.17 mm, the reverse mass flow being most pronounced in conditions favoring disappearance of the wavy structure of joint. The amount of expelled metal also grew for $V_c > 3500$ m/s ($V_l = 200$ m/s) and with increasing V (within subsonic range). The formation of a reverse mass flow is not obligatory for production of a full-strength composite: in our case, explosive welding of model aluminum foils was attained due to plastic deformation of the layers remote from the contact surface, where the cumulative process is impossible.

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OPTIMIZATION OF BLAST CHARACTERISTICS FOR EXPLOSIVE PRODUCTION OF LARGE-SIZE CLAD PLATES

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This communication summarizes the experience assimilated by our company in developmental and commercial work performed jointly with specialists of CRISM PROMETEY Co. in the years 2005–2007.

A type of high explosive was selected upon a compromise between the necessity to obtain proper blast characteristics over a wide range (controllability of the process) and economic effectiveness of the process.

At the first stage, we used a liquid mixture of nitric tetroxide with kerosene containing powder additives of varied density, as well as the mixtures based on amatol and ANFO. The obtained data have shown that of key importance is not only the particle size (what is well known) but also the density of the additives.

At the second stage, we analyzed the properties of industrial explosives produced by FORCIT Co. (Finland) and commercially available powder additives.

Among other industrial explosives, amatol is most convenient. But according to purchasing statistics, even certified industrial explosives of high quality exhibit a wide spread in the detonation velocity D, from 3530 to 4040 m/s, that is, within the limits of ±7.5%.

Our production testing was carried out in a vacuum chamber 300 mm long. The D values were measured using fiber optics and a specially designed Explomet 2000 device. When using this device in the field, it has become evident that, for practically significant lengths L above 300 mm, D was found to markedly vary even in the presence of ballast powders, quartz sand with a particle size of 1–200 μm, and edible salt.

The powder additive (whose amount is difficult to control in real conditions) was found to be insufficient for making $D < 2000$ m/s and sometimes led to failure. In case of edible salt (with uniform size distribution of particles) as an additive, we managed to reduce D values down to 1600 m/s. Full-scale experiments ($l = 0$–3 m) have shown that D values can be kept constant (which is a prerequisite for high-quality joining) only in the mixtures of some critical composition.

Also, minimal deformation of clad plate can be ensured upon proper choice of damping pillow (sand or composite).

The above measures afforded us to produce high-quality clad plates with minimal and uniform one-side strains and without local bending.

NEW TECHNIQUE FOR EXPLOSIVE WELDING OF HIGH-STRENGTH ALUMINUM ALLOYS

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Heat-hardenable high-strength aluminum alloys 7xxx have low ductility and can hardly be hardened upon their deformation. However, their mechanical properties can be varied within a wide range by heat treatments. These alloys also exhibit the effect of natural ageing (spontaneous hardening) and are hard to weld by fusion-type welding and explosion welding. Therefore, improving their weldability is a current problem of modern welding engineering.

We explored the explosion welding of these alloys in the absence of a soft interlayer of commercially pure aluminum. In our experiments, we carried out preliminary heat treatment (tempering) of the cladding plate (which improved its ductility), explosion welding to the base plate in as-delivered state, and subsequent holding (natural ageing) of resulting composite to achieve partial or full recover of initial mechanical properties of cladding plate.

Cladding of a 150-millimeter plate (UTS ≈ 550 MPa) with a 15-millimeter 7018T7651 alloy plate (UTS $=$ 350 MPa, 0.2% YS $=$ 291 MPa, $E = 16\%$) gave a full-strength joint (UTS $=$ 350 MPa) due to preliminary tempering of the cladding plate at $T = 465$ °C for 1 h and subsequent natural ageing for 1 month. Without preliminary tempering, no full-strength joint was formed. For optimizing the welding conditions, it is desirable to maximize the duration of impact with the cladding plate.

Our technique for explosive welding of dissimilar aluminum alloys of series 7xxx can find its application to production of various transition pieces for aircraft engineering.

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DETONATION SYNTHESIS OF SHPERICAL ULTRAFINE NANOSTRUCTURED Al_2O_3

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Ever growing use of nanomaterials in numerous areas of modern technology gave birth to interest in production of nanocrystalline fine (5–20 μm) and ultrafine (0.1–5.0 μm) high-quality powders. A degree to which the above specifications can be achieved is believed to depend, among other things, on the quenching rate at the final stages of particles' synthesis. As concerning metal oxides, one of the promising routes to the target seems to be the fast detonation-assisted oxidation of metals at high pressure and temperature.

Under such conditions, we have synthesized spherical ultrafine alumina particles from aluminum particles suspended in aqueous solution of ammonium nitrate used as an emulsion explosive. The composition, physical/structural properties, and thermal stability of synthesized powder were characterized by helium picnometry, laser diffraction, X-ray diffraction (XRD), transmission electron microscopy (TEM), and scanning electron microscopy (SEM). The data obtained were used to optimize some process parameters, such as the amount and size of aluminum particles in emulsion explosive. Some details of the kinetics of the process were assessed by inverse analysis using the measured values of detonation velocity and the thermodynamic equilibrium code THOR in order to evaluate the fraction of aluminum particles reacted immediately after the detonation front and the fraction of the particles reacting in the expansion wave.

EXPLOSIVE WELDING OF SOME THIN MATERIALS ONTO MAGNESIUM ALLOY USING UNDERWATER SHOCK WAVE

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It is known that magnesium is a very light material compared with other structural materials. The use of magnesium alloys is growing rapidly due to their high specific strength for producing lightweight metal components. However, due to the low elastic modulus, poor corrosion resistance, and low plasticity of magnesium, its application is limited. To improve the surface characteristics, like corrosion resistance, thin metal films welded on a magnesium alloy are proposed. In this study, explosive welding using underwater shock wave was employed to weld some metal foils on a magnesium alloy plate. This technique is effective to control the pressurizing conditions easily by changing the distance between the explosive and sample. In this presentation, the experimental results on various dissimilar combination of magnesium are demonstrated.

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EXPLOSIVE WELDING OF CORROSION-RESISTANT MATERIALS WITH SINGLE- OR DOUBLE-SIDED CLADDING

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Joining various metals by the methods of soldering, rolling, metal spraying, fusion-type, or explosive welding to produce a wide range of laminate composites remains to be in focus of modern R&D. Such composites are known to exhibit elevated corrosion resistance, surface hardness, wear resistance, shock resistance, ductility, toughness, thermal conductivity, thermoelasticity, electromagnetic properties, etc.

In this communication, we report on improvements in the technology of explosive cladding of steels with aluminum or titanium, the pairs which are difficult to join because of concomitant formation of brittle intermetallic compounds at the interface. We investigated the structure and properties of bonding zones in different ways. It has been shown that pulsed methods in conditions of restricted diffusion are most suitable for attaining the utmost toughness and viscosity of bonds. The compositions fabricated by explosive welding were found to be highly reliable in numerous applications. Introduction of thermostable bimetallic junctions on some metallurgical enterprises (see Figs. 1 and 2) has allowed us to replace mechanical joins with more reliable electrically welded ones, to exclude electrochemical corrosion, and also to improve the toughness, thermal conductivity, and sealing property of joins. Bimetallic connectors find applications in railway/motor transport and shipbuilding industry. Light-weight aluminum and titanium ensure a decrease in overall weight of resultant structures and their corrosion resistance while steel, their toughness and stability of

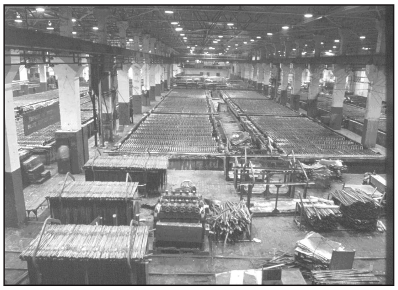

Figure 1 Ti–Cu transition joints for hydrometallurgy

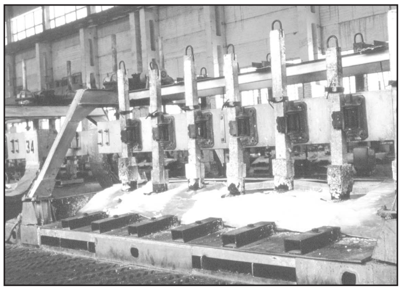

Figure 2 Steel–Al transition joints for aluminum industry

service parameters. Steel cladding by aluminum, through interlayer of stainless (to elevate heat resistance) or through nickel and titanium, has allowed us to solve the above problems. The samples of junctions for use in shipbuilding have been fabricated at RIPP for some Belorussian and Korean companies.

The implementation of new methods for explosive welding was accompanied by profound basic research in the field of blast dynamics. As a result, software for calculating technological parameters for welding a wide range of laminate composites has been elaborated and then found its use in chemical and nuclear engineering [1].

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TESTING Ti–STEEL CLAD METALS BY THERMAL LOADING

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Featured are the results of macro/micro-structural, microhardness measurements, as well as the mechanical and service parameters of weld joins between titanium (ASME SB-265 Gr. 1) and chromium nickel austenitic stainless steel (ASME SA-240 304L) obtained by explosive cladding. Preliminary results of electron probe microanalysis for selected sites of the joint will be presented. Specimens for testing were cut from full-format clad plates and subjected to thermal loading to elucidate its influence on the properties of joint, weld zone, and welded materials. Structural changes (including diffusion-type ones) will be discussed as a function of process parameters. In short, similar results will be presented for titanium–carbon steel joints. The above data were used as a basis for launching the production of the above clad metals.

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SPECKLE INTERFEROMETRY AS A TOOL FOR TESTING CLAD METALS

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As is known, the existing methods for nondestructive testing of clad metals — radiographic, ultrasonic, magnetic, eddy-current, and liquid penetrant ones — are inapplicable to bimetals 2 mm thick fabricated by explosive welding. In this context, we have developed a high-precision holographic method for evaluating deformations on the surface of three-dimensional (3D) items.

Emission from a He–Ne laser is allowed (through a collimating optical system) to reflect from the surface under study, and the scattered emission is recorded with a photosensitive matrix array. With a system of mirrors installed at an angle of 180°, the surface images can be shifted relative to each other (so-called interferometer with separation of speckle structures). Two coherent images interfere on the array surface. The presence/absence of defects is inferred from a character of interference fringes.

EXPLOSIVE WELDING OF MULTILAYER PACKAGES: DURATION OF INITIAL ACCELERATION

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Calculation of impact velocity V_{pi} in a multilayer package is a complicated problem that can be solved (in a rough approximation) using some existing models. In terms of these models, upon the ith collision, a package of $i+1$ sheets immediately acquires some flight velocity calculated from the law of momentum conservation for an isolated system (which is not confirmed by experiment).

Numerous experiments have demonstrated that the flight speed changes not step-wise but abruptly, the $V_p = f(h_\Sigma)$ function being characterized as a family of independent acceleration curves. The acceleration of package sheets after impact proceeds in two stages:

(1) transmission of momentum from a flyer plate to a fixed one, and

(2) acceleration of the package of welded plates under the action of the residual pressure of detonation products.

In this work, we experimentally estimated the duration of the initial stage of acceleration of metal plates during explosive welding of multilayer packages under varied conditions. In experiments, we recorded the velocity of the back surface of the ith plate by rheostat method and plotted the respective acceleration curves. The duration of the initial stage of acceleration of the system of sheets at the second and follow-up interfaces was found to depend on the mass of welded elements, acceleration, and detonation velocity and to vary within the range 1.5–15 μs. This circumstance should be taken into account while optimizing conditions for explosive welding of multilayer composite materials.

NUMERICAL STUDIES ON EXPLOSIVE WELDING BY SMOOTHED PARTICLE HYDRODYNAMICS

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A particular characteristic of an explosively produced weld is that the profile of the interface has a regular wavy structure. Effects of detached shock wave and jetting on the metal interface of explosive welding have been considered by smoothed particle hydrodynamics (SPH) analysis. Numerical results show a wavy interface which is observed in several experiments. A high-speed jet between interface and Karman vortex after oblique impact of a flyer plate to a parent plate was major mechanism of explosive welding. The SPH-2D particle size Δr used in these studies is 10 or 20 μm. Thickness and length of a flyer plate and parent plate are 1 and 10 mm, respectively. An inclined flyer plate is assumed to impact normal to a parent plate. Various bimetallic combinations are studied. In case of soft and hard materials, the effects of material strength just the same as in case of SUS304 brass. The SUS304-2024 aluminum shows the effect of difference of shock velocity and material strength between two metals. The SUS304 iron and aluminum–aluminum show an effect of detached shock wave with elastic precursor wave followed by plastic wave. The SPH analysis suggests that explosive welding by the mechanism of jetting and Karman vortices activated by the Richtmeyer–Meshkov instability. Mechanical properties of clad metals obtained by explosive welding can be controlled by impact velocity and collision angle. The SPH results of this work also indicate the importance of microscopic roughness of metal plate. The wave length calculated by SPH is relatively larger than experimental observation in which the interface of clad metal shows complicated microstructures between grain boundaries. The SPH results indicate a demand for more microscopic analysis by the methods of molecular dynamics taking into consideration melting of metals and interatomic diffusion.

EFFECT OF MATERIAL MICROSTRUCTURE ON WAVE FORMATION UNDER EXPLOSIVE LOADING

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The phenomenon of wave formation on transverse metallic partitions separating copper-powder layers undergoing explosive compaction in a cylindrical ampoule was first reported in [1]. The effect observed for the plates made of transformer steel was numerically modeled in [2]. The wave formation was found to occur due to loss of stability during compression of the plate and powder softening upon collapse of pores. The formation of waves on the metal surface was initiated by some weak perturbations whose nature remained unclear.

In order to fill this gap, we carried out experimental and theoretical study on shock-wave compaction of metal powders separated by thin transverse partitions in a metallic container. It has been shown that structural defects and internal stresses in transformer steel produce the initial perturbations that subsequently develop during explosive compaction of the powder. Unlike other materials (copper, aluminum, carbon, stainless steel), the mean grain size in transformer steel is commensurable with the minimal wavelength of developing perturbations, which favors macrodeformation of the entire plate. When the powder skeleton weakens upon collapse of pores, this gives rise to the formation of waves at the interface between powder and metal.

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MODELING EXPLOSIVE WELDING BY USING LS-DYNA SOFTWARE

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LS-DYNA is a multipurpose, explicit/implicit finite element program that is being used to analyze the behavior of two- and three-dimensional nonlinear dynamic systems: nonlinear dynamics, thermal failure, crack propagation, state of contacts, quasi-static fluid mechanics, real-time acoustics, etc.

We calculated the impact parameters for projection of a clad plate onto a fixed base one in two-dimensional (2D) approximation for copper–copper, copper–aluminum, and copper–carbon steel pairs and TNT – ammonium nitrate mixtures as explosives. We determined the velocity of contact point, dynamic angle, pressure at the contact point, and estimated the weld profiles using LS-DYNA software.

In experiments, we prepared the samples of copper–copper, copper–aluminum, and copper–carbon steel clad metals, carried out their metallographic analysis, and determined longitudinal wave profiles. Calculated data were found to agree with experiment.

A CONDITION FOR WAVE FORMATION DURING EXPLOSIVE WELDING

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The existing hydrodynamic model describing the formation of waves at the clad interface has a serious drawback: it does not take into account individual properties of welded bodies, which leads to disagreement between theory and experiment in determining the lower weldability boundary.

Here, we suggest a criterion for wave formation based on the elastoplastic model of this phenomenon. It is postulated that collision of metals during explosion welding may result in formation of a wavy joint if and only if proper conditions for combined plastic deformation (mutual penetration) of metals are ensured. In other words, the forced interaction of metals to be explosion welded, which is defined by a set of kinematic collision parameters, must give rise to a combined plastic flow of the surface layers at such deformation rates that exactly correspond to the identical dynamic yield stresses; for sustaining the steady wave propagation, the above equality must be steadily established.

Explosion welding is accompanied by very high rates of deformation of the contact metal layers. It is also known that the resistance of metals to plastic deformation drastically grows with increasing strain rate, especially for low static yield stresses. Therefore, it may be expected that, at some sufficiently high strain rate, the absolute values of the dynamic yield stress of metals having different static yield stresses will become equal at a level that affords determination of the lower boundary for explosion welding of different metal combinations by using the classic formulae upon replacement of the dynamic yield stress by the Vickers hardness (commonly used nowadays).

Presented are general considerations and experimental data which suggest that, for explosion welding of metals with strongly dissimilar mechanical properties, it is admissible to use the values of dynamic yield stress and toughness, the density of a less strong metal, and the stress relaxation time in order to determine the lower weldability boundary by using the classic equation.

EXPLOSIVE WELDING OF Ni- AND Fe-BASED AMORPHOUS FOILS FOR MICROTOOLING APPLICATIONS

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In spite of commercial advantages, the available engineering materials for integrated circuits (IC) and microelectromechanical systems (MEMS) are not able to meet the manufacturing demands for 3D high-aspect-ratio nano/micro-structures and high precision. There is a group of energy-assisted processes, such as laser ablation, e-beam and ion beam machining, that could provide required high specific processing energy to create 3D microstructures. However, the required surface integrity of the manufactured nano/micro-structures cannot be achieved without developing appropriate materials with adequate processing response. In order to extend the range of microengineering products and their capabilities, development of novel compatible amorphous or composite materials is required.

In this communication, we will report on the capability of explosive welding technology to prepare a bimetallic sandwich foils (40 μm thick) of amorphous Ni- and Fe-based alloys, on retention of their structure. Direct patterning by focused ion beam was used to produce masters from these materials for injection moulding and hot embossing tools. It was demonstrated that high feature resolution and surface quality of the manufactured nano/micro-structures can be easily achieved by employing this technological chain.

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NATURAL STRAINS NEAR WELD INTERFACE FOR DIFFERENT COLLISION ANGLES

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It is useful to analyze the acting of mechanics and thermodynamics near the stagnation point, analyze the product of wavy interface by studying the distribution rule and changes of the strain near the stagnation point. The objective of this study was the effect of collision angle on natural strains arising at the weld interface by using an ideal fluid model of symmetrical collisions. It has been found that the smaller relative streamline function, the flatter the natural strain curve. The points with maximal value of natural strains $|E11|$ and $|E12|$ can be found out for collision angles in the range 6°–20°.

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EXPLOSIVE PRODUCTION OF ULTRAFINE-GRAINED MATERIALS

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Addressed are different approaches to explosion-assisted fabrication of ultrafine-grained bulk materials. One of these is the shock-assisted compaction and consolidation of fine powders. Upon proper choice of conditions for shock loading and subsequent thermal treatment, one can markedly hamper the process of grains growth in a resultant material. Thus prepared nanocrystalline bulk nickel was found to exhibit elevated mechanical properties compared to conventionally produced nickel.

Another promising method for compaction of powders (such as nanodiamond and boron nitride) is combined dynamic–static compression. In this case, powder to be compacted is compressed in a two-walled recovery fixture the inner layer of which can undergo a reversible phase transition, due to which the powder can be held under pressure for a longer period of time.

Still another approach is based on the refining of grains in bulk materials due to high-speed straining and subsequent dynamic recrystallization under shock loading. Upon proper choice of temperature regime, this technique can be applied not only to metals and alloys but also to cermet materials. For instance, thus prepared off-stoichiometric titanium carbide was found to exhibit some unique properties (such as superplasticity) within the technically accessible temperature range.

Rather promising for fabrication of fine-grained ceramics and cermets is the shock-assisted quenching of these materials in the course of their synthesis. The action of shock wave on still hot reaction products was found to result in their rapid densification and hence in elevated thermal conductivity. In this process, structure formation in a resultant material is hampered due to a contact with a metal wall of recovery fixture. Varying time delay for application of shock loading, one can interrupt the process of structure formation at any desired stage (including the initial one) in order to suppress grains' growth.

HOT EXPLOSIVE PRESSING OF HIGH-STRENGTH AND SUPERHARD MATERIALS

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Aiming at comparing the main features of hot isostatic pressing (HIP) and hot explosive pressing (HEP), a simple device has been designed for multiple explosive compaction experiments. It is based on the principle of direct explosive (cylindrical) compaction. An atomized powder of UDIMET 700 Superalloy was subjected to HEP to obtain bulk samples with improved mechanical properties compared to those of the samples prepared by HIP. The HEP of diamond powder with a grain size of 1 μm at 1100 °C yielded bulk samples with a 100 percent density and a hardness of 7000. High values of lattice distortion and a decrease in subgrain size (as detected by XRD) are indicative of the plastic deformation of diamond taking place under HEP conditions.

DYNAMIC TREATMENT OF PARTICLES, FROM MACRO- TO NANOSCALE

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Macro-, *micro-* and *nanoproducts under shock* involve the production of ultrafine materials (metals, ceramics, mixtures) by *explosive* and/or *electromagnetic compaction techniques.* The powders, synthesized by explosion and mixtures on their basis can be utilized as a basic material or as modifying additives at manufacturing sintered powdery ceramics, hard-alloy/ceramic composites, nanoparticles reinforced metals and polymers, matrix composites, abrasive pastes and suspensions (including polishing ones), chemical catalysts, and sorbents. Crushing of brittle materials grains can be achieved by shock loading. These phenomena are used for producing materials of micro- and nanoscale grains. By applying properly calculated and directed shock waves created by explosion, Al_2O_3, MgO, ZrO_2, Mo, Ti, W, MgB_2, and ceramic high-T_c superconductors are being treated for reducing their grain size into nanoscale. Compaction of such materials by shock waves has the advantage that, during compaction, phase grain growth does not occur. The high-speed shock waves with high energy content can be created either by initiating high explosives (explosive compaction) or by discharging electric capacitors (electrodynamic compaction). During compaction, the powder surfaces are accelerated into the pores at high velocities, impacting each other, with frictional energy release. This leads to melting at the surface regions with the associated bonding once this material is solidified. If brittle materials are consolidated, particle fracture also occurs, thus leading to filling the gaps. Reactive elements can also be added to help bonding process. The high-pressure state creates numerous lattice defects and dislocation substructures leading very often to localization of shearing and microcracking. An overview of the above mentioned phenomena is outlined in the present keynote paper.

APPLICABILITY OF ANALYTICAL MODELS TO PREDICTING THE HUGONIOT OF PREPRESSED LOW-DENSITY COMPACTS OF IRON NANOPARTICLES

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The shock compression (Hugoniot) behavior of distended materials (e.g., porous media and powder compacts) is of significant interest due to their shock dissipation properties in engineering applications, as an approach for fabricating bulk materials via consolidation of powders, and for developing a complete equation of state over a wide range of state variables. The densification response of nanosized powder particles is of even greater interest, since the effects of their high surface area can make it challenging to attain interparticle bonding, and the internal energy of the system can be dominated by the large surface energy contribution of the nanosized powder particles.

We examine the applicability of analytical models proposed by McQueen *et al.* and Wu-Jing, which are representative of isochoric and isobaric approaches for predicting the Hugoniot of prepressed low-density compacts of prepressed $\sim$ 35% and $\sim$ 45% TMD compacts of iron nanoparticles obtained from experimental measurements. The Hugoniot measurements were performed using piezoelectric stress gauges to monitor the input and propagating stress profiles, and the shock velocity based on time of travel through the powder layer of known thickness. The results show a densification-distension transition at $\sim$ 2 GPa for the $\sim$ 35% TMD, and $\sim$ 6 GPa for the $\sim$ 45% TMD compacts. Correlations of the model calculations with the measured data indicate that the shock Hugoniot of prepressed nanoiron powder compacts cannot be correctly described by the analytical models, which are otherwise capable of predicting the Hugoniot of highly porous materials (prepressed compacts) of micron-sized powders of similar density. The principal cause for the ineffectiveness is possibly the lack of incorporating the difference in internal energy between the powder compact and the solid.

Acknowledgments

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EXPLOSIVE LOADING OF POWDERED MATERIALS: BASIC RESEARCH AND APPLICATIONS

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In the presentation, the main results of studies performed since the 1950s will be discussed with special emphasis on practical applications of explosive loading of powders (ELP). Interest in ELP has risen steeply after the early studies by McKenna *et al.* [1] in the USA and by Ryabinin [2] in the USSR. Since that time, a huge amount of research work has been done, and a number of industrial applications have been implemented. One of the impressive applications of ELP is the production of synthetic diamond organized by DuPont de Nemour Co. [3]. Later on, great efforts were made in explosive compaction of diamond powder in order to get a strong bulk material. Nevertheless, the shock-wave technique still cannot compete with a high-temperature sintering under a high static pressure. The main problems which still remain are cracking and nonuniformity of bulk samples made by ELP. This refers not only to diamond but also to other hard and brittle materials as well. In our opinion, these problems can be solved by using the technique of long-pulse explosive compaction [4]. The ELP has appeared to be very effective in production of sealing elements for gas turbines [5]. These elements consist of a cermet antifriction layer and a steel base made by explosive compacting of nichrome–g-BN powder mixture followed by sintering and machining. Another example of successful industrial use of ELP is the production of three-layered electroinsulating metal–ceramic–metal bushes for electrothermal and metallurgical applications [6]. Future trends of ELP development are associated with synthesis of new materials [7] and compaction of nanostructured and ultrafine-grained materials [8].

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CAN CARBON BE INCORPORATED INTO SPINEL-TYPE Si_3N_4?

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Incorporation of carbon into the spinel-type silicon nitride may affect significantly the properties of the spinel that has been synthesized and investigated recently. We have carried out shock recovery experiments on this subject. We employed samples in the Si_3N_4–C_3N_4 system but they contained some amounts of oxygen. The postshock samples were investigated by XRD, TEM, ELNES, and other techniques. Presented will be the results of these studies.

COMPACTION AND SYNTHESIS OF MgB_2 SUPERCONDUCTORS BY EXPLOSIVE TECHNIQUES

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Magnesium diboride MgB_2 was prepared from Mg and B powders/flakes using the powder-in-tube method and subsequent sintering in Ar at 960 °C. Compaction of Mg flakes and B powder resulted in formation of two-phase alloy, with almost zero porosity and high hardness. The apparatus used for the explosive consolidation of powders and flakes was designed in such a way that the shock waves generated by explosion were directly transmitted to the interior of the stainless steel container. The explosive was placed in a cylindrical tube made of PVC, and the whole arrangement was mounted on a specially designed 25-millimeter thick steel plate which acted as a shock wave absorber. The ends of the steel container were filled with some quantity of MgO powder and sealed with two plastic lids. MgO powder was used in order to avoid loosing a part of the Mg or B material since during the explosion process some amount of the tube content is blown into the air together with the plastic lids. The explosive compaction experiments involved two stainless steel containers filled with Mg flakes and B powder and a third one which included Mg and B powders after being blended in stoichiometric proportions (55.3% Mg and 44.7% B) in a ball mill for 2 h. Scanning electron microscopy and XRD illustrated that the well packed cylinders did not form the MgB_2 superconducting phase. X-ray diffraction data are simply the superposition of both the Mg and B phases. After explosive compaction, the specimens were sectioned in several parts and sintered in an Ar atmosphere. The compacts were

heated up from room temperature up to 630 °C at a pace of 5 deg/min. The temperature remained constant at 630 °C for 30 min, and then slowly rose to 960 °C (at a rate of 1 deg/min) where it stayed for 90 min. Then slow cooling was performed down to 700 °C (1 deg/min) and at last, the physical cool-down to ambient temperature. Samples structure was characterized by SEM and XRD.

The achieved results indicated the presence of superconducting phase. Indeed, susceptibility measurements showed the presence of superconducting phase around 40 K.

EXPLOSION-ASSISTED SYNTHESIS OF MAGNESIUM DIBORIDE

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Superconducting MgB_2 is normally prepared under argon either by self-propagating high-temperature synthesis (SHS) or by heating a mixture of the elements up to 850 °C to obtain powders with a particle size of several dozen microns. After mechanical activation (MA) of starting powders, the synthesis temperature can be reduced down to 650 °C, the annealing time to one hour, while the particle size, down to 7–70 nm, magnesium oxide being a major contaminant.

The use of explosion makes possible to prepare $MgBr_2$ either from the elements [1] or through the magnesiothermic process [2]. In this case, the output attains a value about 90% in the central and lower regions of a compact recovered (after explosion) from a cylindrical ampoule. However, remained unclear a driving force of the reaction: high pressure or high temperature.

After 3-gigapascal explosive loading of a $Mg + 2B$ powder mixture in a cylindrical metallic ampoule, the yield of $MgBr_2$ was found to be only 10%. In experiments carried out under similar conditions (identical pressure) but after MA (in an AGO-2 planetary mill), the output of MgB_2 was markedly higher (up to 90%).

The XRD data did not reveal the presence of crystalline of MgB_2 (MA without explosion). The amorphous phase of $MgBr_2$ after MA could be detected by the method of differential dissolution. According to these data, the MgB_2 phase is formed in a $Mg + 2B$ mixture after 3-minute MA and subsequent heating up to 430 °C. The $Mg_{0.55}B$ was found to form after 10-minute MA in the amorphous state. Subsequent annealing above 430 °C or explosive treatment converts the amorphous $MgBr_2$ into its crystalline state. Therefore, the effect of explosion can be reduced to the action of temperature on the particles' surface, formation of melt, and rapid quenching to the amorphous or partly amorphous state.

Acknowledgments

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DETONATION SYNTHESIS AND CONSOLIDATION OF NANODIAMOND

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Ultra-fine diamond (UDD) particles are formed upon decomposition of high explosives $C_aH_bN_cO_d$ with a negative oxygen balance. Condensed carbon in detonation products is formed largely in the following two reactions: $2CO \leftrightarrow CO_2 + C$ and $CO + H_2 \leftrightarrow H_2O + C$. Composition of explosion products is calculated using the laws of thermochemistry and gas dynamics as a basis. With decreasing gas pressure, equilibrium shifts to the left (due to expansion of products), and the amount of carbon decreases. Comparison of p and T values in the detonation wave with the phase diagram of carbon shows that excess carbon from high-density (above 1.6 g/cm^3) TNT + RDX mix charges is condensed from carbon microdrops in the form of diamond because the Jouget point is located within the area of fluid carbon. Despite a relatively high threshold for intensity of detonation waves, the amount of diamond (in case of heterogeneous mixtures) is limited due to a low carbon content of explosive. The amount of condensed diamond depends not only on the explosive composition but also on the charge diameter, its density, initiation mode, and geometry of experiment. Converging waves and accumulation of energy are illustrated in Fig. 1 for the case of cylindrical RDX–TNT charge initiated from start lines ($z = \pm 25$ mm, $r = 15$ mm) disposed in such a way that collision of detonation waves takes place at $z = 0$ and along the axis $r = 0$, where carbon-containing insertion with a diameter of 10 mm is installed. At the front of converging waves and in the plane of the symmetry, the parameters of shock waves attain their extreme values. Such geometry favors the polymorphic transformation and hence a high yield of target product. In during dynamic consolidation of hard materials based on nanodiamond, of key impor-

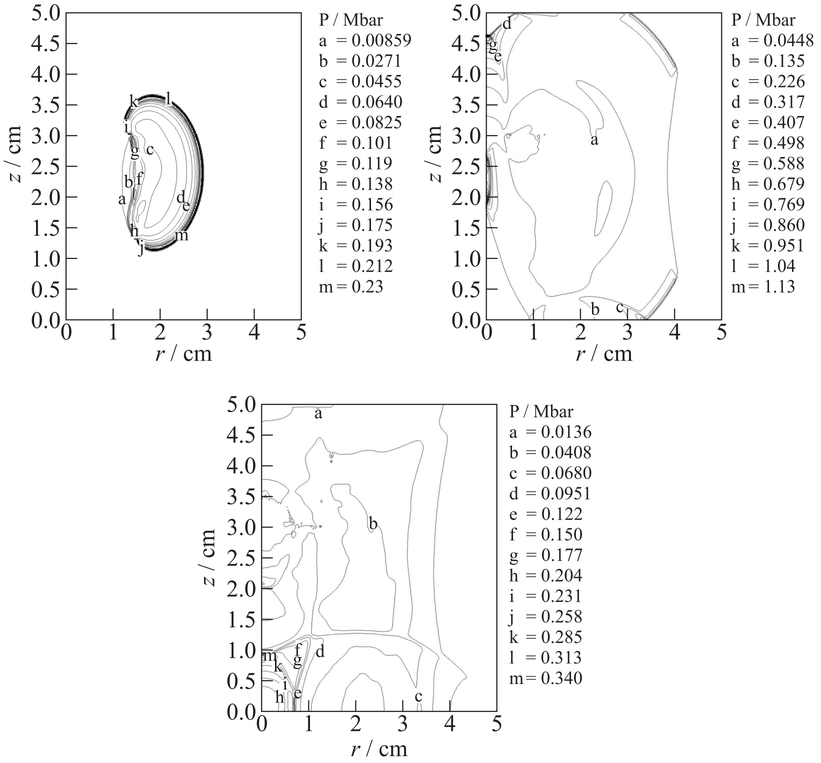

Figure 1 Isobars for a detonation wave in a 80-millimeter RDX–TNT charge

tance is thermal activation. The parameters of hot shock consolidation are close to those required for synthesis, as there always some amount of graphite is already present and some can also be formed upon impact-induced overheating. A necessary condition for metamorphosis within a shock wave is the interception of the Hugoniot curve of hot powder with the hysteretic line corresponding to the rate of shock compaction. Hot and cold schemes for syntheses and consolidation of UDD particles have been compared. The quality of metamorphosis and compaction was found to depend on the mechanism of diffusion, despite a short duration of pressure and temperature pulses.

HOT EXPLOSIVE CONSOLIDATION OF TUNGSTEN–METALLIC GLASS MATRIX COMPOSITES

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W(40%)–MG powder mixtures were formed into cylindrical rods using a hot explosive consolidation (HEC) process. One type of W–MG precursor composition with tungsten with a grain size of 5–6 μm was consolidated to nearly theoretical density at 20–800 °C. The shock wave loading intensity was under 10 GPa.

The investigation showed that the combination of high temperatures (above 800 °C) and two-stage shock wave compression was beneficial to the consolidation of the W(40%)–MG composites, resulting in high densities and good integrity. The structure and properties of the samples obtained depended on the temperature of loading. It was established that above the recrystalization temperature of MG matrix (400 °C), it is possible to consolidate W–MG composition to nearly theoretical density with a nanograined MG phase. Below this temperature, the matrix of MG always stays amorphous. The investigation of hardness distribution shows that the maximal value of hardness for W–MG compositions equal to 703 kg/mm^2 can be reached during the consolidation at 580 °C.

The above mentioned and other features of the structure-property relationship depending on the temperature of HEC changes will be presented and discussed.

HOT SHOCK WAVE CONSOLIDATION OF WC–NiAl COMPOSITES: A STRUCTURE/PROPERTY RELATIONSHIP INVESTIGATION

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WC–NiAl and NiAl powder mixtures were formed into cylindrical rods and tubes using a hot shock wave consolidation process. This technique was also applied to form WC–NiAl coatings on cylindrical steel surfaces as well. The WC–NiAl composite consisted of WC particles dispersed in a Ni–Al matrix made from a Ni-clad Al precursor powder, wherein each Al particle is coated by a Ni layer. The consolidation temperature was varied from room temperature to 1000 °C; the shock loading intensity was as high as 10 GPa.

The investigation showed that the combination of high temperatures and explosive compression was beneficial to the consolidation of the WC–NiAl and Ni–Al composites, resulting in nearly theoretical densities, high hardness values, and the formation of transient layer between the sample and the steel container's wall. The structure and property of the samples obtained, and the formation of the transient layer depended on the shock loading conditions and the phase content of precursor powders. It was established that, in comparison with pure Ni–Al, the consolidation of WC–NiAl powders provides the formation of single-phase NiAl matrix in the WC–NiAl composition after hot shock wave loading.

The above mentioned as well as other features of the structure–property relationship of the consolidated WC–NiAl samples as a function of the loading conditions (experimental setup, intensity of loading, or preloading temperature) are discussed.

NANOSTRUCTURED POLYMERIC MATERIALS STRENGTHENED WITH CARBON NANOPARTICLES SYNTHESIZED BY DETONATION

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The paper presents our results on the synthesis and deaggregation of carbon nanoparticles synthesized by detonation. It reports on the analysis of their introduction into nanostructured polymeric materials resulting in achieving heat conductivity lower than 0.03 W/(m·K). Fields of application concerning energy-saving are outlined: heat insulation of houses and buildings and heat insulation in the industry.

RECYCLING Al-RICH BYPRODUCTS OF ALUMINUM SURFACE TREATMENT INDUSTRIES: SHOCK-ENHANCED SINTERABILITY OF WASTES

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Over the past decade, the recycle of Al-rich sludge from aluminum surface treatment has been in focus of the scientific community engaged in materials science research. The presence of contaminants and a need for preliminary high-temperature heat treatments are known to markedly reduce the sinterability of these wastes. For this reason, despite numerous efforts made on this specific research subject, no interesting hi-tech applications for recycling this kind of wastes have been suggested so far, so that a search for new approaches to the problem seems to be of current importance. One of such approaches is enhancing the sinterability of powders by explosive compaction.

In this work, we explored the applicability of explosive compaction as one of the steps of the aluminum-rich sludge recycling process. The obtained results are compared with those obtained for conventional materials and routes. Our data have shown that the heat-treated sludge, when explosive compacted and fired at 1650 °C, exhibits the density and microhardness close to that of conventionally produced aluminum.

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HYDROGEN CORROSION OF EXPLOBOND IN CLAD STEELS

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It is well known that hydrogen induces degradation of the microstructure and mechanical properties of stainless and low-alloy steels. In case of clad steels, hydrogen may induce underclad cracking. In this work, we investigated the effect of hydrogen on the microstructure and adhesion of the interface between low-alloy steel (back) and 304L austenitic stainless cladding in explobonded plates. Optical and scanning electron microscopies were used for microstructure and microhardness examinations of specimens before and after heat treatment. The adhesion was tested in bond shear measurements.

It has been shown that explosive bonding process results in a strong deformation and specific microstructures in the near-bond area. These microstructural features increase the susceptibility to hydrogen embrittlement of the stainless steel cladding within the narrow zone close to the clad interface. This embrittlement can be prevented by a heat treatment after explosive cladding. As expected, heat treatment (annealing) of the clad plates was found to decrease the bond shear strength but markedly hamper the hydrogen-induced deterioration in the shear strength.

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IMPROVEMENT OF JOIN QUALITY BY USING UNDERWATER EXPLOSIVE WELDING

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An improved method of explosive welding using underwater explosive welding technique is introduced. It is a moderate technique to weld a thin plate or plates onto a substrate. The device and the welding process including a method to homogenize the pressurizing condition are explained. Some experimental results are demonstrated showing the improved quality of welding by changing the process parameters. These results are compared with those obtained by regular explosive welding technique. Based on the welding window, welding parameters for difficult-to-weld combinations of materials are discussed.

INFLUENCE OF INITIAL DENSITY ON THE STRUCTURE OF DETONATION WAVES IN PRESSED HIGH EXPLOSIVES

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The laser interferometry system VISAR was used to investigate the structure of detonation waves in pressed high explosives (HEs) (HE = RDX, HMX, $C_6H_6N_6O_{14}$, and $C_6H_8N_{10}O_{16}$) with different initial density. Obtained were the profiles of the surface velocity of foils placed at the boundary between a HE sample and a water "window." Determined were the critical initial densities ρ_c at which the reaction zone structure changed crucially. The von Neumann spike was recorded for $\rho < \rho_c$; otherwise, a monotonous pressure rise in the reaction zone was observed. It was found that $\rho_c = 1.73$, 1.56, and 1.71 g/cm^3 for RDX, $C_6H_6N_6O_{14}$, and $C_6H_8N_{10}O_{16}$, respectively, and $\rho_c > 1.77$ g/cm^3 for HMX. An unusual structure of detonation wave at high ρ values was explained by formation of the final state of reaction products on a weak branch of the detonation Hugoniot. In this case, propagation of the detonation wave is governed by the rate of chemical reaction and shock wave structure.

DEFORMATION CONTROL IN EXPLOSIVE FORMING

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Explosive formed products are more and more commonly applied in Western Europe. The state-of-the-art is rapidly extended towards new product groups. Material characterization and process control becomes more important for efficiently designing new explosive forming processes.

A method was developed for determining the forming limits of metals in explosive forming. A test shape was designed with features that represent different strain paths in the Forming Limit Diagram. A regular dotted pattern is electrochemically etched on the sheet surface. Test plates are formed and analyzed using photogrammetry.

The resulting Forming Limit Curve is used as an input for forming simulation software that works with a hydrostatic code. This approach provides a straightforward method for predicting the forming characteristics that come with a certain workpiece and it strongly enhances the design of new products that are to be formed by explosive forming. This approach is also applied for heat treated and for welded metals. The Forming Limit Diagrams of both the simulation and the photogrammetric analysis of a real explosive formed shape are compared for validation.

NEW MIX EXPLOSIVES FOR EXPLOSIVE WELDING

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Suggested and tested were some mix explosives — powder mixtures of brisant HE (HE = RDX, PETN) and inert diluent (baking soda) — for explosive welding. RDX and PETN were selected in view of their high throwing ability and low critical diameter. Since the decomposition of baking soda yields a huge amount of gaseous products, its presence ensures (even at low HE percentage) a throwing speed that is sufficient for realization of explosive welding, at a reduced brisant action of charge.

Mix chargers containing 30–70 %(wt.) HE (the rest baking soda) have been tested experimentally and optimized. The sensitivity of optimal compositions to mechanical and thermal influences was found to be lower than that of pure HE. Optimal mix explosives exhibited the detonation velocity $2.0 \leq D \leq 2.3$ km/s (depending on the thickness of bulk layer) at a charge density of $\rho \approx 1$ g/cm^3 and the critical diameter of detonation $5 \leq d \leq 10$ mm. The above explosives afford to markedly diminish deformations within the oblique impact zone and thus to carry out explosive welding of hollow items and thin metallic foils.

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INFLUENCE OF VARIOUS FACTORS ON DETONATION OF COMPOSITE EXPLOSIVES BASED ON AMMONIUM NITRATE

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In designing composites for low-sensitive explosives, it is important to provide necessary detonation parameters. The use of plasticized polymeric inflammables and ammonium nitrate as oxidants is one of the most promising directions for R&D of industrial explosive materials. In this work, we explored the detonation of mixed composite explosives of the oxidant–fuel type based on thermally reversible plasticized polymeric binding agents and ammonium nitrate (AN). The polymeric binding agents contained the copolymer of ethylene and vinyl acetate and liquid hydrocarbons as plasticizers. The thermodynamic compatibility of the chosen copolymer–plasticizer systems and the mass transfer parameters were estimated by the microinterference method. Granulated AN (comprising of porous and nonporous particles) and finely dispersed AN (prepared by fragmentation of nonporous granules) were used to prepare composite explosives. The main experimental series were carried out with explosive charges of the same diameter at different charge densities and percentage of components in the mixture. The detonation parameters were determined using a Doppler-type VIZAR rate meter, the detonation velocity was measured using a digital time meter. Testing the mixtures under study in a steel shell 28–30 mm in diameter gave a detonation velocity of 2–2.5 km/s (for a composite density of 0.8–1.1 g/cm^3). The detonation velocity was found to depend largely on the size of AN particles and charge density. The explosives characteristics of the compositions based on AN, thermoelastoplastics, and plasticizers of different content were also calculated using the TDS Software for Equilibrium and Non-Equilibrium Thermodynamic Calculations.

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INTERNAL EXPLOSIVE LOADING OF CLOSED VESSELS

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The explosion-assisted synthesis of nanopowders and their subsequent compaction are normally carried out in closed explosive cameras. In the design of such vessels, one has to take into accounts the following factors: (*i*) type of the process and charge power, (*ii*) number of operation cycles, and (*iii*) climatic conditions.

In this work, the camera volume and its wall thickness are being calculated in terms of the theory taking into account balance between the energy of HE and kinetic energy of deformations and vibrations of the camera wall.

Our experimental setup for *in situ* tensometric determination of strains in camera walls is being used to determine the strain σ, amplitude and type of wall vibrations for varied charge weight in the presence/absence of obstacles between a shock wave and inner wall surface. For various spherical and cylindrical camera geometries, the calculated data were found to reasonably agree with experiment.

It has been concluded that the camera walls will retain their strength is the depth α of hypothetical cracks is below $0.25S$, where S is the wall thickness.

CORROSION-RESISTANT EXPLOCLAD METALS: PROPERTIES AND PRODUCTION EXPERIENCE

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In 2003, industrial-scale production of exploclad metals in Krasnoarmeisk (Moscow Region) has been launched by joint efforts of Bitrub International Ltd., Institute of Bimetallic Alloys, and ISMAN. Thermal treatment and straightening of clad sheets are being carried out at the Podol'sk Machine Works (Moscow Region) and DzerzhinskKhimMash Plant (Nizhnii Novgorod Region).

Our clad metals were found to meet the requirements of the State Standard GOST 10885-85 and Technical Specifications 27.32.09.010-2005 and 27.81.09.009-2005, as well as of some foreign standards, such as NC 501 (France), AD Merkblatt W8, 1987, and Specification no. 1264, 1985 (Germany).

The quality of clad metals is being estimated from the magnitude of strains, weld continuity, and adhesion strength (as detected by ultrasonic defectoscopy) and also from the data of tear, shear, and bending strength measurements according to the above mentioned national standards.

The data of certification testing (at TsNIITMash) of our clad sheets — 74 (70 + 4) × 1400 × 5900 mm (low-alloy steel – corrosion-resistant steel), 61 (57+4) × 1400 × 5900 mm (low-alloy steel – corrosion-resistant steel), and 36 (30 + 6) × 2900 × 2900 mm (carbon steel – titanium) — will be reported at presentation.

Among our customers are the leading manufacturers of equipment for petrochemical industry and power engineering, such as PenzKhimMash (Penza), VolgogradNefteMash (Volgograd), KurganKhimMash (Kurgan), DzerzhinskKhimMashEksport (Dzerzhinsk), etc.

We also developed a novel technology for explosive welding of steel–titanium pairs under argon. In 2005–2007, this technology was used to manufacture tube plates 38 (30 + 8) × 2700 × 2900 and 48 (40 + 8) × 1800 × 3400 mm in size. The shear strength of explobond was above 150 Pa while the tear strength above 250 Pa. The explobonds exhibited a wavy structure without brittle inclusions. After thermal treatment and straightening, deformation of clad sheets remained within tolerable limits.

BEHAVIOR OF HEMISPHERICAL EXPLOSIVE CHAMBER IN CONDITIONS OF SHOCK LOADING

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We explored the behavior a hemispherical explosive chamber 36 m in diameter and a 1/6 scale model with a diameter of 6 m. Based on the results of testing and on calculated data for internal shock load, intensity and stability of dynamic/static strains, and ventilation conditions, we came to the following conclusions.

(1) The shock wave intensity drops by 50% in the longitudinal direction and by 10% in the transverse direction, with a marked wave elimination effect.

(2) Under the action of shock wave, the shell surface undergoes vibrations in the state of tensile and compression strain (except for the first peak of shock strain) with the angular vibration frequency between 500–1000 Hz, corresponding to 314 Hz of soil-covered shell as a whole; moreover, the vibration stress reduces down to below 100 MPa immediately after 1–2 back and forth vibrations; a layer of soil can eliminate the vibration of shell and also markedly reduce the effective stress of the shell; therefore, the shell vibratory fatigue

issues can be neglected, although some explosive fatigue problems have to be taken into consideration; the positive pressure characteristic time τ of 5-kilogram explosive's shock wave length is 2.2 ms (calculated on the basis of spherical wave formula), so when the shell strain is determined, only the odd positive pressure shocks need to be taken into account, while the complicated reflecting process within the shell under the explosion shock can be neglected.

(3) Ventilation model test shows that the amount of poisonous gas can be reduced in 3 min to a level that people could enter under ideal windless conditions; however, their amount can be reduced in 10 min to a degree that people could come under upwind conditions.

(4) Rigid displacement test shows that the maximum rigidity of the bottom ring is only 4 mm (in average 2 mm), when the explosive weight is 5 kg.

(5) Over 300 times shock fatigue strengthening tests show that no damage happens to the entire shell structure, but cracks appear on two local welding seams; however, after loosen soil is back filled, the cracks are no longer extending.

EFFECT OF MECHANICAL ACTIVATION ON THERMAL EXPLOSION IN THE Ti–Ni SYSTEM

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In this communication, we report our experimental data on the effect of mechanical activation (MA) on thermal explosion in Ti + Ni powder mixtures. The duration of MA was found to affect the morphology of processed powders and thus to change the parameters of thermal explosion. Irrespective of the particle size of starting powders, MA was found to result in elevated reactivity of the mixtures due to a better contact between particles and increasing amount of structural defects. Upon attaining some critical duration (in our case, 3 min), further MA was found to become useless (formation of agglomerates and their destruction come to equilibrium). Thermal explosion was found to proceed as a solid-state reaction yielding products that inherit a structure formed during MA.

EFFECT OF UNDERWATER SHOCK WAVE ON JUTE FIBER AND ITS CHARACTERISTICS

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Jute (*Corchorus Olitorious*) is the second most important natural fiber after cotton. It has the ability to blend with other fibers, both synthetic and natural ones. As the demand for natural biodegradable comfort fiber increases, the demand for jute and other natural fibers that can be blended with cotton increases. To meet this demand and to get improved properties, we have to modernize processing of jute.

In this investigation, we have developed an underwater technique to treat jute for the improvement its properties (permeability) by inducing microcracks on the surface of jute fiber. To make the process efficient, the optimum underwater shock wave parameters were chosen, such as pressure or shock strength, D_h, polyethylene paper thickness, etc. After shock wave treatment, some characteristics of jute fiber, such as moisture content, permeability (depending on time, shock strength, dye concentration), and SEM images have been investigated. Flame resistance characteristic and breaking strength of jute fiber after and before shock treatment have also been studied. The result indicates an improvement of permeability and fire proof or flame resistance characteristics upon saturation of jute fiber with fireproof chemicals.

PROCESSING ZnS-BASED ELECTROLUMINESCENT PRECURSOR POWDER MIXTURES WITH TNT

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Display panels made from electroluminescent (EL) materials are a potential replacement for liquid crystal display LCD panels. Electroluminescent panels are self-lighting and do not require the backlight necessary for LCD usage, thus simplifying the manufacture, reducing costs, and allowing for thinner devices. Electroluminescent panels employ an electric field to create emission of light from phosphors with selected chemistries for a particular wavelength. Further phosphor development is necessary to increase the brightness and lifetime of the panels. Recent work has indicated that treatment with TNT explosive during the preparation of the powders could be a method to provide the increased performance necessary to realize the competitiveness of EL panels.

This work will present results of performance of ZnS-based phosphors after treating with TNT. The TNT is used to dope additives into the ZnS-based phosphor for the necessary changes in electronic structure for increased electroluminescence. The effect of detonation and deflagration will be discussed. The short time scale high pressure and temperature of the detonation provides a final material with properties different from the phosphor produced from the longer time low-pressure high-temperature deflagration of the TNT. The performance of the synthesized materials and mechanisms for their differences will be presented.

EXPLOSION STRESS RELIEVING IN WELDED JOINTS OF METAL STRUCTURES

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Tensile stresses formed during fusion welding are known to decrease the service parameters of welded structures, while the existing methods for reliving the residual strains (RS) are expensive, inefficient, labor-consuming, and hardly applicable. In this communication, we report on the use of explosive processing aiming at controlling the state of stresses in welded metals.

Considered are the key points of the developed physical theory of the processes occurring in metal subjected to the action of elastic-plastic wave of moderate intensity and resulting in relaxation of tangential strains formed at the wave front and transformation of elastic strains into the plastic ones, on retention of the magnitude of overall strain. Another factor that facilitates the redistribution of RS is the spreading of metal under explosive loading leading to a drastic decrease in the magnitude of RS, up to a change in their sign. The effect can be used to induce the fields of compression RS at the sites of elevated geometric/technological strains.

Formulated and optimized have been the principles and processing schemes for explosive processing of sheet and axisymmetric metal structures using cord and strip charges. Suggested and tested has been the scheme for external explosive loading of circumferentially welded pipes where compression RS are most pronounced.

Overviewed is our 30-year experience accumulated during diverse commercial application of the technology of explosive processing of welded large-sized metallic structures.

CHARACTERIZATION OF PRODUCTS FORMED IN THE Zn–S SYSTEM UPON COMBUSTION OR DETONATION

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As is known [1], the $\mathrm{Zn} + \mathrm{S} \rightarrow \mathrm{ZnS}$ reaction in the heterogeneous powder system Zn–S may proceed in a recovery fixture either as slow combustion **I** (SHS mode) or as solid–solid detonation **I**–**IV** (detonation mode). In this communication, we report on reaction parameters and composition of products formed in the system under consideration in conditions of slow combustion and detonation.

Table 1 Reaction parameters and composition of products

	Green density	Charge weight, g	Wall temperature after reaction, °C	Pressure, MPa	Product composition
I Slow combustion	0.51	177	300	8	ZnS(w), Zn, ZnO
II Detonation	0.51	177	100	36	ZnS(w), ZnS(c) amorphous phase
III Detonation	0.51	814	800	100	ZnS(w), ZnS(c), ZnO
IV Detonation with depressurizing	0.51	814	20	100	ZnS(w)

Remarks. ZnS(w) stands for the hexagonal (wurtzite) modification while ZnS(c) for the cubic (sphalerite) one.

Experimental conditions were essentially the same as described in [1]. The reaction products were characterized by XRD, energy-dispersive microanalysis, electron microscopy, and chemical analysis. The obtained data are given in Table 1.

In reaction mode **I**, ZnS(w) appeared in the form of concentric granules while in reaction modes **II** and **III**, in the form of platelets. This can be associated with a wide temperature range for crystallization of ZnS [2], so that the reaction may be expected to proceed both above and below the temperature of the sphalerite–wurtzite phase transition. The platelet-like shape of crystallites can be explained by occurrence of the martensitic transformation ZnS(c) → ZnS(w).

The above data directly confirm occurrence of the solid–solid detonation in the heterogeneous Zn–S system. The morphology and phase composition of reaction products were found to depend on synthesis conditions.

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SYNTHESIS OF MULTILAYER COMPOSITES AND OPTIMIZATION OF THEIR STRENGTH PROPERTIES

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A new class of structural materials called metallic-intermetallic laminate (MIL) composites [1] seems rather promising for high-performance aerospace applications. In this work, both experimental and numerical investigations have been done.

In experiments, we used the foils of titanium and aluminum and powder mixtures of stoichiometric composition corresponding to $TiAl_3$ (37.2 %(wt.) Ti + 62.8 %(wt.) Al). Samples were placed in a furnace specially designed for these experiments. The furnace was heated up until initiation of thermal explosion (in air or in an argon atmosphere). The reaction was initiated at the melting point of aluminum and the maximum combustion temperature attained a value of 1320 °C. The XRD data are indicative of the complete transformation of starting powders into $TiAl_3$ and formation of a multilayer structure.

In computations, the high-velocity impact of projectile with a multilayer MIL composite target was investigated in axisymmetrical approximation using a modified finite element method. The target was assumed to consist of 17 composite layers forming the sequence Al_3Ti–Ti (6:4)/Al_3Ti–Ti (6:4)/…/Al_3Ti–Ti (6:4) with a total thickness of 19.89 mm. The projectile, a heavy tungsten alloy rod (93W–7FeCo), was assumed to have a weight about 10 g. In this case, the initial impact velocity was 900 m/s. The obtained data suggest that destruction of the intermetallic layer is brittle, while the metallic layer undergoes plastic failure. In an optimal structure of composite target, a metallic layer must be sufficiently thick in order to suppress the propagation of brittle cracks.

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STRENGTH OF ALUMINUM–STEEL TRANSITION JOINTS WITH RIPPLED INTERFACE: EFFECT OF THERMAL CYCLING

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As is known, bimetallic inserts used for welding aluminum to steel in reduction cells operate in conditions of thermal cycling. Because of burn out, carbon anodes have to be replaced nearly every month. The anodes have to be taken out of melt, the entire assembly must be cooled down to room temperature, a stub to be replaced by a new anode, and then a restored anode holder has to be installed back into the cell. Thermal strains appear upon heating/cooling of a bimetallic insert due to different thermal expansion of steel and aluminum.

In this work, we explored the effect of thermocycling on the strength of different bimetallic transition joints fabricated by explosive welding and the level of resultant thermal strains in aluminum–steel inserts. The specimens with flat and rippled (dovetail) interface with an aluminum interlayer (10 and 20 mm thick) and titanium interlayer (0.5 mm thick) were tested. Thermocycling conditions: heating up to 3500 °C and cooling down to room temperature in air or in water (15–30 cycles). The data obtained can be summarized as follows:

(1) being a part of anode rod assembly, bimetallic inserts operate in conditions of thermal cycling, which is one of the main reasons for their failure. Therefore, the official Specifications for transition

joints must also contain requirements (besides heat resistance) to thermocycling resistance;

(2) thermocycling was found to decrease the strength of aluminum–steel joints prepared by explosive welding, the effect being most pronounced for transition joints with a flat interface; and

(3) transition joints with a dovetail interface exhibited elevated resistance to thermocyclic loading.

INFLUENCE OF INTERNAL RAREFACTION WAVES ON EXPLOSIVE WELDING

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In explosive welding, the oblique impact of plates occurs at the boundary with a wedge-like cavity which can act as a source of internal rarefaction wave. The top of this cavity, a contact point, moves along the base surface at a subsonic speed. Therefore, the shock waves were generated at the impact outstrip the contact point. The irregular reflection of these shock waves from the obverse surfaces is accompanied by formation of two rarefaction waves. One reduces the intensity of the shock wave and bends its front. The collision angle of the shock front becomes critical. Another wave with pressure $P^* = kP_0/\sqrt{R}$ (R is the radius of the shock wave front, P_0 is the initial pressure, and k is the coefficient: $k = 0.32$ for base plate and 0.6–0.5 for flyer plate) moves along the free surface. In every point of contact with the shock wave, the second rarefaction wave arises, which reduces the pressure down to zero. Since the shock wave outstrips the contact point, protrusions are formed ahead of the latter. The size of protrusions on the upper (projectile) plate is higher than of those on the base plate by an order of magnitude. Another consequence of a fact that the shock wave outstrips the contact point is a drop in the impact velocity, which leads to the change in the collision angle and decreasing intensity of loading at subsequent collisions. Worth mentioning is the attenuation of the shock wave due to its spreading over the surface of welded plates. The wave gradually loses its capability of decelerating the impact velocity. Behind a fading shock wave, a flux of compression waves propagating toward the contact surface arises. This flux compensates for the pressure drop due to an increase in the front surface. The pressure at the interface is restored, thus increasing the duration of joining in the contact zone.

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BIOSEALING OF A MARS-SAMPLE CONTAINER USING EXPLOSIVE WELDING

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As part of the European Space Agency's AURORA program, which aims at exploring the solar system and Mars, in particular, ESA intends to participate in an international Mars, Sample Return mission. As this involves extraterrestrial material that may pose a risk to the biosphere of the Earth, strict rules for planetary protection have to be met. This involves multiple biosealing of the samples (while in orbit around Mars) and monitoring of the seals during return to the Earth. One of the potential biosealing technologies to be applied is the explosive welding of the walls of two container parts.

The development of the explosive welding concept is performed at TNO Defense, Security, and Safety. As the container parts are spherical or cylindrical, the weld needs to form a circular closed line. This involves the initiation (point) as well as a meeting point of two detonation fronts that together with the circular parts of the container need to form a hermetically closed weld.

Many requirements have to be met before this welding concept can be used inside a satellite in orbit (microgravity and vacuum conditions), like vibration loading during launch and reduction of explosive mass and loading of the satellite structure. Results of the first experiments using seam welding of Ti rings will be presented.

FATIGUE RESISTANCE OF EXPLOSION CLAD METALS: PROBABILISTIC ASPECTS

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The fatigue resistance of explosion-produced clad metals can be associated with formation of microcracks within the wavy structure of joints. In this communication, we report on the probability-related optimization of explosive welding. In calculations, the distribution of main process parameters — detonation velocity D, technological gap h, and dimensionless parameter R — were assumed to be normal. The probabilities calculated for each of these parameters were assumed to be mutually independent. Based on the published values of D, r, and h, we selected some intervals of these magnitudes that will ensure a desired structure of weld joints. The probability $P(x) = P(x_1 < x < x_2)$ for finding each parameter x ($x = D$, r, h) within the interval (x_1, x_2) was calculated using the Laplace function. The probability P' for obtaining a high-quality joint (without microcracks) was determined upon variation of each x within the admissible limits. Upon variation of D within the interval [$x'_1 = 2000$, $x'_2 = 3000$], we obtained that $P'(D) = 0.7228$; for r within [$x'_1 = 0.9$, $x'_2 = 1.6$], $P'(r) = 0.8415$; and for h within [$x'_1 = 4$, $x'_2 = 16$], $P'(h) = 0.8185$. Multiplying the above probabilities, we obtain:

$$P'(D, r, h) = P'(D)P'(r)P'(h) = 0.4978\,.$$

Therefore, further progress in the quality of weld joints can be achieved upon variation in process parameters with the highest consideration for special service conditions of a given workpiece, and all additional efforts in this direction must be included in the production cost.

THREE-LAYER COMPOSITE MATERIALS BY BATTERY-TYPE EXPLOSIVE WELDING

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Explosive welding of composite materials with overall bilateral or local cladding can be carried out in two ways: (*i*) in a plane-parallel configuration with consecutive bilateral cladding of base metal and (*ii*) upon simultaneous symmetrical bilateral cladding (so-called "battery" scheme). Despite obvious advantages of the latter scheme, its use is restricted by the following factors. With decreasing thickness δ_2 of base metal, the parameters of the wave profile and the amount of melted metal grow, which deteriorates the service parameters of resultant material. In turn, the size of the waves on the boundaries of a three-layer composite depends on temporal conditions for formation of joint.

In this context, it seemed interesting to determine a critical value of $\delta_{2\text{cr}}$ for production of three-layer composites with desired properties by the battery scheme. This was done by comparing the structure/properties of composites obtained by schemes (*i*) and (*ii*). In our experiments carried out at constant contact speed V_c and collision speed V_{cl}, we varied the values of δ_2. It has been found that, for $\delta_2 \geq \delta_{2\text{cr}}$, the properties of joints obtained by the battery scheme are close to those produced by plane-parallel explosive welding. The values of $\delta_{2\text{cr}}$ were found to depend on the properties of composite-forming materials and also on V_{cl}.

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FUSION OF DIAMOND IN SHOCK WAVES

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Conditions for shock-induced fusion of diamond powders were analyzed as a function of their porosity $m = \nu_{00}/\nu_0$ and dispersity. Shock Hugoniots in the $(p,\, u)$ and $(p,\, T)$ coordinates have been calculated.

(1) Assuming that air in pores is compressed by a factor of seven, the mass speed u_p in powder can be determined from the expression $u_p^2 = u_0^2 = 6/7(m-1)p\nu_0$, where u_0 is the shock speed in single crystal as assessed from the Hugoniot adiabat for diamond: $D = 12.16 + u_0$. For some values of u_0, we can calculate the magnitudes of $p = \rho_0 D u_0 = 3.51(12.16u_0 + u_0^2)$ and then, for some values of $\nu_{00} = 1/\rho_{00}$, we find the values of u_p.

(2) Shock Hugoniots in the $(p,\, T)$ coordinates (Fig. 1) were calculated by comparing the pressure dependence of the shock compression energy and the temperature dependence of the internal energy of diamond:

$$E_T = 0.5p(\nu_{00} - \nu_0) = 924 + 1.978(T - 1000)\,.$$

(3) From intersection of shock Hugoniots with a line of diamond fusion, we can determine the equilibrium (over entire volume of diamond powder) values of pressure p (Fig. 2) corresponding to the onset of fusion while those corresponding to completion of fusion, from the energy of shock wave equal to the sum of thermal energy E_T at the melting point T_m and heat of fusion λ:

$$E_\mathrm{m} = E_T + \lambda\,,$$

where $\lambda = \Delta S T_\mathrm{m}$ (at the triple point, entropy change ΔS_∞ for single crystal is 1.6 J/g).

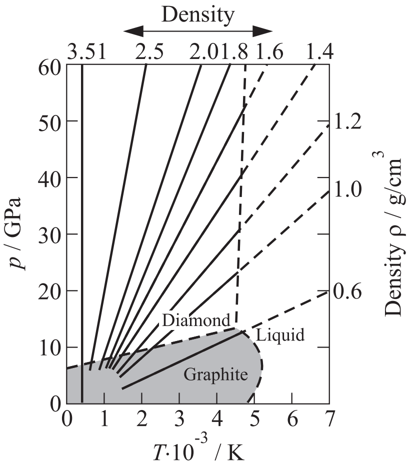

Figure 1 Shock Hugoniots in (p, T) coordinates

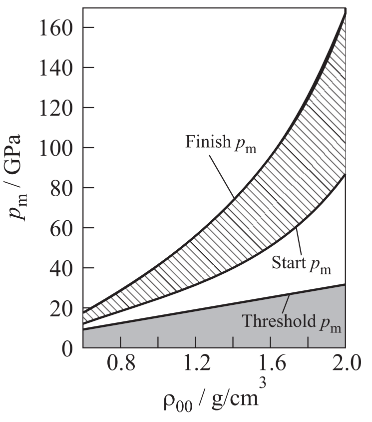

Figure 2 Equilibrium values of pressure

(4) In pores, diamond melts at lower pressures due to nonequilibrium thermal conditions (ratio $T_{\mathrm{pore}}/T_{\mathrm{eq}}$) in shock-compressed powders. At low pressures (below 40 GPa), diamond particles can be regarded as incompressible. In this case, all compression energy is concentrated in pores and $T_{\mathrm{pore}}/T_{\mathrm{eq}} = m/(m-1)$. It is found that, at compression up to $\nu = \nu_0$, for $\rho_{00} < 1.9$ g/cm^3 we obtain that $T_{\mathrm{pore}} > T_{\mathrm{m}}$. With decreasing size d of diamond particles, nonequilibrium thermal conditions gradually undergo equilibration proportionally to $d^{0.5}$ and come to equilibrium at $d = 26$ nm.

(5) With account of the surface energy, the diamond fusion temperature T_d as a function of d (in nm) can be written in the form:

$$\frac{T_d}{T} = 0.5\left[1 + \left(1 - \frac{1}{d}\right)^{0.5}\right] .$$

Under the assumption that the entropy of diamond nanoparticles in an amorphous shell (with thickness δ) is the same as that of liquid diamond, the heat of fusion as a function of d was found to obey the following expression:

$$\begin{aligned}\Lambda(d) &= \Delta S(d) T_{\mathrm{m}}(d) \\ &= \left[\frac{\Delta S_{\infty}\left(d-2\delta\right)^{3}}{d^{3}}\right] 0.5 T_{\infty} \left[1+\left(1-\frac{1}{d}\right)^{0.5}\right],\end{aligned}$$

where $\delta = 0.4$ nm, $\Delta S_{\infty} = 1.6$ J/g, and $T_{\infty} = 4470$ K.

(6) Upon coalescence of fused nanoparticles at the shock front, liberated is the surface energy E_s of nanoparticles: $E_s(d) = 6\sigma/(\rho d)$. For $\sigma = 5$ J/m^2 and $\rho = 3.3$ g/cm^3, $E_s(d) = 9000/d$. It was found that, at $d = 3.3$ nm, $\lambda(d) = E_s(d)$. In this case, a "nanodiamond–liquid diamond" mix disappears and a wave of self-sustained fusion begins to propagate. This phenomenon can also be expected to occur in other nanopowders.

EXPLOSIVE WELDING OF LARGE-SIZED SHEETS: TENSILE DEFORMATION OF BASE SHEET

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As is known, explosive welding is accompanied by bending deformation of clad sheets, their tensile deformation, and by extrusion of base material at the far end. Bending can be fixed up upon subsequent flattening, while shock-induced extension leads to nonrepairable changes in the length, width, and thickness of clad sheets, and also to formation of spall cracks.

Prior to explosive welding, we made witness marks (indents) on the edge of base sheet and on the surface of clad sheet using a special fixture. Prior and after explosion, separation between the marks was measured with an accuracy of ±0.1 mm. The marks were deposited at a pitch of 50 mm at the beginning and of 25 mm at the end of sheet (within the last 300 mm). The sheet length L ranged between 4000 and 5900 mm while the width W between 1400 and 2000 mm. The ratio of base to clad thickness ($R = \delta_1/\delta_2$) was varied from 3:1 to 10:1.

In experiments, separations between the marks on the clad sheet (δ_1 = 3, 4, 5, and 8 mm) were found to remain virtually unchanged. Marked deformation (change in intermark distances) was observed at the end of base sheet. The length l of the deformed zone ($l = 200 \div 1350$ mm) was found to depend on R and L. Within the deformed zone, the strain initially grows, attains its maximum value around $0.5l$, and then gradually decreases down to zero.

Discussed is the tentative mechanism of this phenomenon. The obtained data afford to conclude that the rate of tensile deformation at the far end of base sheet exceeds the velocity of contact point.

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MIXTURE OF POROUS AMMONIUM NITRATE WITH DIESEL OIL FOR USE IN INDUSTRIAL-SCALE EXPLOSIVE WELDING

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Our experimental setup was used to investigate the effect of (*i*) granulometric composition, brand of ammonium nitrate (AN), and ambient temperature on the impregnability of AN with diesel oil; (*ii*) mixture composition and its thickness Δ on the detonation velocity D in the 1200×250 mm samples; and (*iii*) stability of D in large-sized charges.

(1) In experiments, three types of AN — granulated (GAN), ground granulated (GGAN), and microporous granulated (MGAN) — were used. Mixtures of GAN containing 4% diesel oil were found to undergo precipitation. With increasing content of diesel oil (6%–16%), the precipitate thickness δ increased (from 8 to 30 mm). For mixtures of GGAN containing 2%–6% diesel oil, no precipitation was observed. With increasing content of diesel oil (8%–16%), the δ values grew from 14 to 26 mm. No precipitation was found in mixtures of MGAN containing 2%–4% diesel oil, but upon further increase in the oil percentage, δ was found to grow from 10 to 18 mm. At reduced ambient temperatures, the impregnation ability of AN was found to decrease because of decreasing viscosity of diesel oil. These

data imply that, in these conditions, the viscosity of diesel oil must be accordingly adjusted.

(2) The D values were measured using four closure transducers (linked with an oscilloscope) placed onto a 1×0.25 m metal plate. Charged components were mixed manually. With increasing percentage of diesel oil in its mixtures with MGAN (starting with 10%), D values were found to grow from 1770 to 3400 m/s. The mixtures exhibited uniform density and impregnability. During storage of the mixtures containing 4% diesel oil, no redistribution of the latter within Δ was found. With increasing Δ, the D values were found to slightly increase. Under a sand layer, the above mixtures at $\Delta = 20$ mm and $L = 6$ m were found to persistently detonate with $D = 1480$ m/s.

(3) Explosive welding was modeled on metal sheets 6×1.2 m in size. Transducers were placed onto a charge (MGAN–diesel oil 96:4, under a sand layer) surface at a pitch of 0.5 m. Initiation was carried out at the sheet end. Due to high stability of D, good quality of joining was attained even at -25 °C.

HIGH-ENERGY PROCESSING OF MATERIALS: TECHNOLOGIES OF THE 21st CENTURY

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The possibilities for effective use of high-module power sources, employing the energy of explosion and powerful ultrasonic generators, for welding, hardening, synthesis of superstrength materials, and finishing of machine components will be addressed. The implementation of the above techniques to technology-intensive production in the most important branches of industry will be illustrated by numerous examples.

PRESSURE AND DEFORMATIONS FORMED IN METAL LOADED WITH EXPLOSION OF CORD EXPLOSIVE CHARGE

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In this work, we estimated (using a piezoresistive transducer) a magnitude of pressure P developed in a metal upon its loading with explosion of a detonating cord. The peak values of P (several gigapascal) were found to be optimal for relieving residual strains (RS) in weld joints.

In collaboration with Dr. G. P. Yakovlev (Russian Institute for Physicotechnical Problems of the North), we also explored the distribution of residual plastic strains in an explosion-treated plate using the method of moire fringes. A procedure was developed for deposition of an explosion-proof scanning pattern on the plate surface. Two groups of specimens were prepared: (1) scanning pattern lines parallel to the cord axis and (2) normally to the cord axis. Residual strains were calculated from coordinates of the moire fringes. These data imply that the relaxation of strains in shock wave is accompanied by metal spreading, which additionally facilitates the relief of RS.

Surface defects are known to affect the fatigue resistance of materials: the higher the strength, the most pronounced is the effect. In this context, special studies were conducted to investigate the explosion-induced damages of the surface of the welded joints and elucidate the factors affecting the character and magnitude of such damages. This circumstance should be taken into account in optimizing the parameters for explosive processing of welded joints aiming at improvement of their service life.

SHEAR INSTABILITY AT THE EXPLOSION PRODUCT – METAL INTERFACE FOR SLIDING DETONATION OF EXPLOSIVE CHARGE

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Periodic perturbations at the "explosion product – metal" interface were studied experimentally. Experiments were performed for both spherical and plane geometry. Critical conditions for wave formation (detonation velocity of explosive charge $D \geq 6.9$ mm/μs) are determined, and an explanation of this effect is given. It is found experimentally that a dynamic pulse causes intense plastic strains at the explosion product – metal interface, which leads to thermal softening of the steel boundary layer. In this layer, the Kelvin–Helmholtz instability occurs. Analytical estimates for the instability wavelength of the critical boundary were found to agree satisfactorily with experiment.

INSTABILITY OF INTERFACE BETWEEN STEEL LAYERS CAUSED BY OBLIQUE SHOCK WAVE

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Development of instability at the interface between two identical metals in tight contact under the action of oblique shock wave was studied experimentally. The scheme of loading is shown in Fig. 1. The photograph of microsection of the contact boundary after shock-wave loading is presented in Fig. 2.

Numerical modeling of experimental results was performed by using a 2D Lagrangian procedure and elastoplastic model with a functional dependence of the dynamic yield point on the state variables of the material. The calculations have shown that perturbations develop only in the presence of a technological gap of several micron between the

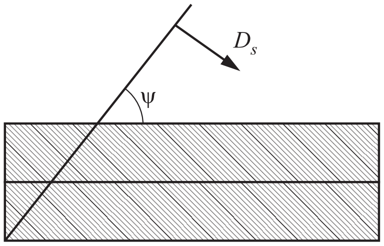

Figure 1 Scheme of loading

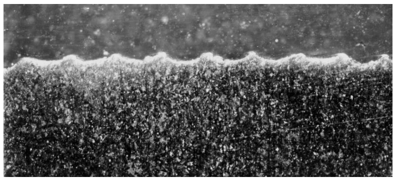

Figure 2 Photograph of microsection

metal layers. Unloading material behind the oblique shock front into the gap gives rise to a marked short-term velocity gradient ($t \leq 0.2$ μs, $\Delta U \geq 3$ μm/μs). Simultaneously, near the interface behind the wave front, there is a short-term loss of material strength due to thermal softening and heterogeneous character of deformation.

PRODUCTION OF CLAD METALS AT BAOTI GROUP Ltd.

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Clad metals obtained by bonding of two or more dissimilar materials are known to combine the advantages of base and clad layers and exhibit a good property to price ratio. These materials are being widely used in a variety of industrial applications such as petrochemical industry, salt production, power engineering, metallurgy, etc.

In brief, this communication reports on production of clad metals at Metal Clad Plate Co., Baoti Group Ltd. Our production facilities involve the processes of explosive bonding, roll bonding, and explosive plus roll bonding. The ultimate surface area of bonding attains a value above 20 m^2 while the thickness of plates up to 10 mm. The nomenclature of our products includes: Ti/steel clad plates; stainless steel/steel clad plates; nonferrous clad plate (Al/steel, Al/Cu, Cu/steel, Cu/stainless steel, Ni/steel, Ni/stainless steel); and three-layer clad plates (stainless steel/steel/stainless steel, Ti/steel/stainless steel, Cu/Al/Cu, Al/Ti/steel, Zr/Ti/steel).

FABRICATION OF NANOCOMPOSITE PERMANENT MAGNETS BY SHOCK COMPACTION OF POWDERS

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Dynamic densification employing the use of high-pressure shock waves is a promising “bottom-up” approach for consolidating powders of amorphous, nanocrystalline, and nano-sized particles to solid density, without subjecting them to long term thermal excursions and thereby retaining the metastable, and/or ultrafine (nanoscale) grain size structures. During dynamic compaction, the energy of the shock wave is dissipated in heterogeneous plastic deformation and sliding at contact surfaces, in the process of void annihilation. Understanding of these micromechanical effects has enabled us to exploit the unique attributes of shock compression and fabricate fully-dense bulk solids of hard/soft-phase exchange-coupled nanocomposite permanent magnets starting with $Pr_2Fe_{14}B$–20 %(wt.) α-Fe polycrystalline powders and FePt/Fe_3Pt nanoparticles. Consolidation of powders is performed using our 80-millimeter diameter gas gun and explosive shock loading to produce compacts of 97%–99% of full density, with solid-state interparticle bonding and $\sim$ 25 nm average grain size. The magnetic properties measured for these bulk nanocomposite magnets show hysterisis loops illustrating exchange-coupling between hard/soft phases and remanence ratio $MR/MS > 0.50$. The product energy is $\sim$ 17.8 MG Oe, which is higher than that of conventional resin-bonded permanent magnets. Subsequent heat treatment of the shock-consolidated compacts results in some improvement of coercivity, without change in energy product.

In this presentation, results of our work on structure-properties characterization of exchange-coupled $Pr_2Fe_{14}B/\alpha$-Fe, FePt/Fe_3Pt and

$SmCo_5/\alpha$-Fe hard/soft phase nanocomposite permanent magnets will be described. The possibilities and challenges that need to be overcome for fabrication of bulk nanostructured materials by dynamic shock compaction of powders will be also presented.

Acknowledgments

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EXPOSIVE WELDING: TEMPERATURE PROFILE OF HEAT-AFFECTED ZONE

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In our experiments, the mean (residual) temperature was measured with thermocouples using the following two schemes: (1) a tossed plate was welded with a motionless base with insulated inserts of a material to be studied and calked thermocouples. Signals from the latter ones were recorded with a digital oscilloscope at a time delay of 100–200 ms; and (2) upon completion of deformation in the tossed plate and insert, the formed composite spontaneously decomposed during welding, and the metal of the tossed plate was thus excluded from subsequent heat exchange processes. This was achieved upon deposition of an antiweld compound onto the surface of base material. Therefore, experiments (1) gave the residual temperature of the tossed plate and insert (bundle) while experiments (2), the temperature of insert. Knowing the mean temperature of insert and bundle, we could determine the specific heats Q released in the entire bundle (Q_{tot}), tossed plate (Q_1), and motionless insert (Q_2). In parallel, we have studied the plastic flow in the heat-affected zone using reference inserts in order to obtain the distribution of maximum shear stresses in the motionless material. Having determined the distribution of residual plastic deformation $\varepsilon(y)$ over the insert cross section, specific heat Q_2, and the proportionality of ε to Q_2, we could calculate the initial heat distribution, i.e., starting temperature profiles.

The obtained data shed light on the thermal situation in the heat-affected layers of explosion-welded plates of similar and dissimilar materials, which provides means for controlling the structure/properties of clad materials. Moreover, our method can be used to determine the relative amounts of energy liberated in tossed and motionless plates with a higher accuracy compared to conventional calorimetry.

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TECHNOLOGICAL CAPABILITIES OF BOM Ltd. IN EXPLOSIVE FORMING AND JOINING OF METALS

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BOM Ltd. is working in the field of explosive welding and forming technologies since 1987 and offers the following processes and products:

(*i*) hydro-explosive forming of parabolic satellite antennae of aluminum plates 1.2–3.0 m in diameter;

(*ii*) explosive welding of bimetal Al/Cu bands and rods (dia > 600 mm), steel/Cr–Ni-alloy flanges, steel/Al–Sn-alloy bands for tribological applications; and

(*iii*) explosive strengthening and stress relaxation of Hatfield steel components for mining industry and power engineering.

Parabolic antennae for TV and digital radio relay satellite systems become the core production of the company. The hydroexplosive method ensures high precision and reproducibility and improves the mechanical properties (20%–30% in Al hardness) of products. The receiving parameters of the dishes exceed those of conventional ones.

Bimetallic Al–Cu components abate the electroerosion in the components and are widely implemented in power engineering and high voltage installations, e.g., high voltage disconnectors for 110, 220, and 400 kV.

The efforts of BOM Ltd. are focused on the following lines of R&D:

(1) joining complex shape parts;

(2) extending the range of alloy combinations;

(3) utilization of explosive processing for micromanufacturing; and

(4) impact of shock waves on amorphous and microcrystalline materials.

Acknowledgments

The work is carried out in collaboration with Rousse University, Bulgarian Ministry of Education & Science, Ministry of Defense, communication technology enterprises, ISMAN (Russia), M. A. Lavrent'ev Institute of Hydrodynamics (Russia), and many other European partners.

IMPACT OF HIGH-SPEED PARTICLES WITH A METALLIC OBSTACLE

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Abnormally deep penetration of high-speed (1000–3000 m/s) particles (8–100 μm in size) into an obstacle is known [1] to attain a value of several dozens of particles' size. This phenomenon which is difficult to rationalize in terms of hydrodynamic theory still remains a subject of controversy. In this work, we investigated the ultradeep penetration of TiN particles (10–70 μm in size) into low-carbon steel targets and its influence on the structure/properties of thus processed steels. Cylindrical samples were 40 mm long and 24 mm in diameter. Acceleration of TiN particles was achieved upon explosion of RDX charges ($\rho = 1.77$ g/cm^3) in an iron tube 24 mm in diameter. Separation between the powder and target was 60 mm. Processed specimens were characterized by XRD, electron microscopy, and hardness measurements. The effect of ultradeep penetration was found for all the samples studied. The data of electron probe microanalysis showed the presence of TiN particles (with a size of 5–6 μm) embedded into a steel matrix. A marked decrease in the size of embedded TiN particles can be associated with their partial fusion during the penetration process.

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EXPLOSIVE WELDING OF STEEL–ALUMINUM COMPOSITES WITH AN ANTIDIFFUSION CHROMIUM LAYER

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Due to their reliability, durability, good conductivity, and low cost, steel–aluminum composites are being widely used in industry as coupling (adapter) materials. However, their use is restricted by formation of fragile intermetallide layers in weld joints under the action of high temperatures, dynamic pressures, and aggressive media, which reduces the strength of material. This drawback can be overcome by placing an antidiffusion interlayer in between clad metals to suppress the formation of fragile intermetallides during their service life. In this work, we explored the explosive welding of steel–aluminum composites in the presence of an antidiffusion chromium layer.

The clad metals containing a Cr interlayer were found to exhibit elevated heat resistance. In order to ensure a reliable diffusion barrier between aluminum and steel, a galvanically deposited (prior to welding) chromium layer must have a thickness within the range 0.03–0.07 mm. It has been established experimentally that the strength/structure of welded steel–aluminum composites is most affected by a value of the collision velocity V_{cl}, its optimal magnitude being within a very narrow range of V_{cl}. With increasing V_{cl}, a Cr layer becomes damaged, which facilitates the formation of fragile intermetallides upon heating.

DYNAMIC COMPACTION OF IRON DISILICIDE POWDERS

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Iron disilicide is an attractive material for use in semiconductor thermoelectric cells. When prepared mechanochemically, ground disilicide is very difficult to compact, especially in case of nanopowders. This circumstance seriously restricts the industrial implementation of this material.

In this work, we tested the method of dynamic loading for compacting iron disilicide powders. Powder to be compacted was placed into a metallic container and then subjected to the action of a shock wave generated upon detonation of high explosive. In our experimental setup, the dynamic pressure could be varied from a few to several dozens of gigapascal. Planar loading (with direct and reverse shock waves) of a precompacted cylindrical iron disilicide sample was carried out in a metal container placed in a thick steel shell. The density of shock-compacted samples was found to depend on the magnitude of dynamic pressure. For thus compacted material, we measured its electric conductivity, thermal conductivity, and thermoelectromotive force.

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PREPARATION OF NANOSTRUCTURED TiO_2 PARTICLES BY GAS-PHASE DETONATION

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The nanostructured polycrystalline titanium dioxides were produced by gaseous detonation and pyrohydrolysis. Titanium tetrachloride ($TiCl_4$) was used as a gas-phase precursor while $O_2 + H_2$ mixtures as a source of energy. The obtained samples were characterized by XRD and TEM. It is found that smaller particles and lower amount of rutile can be produced at a lower temperature using a reduced amount of $TiCl_4$. The reaction occurs within the zone of deflagration-to-detonation transition, which explains irregular phase composition, particle size, and morphology of synthesized particles.

CHARACTERIZATION OF A TITANIUM–STEEL EXPLOSION BOND INTERFACE

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The explosion welding process is a well established, technically based industrial welding process. Explosion bonding has been used for over forty years for industrial production of welds between broad ranges of metals. Its major advantage is that it is a "cold welding" process which is free of the physical, mechanical, and thermal limitations imposed by traditional welding processes. Current manufacturing technology is primarily empirically based and is well codified by several manufacturers. The physical and mechanical fundamentals of the technology are less fully understood.

DMC Nobelclad and ENIT, a renowned French Engineering School, undertook a joint research program to develop knowledge on the true nature of the bond that is created during explosion welding. The paper presents the work of this joint program in which the titanium–steel bond was studied. Analysis of results by SEM, atomic force microscopy, and TEM are presented for titanium–steel samples in both the as-clad condition and after post-clad heat treatment. The results generally support the theory that explosion welding produces a mechanically induced fusion-type weld with an extremely small fusion zone and extremely high cooling rates.

EFFECTS OF HEAT TREATMENT TEMPERATURE AND TIME ON THE PROPERTIES OF TITANIUM/STEEL AND ZIRCONIUM/STEEL CLAD

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Titanium and zirconium clad steel materials are frequently fabricated into process equipment. The fabrication may require elevated temperatures for metal forming, postweld heat treatments, or postfabrication heat treatments. These heat treatments can affect the shear strength of the clad metal interface. An extensive test series has been performed to evaluate the shear strength after heat treatments between 500 and 815 °C for hold times up to 20 h. Metallographic microstructures of the cladding metal, the base metal, and the interface were also documented.

EXPLOSIVE WELDING OF DISSIMILAR METALS: TEMPERATURE–DEFORMATION RELATIONSHIP

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In this work, we explored the temperature–deformation relationship during explosive welding of dissimilar metals by evaluating the heat release from the contact zone due to its plastic shear deformation. It has been established that the heat liberated in the heat-affected zone is distributed nonuniformly due to a different extent of plastic deformation of welded metals (e.g., copper and aluminum). Shear plastic deformation in a harder material (Cu) is localized in a smaller volume compared to a less hard material (Al). It causes a considerable temperature rise of its contact volumes, changes a metal structure in the contact zone, and also affects the formation of melted metal areas, predominantly from the side of a less hard metal (normally, with a lower melting point).

Therefore, under properly chosen conditions for explosive welding of dissimilar metals, the plastic shear deformation must be kept within the limits when the resultant heating will not affect the structure of the heat-affected zone.

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HOT EXPLOSIVE JACKETING AND STRENGTHENING OF TUNGSTEN HEAVY AND HARD ALLOY RODS

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The jacketing process of cylindrical rods made from tungsten heavy and hard alloy and the resultant strengthening processes after hot explosive treatment were studied. The temperature of jacketing was varied from 20 to 1000 °C and the intensity of loading was as high as 10 GPa. The investigation showed that the combination of high temperatures and explosive compression of WC–Co and W–Ni–Fe alloy rods prevents cracking and improves the plasticity of the deforming grains of W and WC. The quality of jacketing was found to depend on the loading intensity and preloading temperature. It was also found that a transient zone forms between the cylindrical rod and the jacketing steel. It was established that, with increasing preloading temperature, the intensity of cracking (at the shock wave front) in the tungsten alloys decreases. For W–Ni–Fe above 400 °C and for WC–Co above 900 °C, no cracking occurs. X-ray diffraction, scanning and transmission electron microscopy, and hardness measurement were used to evaluate the structure and property of the transient and hot explosively treated W–Co and W–Ni–Fe alloys.

The above mentioned as well as other features of structure–property relationship of tungsten heavy and hard alloys depending on the loading conditions (setup, intensity of loading, and preloading temperature) are discussed.

STRUCTURE AND PROPERTIES OF HOT SHOCK WAVE CONSOLIDATED Cu–W COMPOSITES

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Cu(20%)–W powder mixtures were formed into cylindrical rods using a hot shock wave consolidation (HSWC) process. Two types of the Cu–W precursor composition with nanosized Cu and tungsten with a grain size of 5–6 μm were consolidated to nearly theoretical density at 800 °C. The shock wave loading intensity was under 10 GPa. The investigation showed that the combination of high temperatures (above 800 °C) and two-stage shock wave compression was beneficial to the consolidation of the Cu(20%)–W composites, resulting in high densities, good integrity, and good electronic properties. The structure and properties of the samples obtained depended on the sizes of tungsten particles. It was established that in comparison with Cu–W composites with a grain size of tungsten 5–6 μm, the application of nanoscale W precursors gives a positive result. The coefficient of relaxation is equal to 4.3–8.6 against 8.0–10 for Cu–W composition with a micron grain size of tungsten. As for electronic properties of consolidated compositions, it was established that composites with nano W characterized by lower dependence of their susceptibility on applied magnetic field.

The above mentioned and other features of electronic and mechanical properties, as well as the structural changes of HSWC Cu(20%)–W composites will be presented and discussed.

INSTRUMENTATION FOR STRAIN MEASUREMENTS IN EXPLOSION-LOADED CLOSED VESSELS

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Our instrumentation set involves (*i*) software for numerical calculation of strains in vessel walls, (*ii*) computer modeling of camera loading upon explosion of a charge placed at the vessel center, (*iii*) devices for *in situ* tensometric determination of strains in camera walls, and (*iν*) software for mathematical processing of spectral, temporal, and amplitude characteristics of the process.

In terms of the theory taking into account balance between the energy of HE and kinetic energy of deformations and vibrations of the camera wall, the strain σ developed in the wall material can be calculated from the expression:

$$\sigma = \frac{0.236}{R^2\delta}\sqrt{\frac{r_0^3\rho_o\rho_a\left(R^3-(R-\alpha r_0)^3\right)QE}{(1-\mu)\rho}}\,,$$

where R is the camera radius; δ is its thickness; Q is the specific energy of HE (kJ/kg); E is the Young modulus of wall material; r_0 and ρ_0 are the radius and the density of charge; ρ_a is the density of ambient atmosphere (air); α is the coefficient characterizing the expansion of detonation products ($\alpha = 8$–10); and μ and ρ are the Poisson coefficient and the density of the wall material.

Computer-aided modeling using the ANSYS program is being used to elucidate the most strained sites in the camera wall at varied size/location of charge and shock propagation conditions inside the camera.

In experiments, strain gauges were installed at the most strained sites predicted by calculations. Our facilities afford computer recording of data and their subsequent processing using the ZetLab program.

In presentation, experimental data will be analyzed in comparison with the calculated ones.

METHOD OF TRAPS FOR ANALYSIS OF PARTICLES FLYING OUT FROM TECHNOLOGICAL GAP

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In this communication, we report on the experimental setup used to analyze fine particles flying out from the technological gap and trapped at the end of clad plates. An alluvion formed on the surface of traps was analyzed by thickness/configuration measurements, optical/electron microscopy, XRD, and microhardness measurements.

In an experimental configuration 1, the role of traps is played by the end sections (0.5 m long) of plates to be welded (Fig. 1). The side edges of the gap were shut with vertical metallic strips.

In other geometry, the trap has a configuration shown in Fig. 2. An advantage is that this setup can be used in the course of fabrication process.

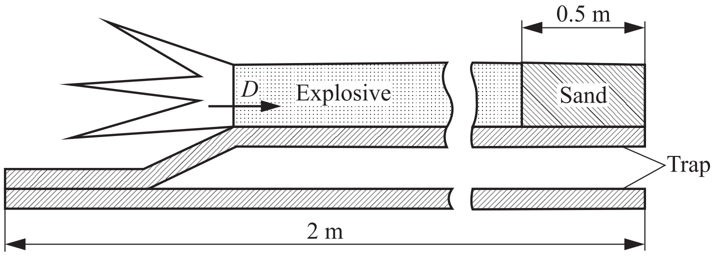

Figure 1 Experimental configuration 1

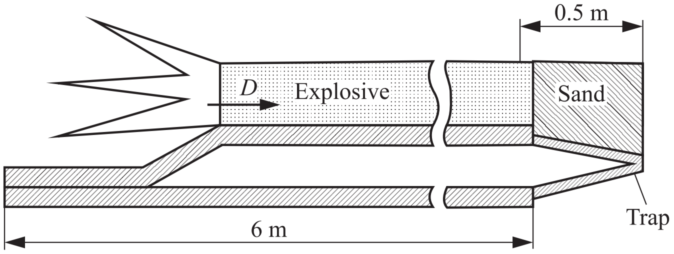

Figure 2 Experimental configuration 2

The above techniques were used to investigate the subtle details of explosive welding of different metal pairs and the role of gas in the gap.

NEW MODEL OF ELASTIC MEDIA: NUMERICAL STUDIES

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The model of nonlinear elastic media initially suggested by S. K. Godunov has been modified in view of some its inconsistencies that were noticed during many years' research. The mathematical aspects of this work were presented at the conference dedicated to the centenary of L. I. Sedov (Moscow, November 2007) and at the 20th Seminar on Computational Fluid Mechanics (Paris, January 2008) organized by the French Commission on Atomic Energy (CEA). The model is based on the equation of state and a new differential form of conservation laws in the Lagrangian coordinates. It was found applicable to both low and strong deformations under high pressure.

In this communication, new data of numerical calculations will be presented. On the basis of new model, we considered one-dimensional (1D) and 2D problems. In terms of the 1D problem, we modeled the process of wave propagation (including the shock one) in one-layer and multilayer media. The collision of two plates at different angle of concussion was modeled in terms of the 2D problem.

EFFECT OF INITIAL TEMPERATURE ATTAINED AT CONTACT POINT ON EXPLOSIVE WELDING

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Within some initial zone (100–400 mm long), the strength of weld join is known to increase from zero up to some optimal value typical of a given mode of explosive welding, which is associated with speed-up of plates and instability of detonation setup. The use of detonators with a higher detonation speed (compared to that of major explosive) can be expected to refine the situation but not exclude the presence of the above stabilization zone. The temperature attained ahead of the contact point is known to attain a value of 5000–6000 K, depending on the type of welded materials and welding conditions. Based on the above data, it could be assumed that the length of the stabilization zone corresponds to a time period required for heating-up of a thin layer (2–3 μm) of metals to be welded to their melting point. In order to investigate the effect of temperature attained at the initial stages of explosive welding, we coated the clad and base plates with a layer of metals (copper, titanium, steel) exhibiting different thermophysical properties. The data of ultrasonic checking imply that, in case of Cu, the area of incomplete fusion at the initial stage was essentially the same as in the absence of Cu coating. In case of Ti, no incomplete fusion and stabilization area were found. The tearing strength above 250 MPa was attained at the very beginning of welding. The wavy structure within the initial area was identical to that at a separation above 500 mm. No particles of plate material were detected in the eddy zones already at a separation of 40 mm. Our data imply that the temperature attained at the contact point begins to define the welding process only when it reaches some value typical of a given pair of metals to be welded.

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MULTILAYER CLAD METALS BY EXPLOSIVE WELDING

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Special three-layer clad metals fabricated by explosive welding are being widely used in chemical and petrochemical industry. These materials are known for their high resistance to pitting corrosion. The combination of metals in these composites is selected with regard to their electrochemical potentials.

In this work, we used the modified parallel setup of plates. This scheme excludes the formation of imperfect zones at the weld interface. Other techniques, such as roll welding or surfacing, do not provide desired properties of joint. Using our method, we performed explosive welding of nickel chromium alloy (66% Ni, 15% Cr, 15% Mo, 4% W) to stainless steel, of stainless steel to carbonaceous steel, and of titanium to steel, the influence of thermal processing on the microstructure a three-layer. For "nickel chromium alloy – stainless steel – nickel chromium alloy" clad metal, we analyzed the weld microstructure, explored the effect of thermal treatment, and tested the material in different aggressive media.

EXPLOSIVE DEPOSITION OF POWDERS ONTO MAGNETRON TARGETS

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Targets for magnetron evaporation are being widely used in electronic engineering for deposition of desired coatings. The composition of coating is defined by composition of deposited powder. A drawback of existing technology is the presence of binders that are difficult to remove by subsequent heat treatment, which leads to contamination of resultant coatings with a binder material and, as a result, to lower service parameters of produced items.

The technology of explosive pressing affords deposition of such coatings in the absence of binders. In our specially designed container, one side is used as a target base. The developed process is applicable to a wide range of powders with different chemical composition, grain size, and microhardness. The data obtained are indicative of good perspectives for industrial implementation of this technology.

SINTERING OF SHOCK-PROCESSED POWDERS

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The kinetics of sintering was analyzed as a function of powder properties (lattice defects, particle size, and state of the contact zone). The activating effect of the above parameters after static pressing (SP), shock-wave activation (SWA), and explosive pressing (EP) was inferred from the activation energy for removal of lattice defects (E_a) and activation energy for the material flow caused by the presence of these defects (E_b). The latter ones were derived from dilatometric data obtained in conditions of step-wise temperature rise.

The sinterability was found to grow with increasing deficiency of particles and contact area between the particles formed at the stage of compaction. After EP and SWA, the process of sintering was found to proceed at lower values of E_a and E_b, i.e., at reduced temperatures. The data of ultrasonic testing show that, after EP, sintering gets started at temperatures by 100–170 K lower compared to SP and by 70–90 K lower compared to SWA.

Out data also demonstrate a significant influence of materials rheological heredity on the process of compaction during sintering. Explosive pressing and shock-wave activation can be expected to reduce a temperature threshold for viscous flow of dislocations, thus facilitating shrinkage at reduced temperatures. As a result, mass transfer and strong bonding between particles take place prior to collective recrystallization, which ensures formation of fine-grained products with low porosity.

FABRICATION OF CERMET COMPOSITES BY EXPLOSIVE WELDING COMBINED WITH THERMOCHEMICAL SYNTHESIS

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In this work, we explored two different approaches to preparation of layered metal/ceramic/metal composites that are being regarded as promising materials for modern mechanical engineering.

In one group of experiments, Ti–C–Ni powder mixtures were placed in a pocket made in a steel base, covered with a thin foil, and then steel-cladded by explosive welding. Thus obtained clad was subjected to thermal treatment at 850 °C to initiate the SHS reaction inside the welded sheet (in closed volume).

In other experiments, we attempted to carry out compaction, explosive welding, and ignition of SHS reaction in Ti–C and Ti–B systems (three in one) under the action of shock wave induced by a planar flyer accelerated up to a velocity of 1 km/s. Temperature was monitored with an optical pyrometer. The obtained samples were characterized by XRD and ultrasonic check.

The best results were obtained in the first group of experiments. The shock activation of reactive mixtures in the second group of experiments turned out insufficient for initiation of steady combustion wave in a closed volume, tentatively because of relatively low values of pressure and velocity attained in the systems under study.

SHOCK-ASSISTED COMPACTION OF AlN-BASED CERAMICS

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Due to their high thermal conductivity and heat resistance, AlN and its mixtures with Al_2O_3 are being regarded promising materials for use as electric insulators in conditions of high temperature gradients. As is known, AlN can be sintered only around 2000 °C in an atmosphere of ammonia or nitrogen. According to Prümmer [1], shock-assisted compaction of AlN gave rise to deformation of AlN crystals already at $P = 0.55$ GPa, which opens up a way to using the shock consolidation of AlN and $AlN + Al_2O_3$ powders as an alternative process. Shock-assisted compaction of AlN and $AlN + Al_2O_3$ powders was carried out in cylindrical recovery fixtures with a central rod. A cylindrical converging shock wave formed upon detonation of explosive ensured uniform compression of powders into tubular compacts. Some compacts were subjected to thermal treatment at 700 °C (compare to 2000 °C at conventional sintering). The compression strength of AlN compacts ($\sigma_c = 100$ MPa) was found to be higher than that of $AlN + Al_2O_3$ compacts by a factor of two. For thermally treated AlN compacts, $\sigma_c = 250$ MPa. The XRD data imply that the phase composition of both the compacts is essentially the same. As follows from micrographs, the microstructure of the compacts is pore-free. Both ceramics exhibited high thermal conductivity and electrical resistance. Shock activation of the powders under study was found sufficient for good sintering even without subsequent thermal treatment.

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DYNAMIC COMPACTION OF FINE IRON DISILICIDE POWDERS: NUMERICAL SIMULATION

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Iron disilicide is an attractive material for use in thermoelectric generators and temperature sensors. One of alternative ways to fabricating high-density iron disilicide is the technique of dynamic compaction.

In this communication, we report on 2D simulation aiming at optimization of experimental setup for dynamic compaction of fine iron disilicide powders. The optimization was carried out in 2D geometry using the EGAK code. The temperature and pressure values were calculated as a function of loading conditions and initial powder density using the equation of state in the Mie–Grüneisen form and the temperature dependence of heat capacity for crystalline β-FeSi$_2$. The elastic pressure versus compression relationship was calculated using the Abinit code, while thermal energy calculation was based on the Debye model for the heat capacity of crystal structures. The data of numerical calculations are compared with relevant experimental data.

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DYNAMIC VISCOSITY OF METALS: EXPERIMENTAL DETERMINATION AND MATHEMATICAL MODEL

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In this work, we measured the dynamic viscosity μ of some metals and mathematically modeled the process of shock loading for a disk of compressible visco-plastic material.

The mathematical model employs:

(1) the equation of motion in a given field of mass forces;

(2) the condition for continuity of medium;

(3) the equation for entropy change;

(4) the functional dependence of mechanical properties;

(5) the equation of state; and

(6) boundary/initial conditions.

For practical determination of μ based on the data of shock compression measurements, we suggest the following formula:

$$\mu = \frac{3\rho_0 u_0 (u_0 - u_1)}{\varepsilon_0},$$

where u_0 is the shock wave velocity; u_1 is the mass velocity of matter behind the shock wave; $\varepsilon_0 = u_1/_0$ is the mean strain rate; ρ_0 is the density of a given metal, and a_0 is the sample height.

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EXPLOSIVE TECHNOLOGIES FOR PRODUCTION OF PLANE BEARINGS

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Significant amount of plane bearings is used in the crankshaft journal–liner assembly of internal-combustion engines. Bimetal liner usually consists of a steel base and an antifriction layer. The antifriction layer as a rule is made from a copper-based or aluminum-based material. In the former case, bimetal is usually made by casting or rolling, while in the latter one, by rolling or explosive welding. The latter technology is being used for production of big Diesel engine liners with a thick steel layer. It should be mentioned that explosive welding provides higher bond strength between bimetal layers compared to rolling. Copper-based antifriction alloys can take a larger load but have an inclination to intensive corrosion in lubricating oil. On the contrary, aluminum-based alloys exhibit a markedly higher corrosion resistance but a lower score-resistance under high load, compared to copper-based materials. To avoid score in running-in period, special coatings are applied to the antifriction surface of most liners. Galvanic metallization is the main technology for applying of led- and tin-based coatings onto the copper-based antifriction materials. To prevent undesirable diffusion of coating material into a copper-based antifriction layer, a special nickel barrier layer is made between them. Galvanic metallization is a hazard technology; besides, it cannot be used for deposition of tin or led alloys onto aluminum-based materials. In this case, some polymerized compositions containing MoS_2 are used, but they have a low working temperature.

As there is a tendency to using aluminum alloys with elevated strength in design of heavy loaded bimetal plane bearings, interest grows in new technologies for applying antiscore coatings. In this work, coatings from a babbit powder Pr-B83 were applied onto bimetal samples by detonation spraying. The samples were cut from bimetal plane bearings $AlSn_{20}Cu_1$–steel made by explosive welding. Tribological tests of coatings were made. These tests show that detonation spraying provides high adhesion of the babbit alloy to the $AlSn_{20}Cu_1$ substrate. And what is more, the coated samples exhibited a significantly higher score resistance compared to pure $AlSn_{20}Cu_1$ alloy. These results show that combination of two explosive technologies — explosive welding and detonation spraying — can be used for production of three-layer plane bearings with high service parameters.

CYLINDRICAL CAMERA FOR EXPLOSION-DRIVEN SYNTHESIS OF NEW MATERIALS

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Most frequently, explosive cameras have a spherical (or nearly spherical) shape. However, for some applications — e.g., synthesis of nanosized oxide materials — such a shape does not seem optimal. In this case, it is wise to use elongated cylindrical charges (exploded from one end), which ensures the maximal surface area of charge and hence the maximal sample weight. For exploding cylindrical charges, conventional spherical cameras must exhibit elevated strength and hence weight.

Our vertically mounted camera has two-layer walls made of stainless steel (inner) and low-alloyed steel (outer). The upper cover (with a hydraulic drive) has a hatch for charge loading. A depress valve has a remote control. There is also a watering mechanism. The camera bottom is conical, with a lock unit and discharge arrangement. Total camera weight is 1650 kg. The camera is suitable for exploding cylindrical charges up to 1000 mm long with a TNT equivalent up to 1.6 kg. After explosion, the camera can be maintained (for some time period) under pressure (up to 20 atm) in order to allow precipitation of solid products onto the bottom. Gaseous products are released though a system of filters.

Our camera is convenient for synthesis of various nanosized materials, such as diamond, titanium oxides, aluminum, silver, etc. Subsequent purification of products is much simplified due to the fact that the inner shell of the camera is made of stainless steel.

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EXPLOSIVE WELDING: VERTICAL MOTION OF WELDED SHEETS AHEAD OF DETONATION FRONT

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As is known, vertical displacement of large-size sheets during their explosive welding may affect the process parameters — welding clearance h, collision angle γ, contact velocity V_c, and collision velocity V_p — and, as a result, lead to variation in weld parameters (elevated wave size, reduced strength, etc.).

In experiments, we could determine vertical displacements of tossed plate and also the distance S from the detonation front where the areas under study begin to move vertically. It has been established experimentally that, with increasing detonation speed D, S decreases nonlinearly, and at some D (depending on experimental conditions), vertical displacement of a tossed plate disappears altogether. Similar behavior of S was observed in the absence of a lower (base) plate. It has also been established that, at constant parameters of explosive (H, ρ, D), S values markedly decrease with increasing thickness of tossed plate δ. The most pronounced vertical displacements were observed for explosive cladding of sheet-mill materials using explosives with a low detonation speed. This observation has to be taken into consideration when designing technological processes for explosive welding of large-size feeds.

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EMULSION EXPLOSIVE FOR EXPLOSIVE WELDING

V. V. Sil'vestrov, A. V. Plastinin, and S. M. Karakhanov

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A suggested emulsion was prepared from water, ammonium nitrate, sodium nitrate, paraffin, industrial oil, and emulsifier. Hollow glass microballoons (up to 8–10 %(wt.) in their amount) were used as a sensitizer. The emulsion density was 1 g/cm^3. This explosive is cap-sensitive and suitable for explosive processing of materials.

For the above explosive, we measured the dependence of detonation velocity D on diameter d of cylindrical charge and on thickness Δ of flat layer. This explosive was found to have a small critical diameter ($d_{\mathrm{cr}} \approx 5$ mm) and low critical thickness ($\Delta_{\mathrm{cr}} \approx 2$ mm). In terms of the "curved front" theory, the relation $D(d) \approx D(2\Delta)$ was found to hold true at the $d_{\mathrm{cr}}/\Delta_{\mathrm{cr}}$ ratio close to two. Upon variation in Δ from 2 to 20 mm, the detonation velocity D was found to grow from 2.7 up to 4.5 km/s. Prospects for decreasing D upon addition of inert fillers and variation in emulsion composition will be discussed.

The examples of application of flat emulsion layers (2–3 mm thick) to parallel explosive cladding of copper and steel plates with thin foils of aluminum, titanium, stainless steel, copper, brass, molybdenum, and tungsten (0.1–0.4 mm thick) will be presented. Other probable applications of the emulsion for "delicate" treatment of materials by explosion will be addressed.

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FORMATION OF PLASMA SPOTS DURING SUPERDEEP PENETRATION OF MICROPARTICLES INTO SOLIDS

V. V. Sobolev[1] and S. M. Usherenko[2]

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[2]Israel Research Center — POLYMATE Ltd.

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New methods for preparation of metal composites based on the effect of superdeep penetration (SDP) of hard microsized particles into metals are suggested. In this technique, accelerated microparticles with typical size d are allowed to penetrate into metallic substrates to depth $h = (10^2–10^4)d$. The penetration depth h was found to depend on d, particles velocity v, and the type of particles/target materials.

It is suggested that SDP becomes possible due to formation of dense plasma spots between the front surface of incident microparticles and the surface of a channel formed in a target material. Plasma is generated mainly due to atomization of target material until the latter exhibits deformability (thermodynamic instability) caused by impact with incident particles.

The formation of high-energy fluxes of dense plasma during SDP was confirmed by detection (using film sensors) of radiation with an energy about 100 MeV typical of thermonuclear processes. Superhigh temperatures in the particle–target system can arise due to cumulative hydrodynamic effects in high-density plasma upon compression of flux energy resulting in formation of plasma spots on the rear surface of microparticles. The newly formed phases were found to contain the elements that were absent in microparticles and target material (or present as minor admixtures).

SYSTEMS FOR SHOCK-ASSISTED AND DETONATION-DRIVEN SYNTHESIS: REACTIVITY OF Ti–C POWDER MIXTURES

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Presented are the experimental data [1] on high-temperature reaction of Ti powder (mean particle size 65 μm) with crystalline flake graphite obtained by the technique of current-induced thermal explosion [2]. Upon reaction ignition at 1300 K, the evolution of the sample temperature has been recorded with a high time resolution. Within the temperature range 1500–2000 K, the reaction rate was found to change by as much as a factor of ten.

The reaction rate was found to be proportional (in terms of the approach suggested in [3]) to a set of structural characteristics of flake graphite that can be determined experimentally. The empirical expression for this set of structural parameters K_r can be written in the form:

$$K_r = \frac{C_g T_x L_c (d_{002} - d_{g1})}{M L_a (d_{g2} - d_{g1})} \,,$$

where C_g is the extent of graphitization; M is the fraction of graphite-like carbon; T_x is the texturization factor (ordering of crystallites in a flake); L_a and L_c are the size of crystallites along the a and c axes, respectively; D_{002} is the interlaminar separation in a crystallite; and d_{g1} and d_{g2} are the interplanar spacing in ideal graphite and turbostratic pyrocarbon (3.354 and 3.44 Å, respectively).

The above relationship can be used for predicting the reactivity of Ti (and other metals) with flake graphite of varied structure within a wide range of K_r. The obtained data may turn out useful for controlling the processes of shock-assisted and detonation-driven synthesis in solid–solid systems containing flake graphite.

References

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TECHNICAL PROGRAM

IX International Symposium on Explosive Production of New Materials: Science, Technology, Business, and Innovations (EPNM-2008)

May 6–9, 2008
Lisse, the Netherlands

Organized by

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  for Applied Scientific Research (TNO), the Netherlands
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MONDAY, MAY 5, 2008

Arrival of participants

19:00
Welcoming reception at *Golden Tulip Hotel*

TUESDAY, MAY 6, 2008

9:00
Opening ceremony

E. P. Carton	**(the Netherlands)**
Yu. A. Gordopolov	**(Russia)**
P. Korting	**(the Netherlands)**

Section I
Explosive Welding of Metals

9:20–10:00

E. P Carton (the Netherlands)
Defense research and explosive processing of materials

10:00–10:20

J. Banker (USA)
Concentric explosion welded products

10:20–10:40

I. M. Richardson, E. P. Carton, Y. van der Drift,
and H. van der Linde (the Netherlands)
Role of gas in the gap during explosive cladding

10:40–11:00

C. Prothe (USA)
Comparative tensile strength and shear strength of detaclad explosion clad products

11:00–11:20
Break

11:20–11:40

E. P. Carton, M. Stuivinga, F. Schmalz,
and J. G. van der Laan (the Netherlands)
(Hot) explosive cladding of tungsten on copper and stainless steel substrates

11:40–12:00

O. L. Pervukhina, D. V. Rikhter, I. V. Denisov,
and L. B. Pervukhin (Russia)
Some aspects of join formation during
explosive welding

12:00–12:20

S. Tanaka, K. Hokamoto, and S. Itoh (Japan)
Tungsten carbide–aluminum multilayer composites by underwater explosive welding

12:20–12:40

S. V. Kuz'min, V. I. Lysak, and V. A. Chuvichilov (Russia)
Explosive welding: Deformation–time relationship

12:40–13:00

E. A. Chugunov, S. V. Kuz'min, V. I. Lysak, and A. P. Peev (Russia)
Cumulative metal losses during explosive welding of model Al-based composites

13:00–14:00
Lunch

14:00–14:20

V. S. Vakin (Russia)
Optimization of blast characteristics for explosive production
of large-size clad plates

14:20–14:40

S. Yu. Illarionov, L. D. Dobrushin,
and Yu. I. Fadeenko (Ukraine)
New technique for explosive welding of high-strength aluminum alloys

14:40–15:00

R. Mendes, J. Ribeiro, J. Campos, and I. Plaksin (Portugal)
Detonation synthesis of spherical ultrafine nanostructured Al_2O_3

15:00–15:20
Break

15:20–15:40

A. Mori, K. Hokamoto, and M. Fujita (Japan)
Explosive welding of some thin materials onto magnesium alloy using underwater shock wave

15:40–16:00

A. F. Ilyuschenko, A. A. Komorny, V. A. Konoplyanik, I. V. Petrov,
G. V. Smirnov, and A. D. Shuganov (Belarus)
Explosive welding of corrosion-resistant materials with single- or double-sided cladding

16:00–16:20

R. Bański , M. Sozańska, Z. Szulc, and A. Gałka (Poland)
Testing Ti–steel clad metals by thermal loading

16:20–16:40

A. E. Rozen, V. A. Solov'ev, D. B. Kryukov, I. S. Los',
and A. V. Khorin (Russia)
Speckle interferometry as a tool for testing clad metals

16:40–17:00

S. V. Kuz'min, V. I. Lysak, and E. S. Arestov (Russia)
Explosive welding of multilayer packages: Duration of initial acceleration

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K. Tanaka (Japan)
Numerical studies on explosive welding by smoothed particle hydrodynamics

9:20–9:40

S. K. Godunov, S. P. Kiselev, V. P. Kiselev, and V. I. Mali (Russia)
Effect of material microstructure on wave formation under explosive loading

9:40–10:00

A. E. Rozen, I. S. Los', A. Yu. Muizemnek, D. B. Kryukov, and E. G. Troshkina (Russia)
Modeling explosive welding by using LS-DYNA software

10:00–10:20

V. G. Petushkov and L. D. Dobrushin (Ukraine)
A condition for wave formation during explosive welding

10:20–10:40

R. Minev, S. Koev, and N. Festchiev (Bulgaria)
Explosive welding of Ni- and Fe-based amorphous foils for microtooling applications

10:40–11:00

H. H. Yan, X. J. Li, Y. X. Ou, X. H. Wang, G. L. Sun, Y. D. Qu, and X. Y. Qin (China)
Natural strains near weld interface for different collision angles

11:00–11:20
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Section II
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11:20–11:40

Yu. A. Gordopolov, S. S. Batsanov, V. A. Veretennikov, N. G. Zaripov, and L. V. Gordopolova (Russia)
Explosive production of ultrafine-grained materials

11:40–12:00

R. Prümmer and K. Hokamoto (Germany/Japan)
Hot explosive pressing of high-strength and superhard materials

12:00–12:20

A. G. Mamalis (Greece)
Dynamic treatment of particles, from macro- to nanoscale

12:20–12:40

C. Dai, D. E. Eakins, and N. N. Thadhani (USA)
Applicability of analytical models to predicting the Hugoniot of prepressed low-density compacts of iron nanoparticles

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A. A. Shtertser (Russia)
Explosive loading of powdered materials: Basic research and applications

13:00–14:00
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14:00
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T. Sekine (Japan)
Can carbon be incorporated into spinel-type Si_3N_4?

9:20–9:40

V. D. Blank, Yu. A. Gordopolov, A. A. Deribas, V. I. Yukhvid,
G. V. Dubitskii, B. A. Kulnitskii, and V. I. Ratnikov (Russia)
Attempt to obtain B–N–C composite by using SHS and explosion

9:40–10:00

A. G. Mamalis, E. Hristoforou, D. E. Manolakos,
and I. D. Theodorakopoulos (Greece)
Compaction and synthesis of MgB_2 superconductors by explosive techniques

10:00–10:20

V. I. Mali, O. I. Lomovskii, G. V. Golubkova (Russia)
Explosion-assisted synthesis of magnesium diboride

10:20–10:40

A. A. Komorny, A. P. Korzhenevski, I. V. Petrov,
and G. V. Smirnov (Belarus)
Detonation syntheses and consolidation of nanodiamond

10:40–11:00

A. B. Peikrishvili, L. J. Kecskes, and N. M. Chikhradze (Georgia/USA)
Hot explosive consolidation of tungsten–metallic glass matrix composites

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11:20–11:40

A. B. Peikrishvili, L. J. Kecskes, M. V. Tsiklauri, E. Sh. Chagelishvili,
and B. A. Godibadze (Georgia/USA)
Hot shock wave consolidation of WC–NiAl composites:
A structure/property relationship investigation

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S. Y. Stavrev and N. V. Dishovski (Bulgaria)
Nanostructured polymeric materials strengthened with carbon nanoparticles synthesized by detonation

12:00–12:20

J. B. Ribeiro, A. R. Farinha, R. A. Mendes, and M. T. Vieira (Portugal)
Recycling Al-rich byproducts of aluminum surface treatment industries:
Shock-enhanced sinterability of wastes

12:20–12:40

K. Lublińska, A. Szummer, K. Szpila, M. Gloc,
and K. J. K. Kurzydłowski (Poland)
Hydrogen corrosion of the explobond in clad steels

12:40–13:00

K. Hokamoto (Japan)
Improvement of join quality by using underwater explosive welding

13:00–14:00
Lunch

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Explosives and Shock Processing of Materials

14:00–14:20

A. V. Utkin (Russia)
Influence of initial density on the structure of detonation waves
in pressed high explosives

14:20–14:40

H. D. Groeneveld (the Netherlands)
Deformation control in explosive forming

14:40–15:00

L. Andreevskikh, A. Deribas, O. Drennov, A. Mikhailov, N. Titova,
and L. Fomicheva (Russia)
New mix explosives for explosive welding

15:00–15:20
Break

15:20–15:40

Yu. M. Mikhailov, L. V. Ganina, E. A. Ivanova, V. V. Lavrov, and A. V. Utkin (Russia)
Influence of various factors on detonation of composite explosives based on ammonium nitrate

15:40–16:00

L. B. Pervukhin, P. A. Nikolaenko, A. G. Kazantsev, A. D. Chudnovskii, and N. G. Merinov (Russia)
Internal explosive loading of closed vessel

16:00–16:20

L. B. Pervukhin, A. D. Chudnovskii, O. L. Pervukhina, D. V. Rikhter, and A. V. Zaitsev (Russia)
Corrosion-resistant exploclad metals: Properties and production experience

16:20–16:40

X. J. Li, X. Y. Qin, Y. Wang, and H. H. Yan (China)
Behavior of hemispherical explosive chamber in conditions of shock loading

18:00
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Section III

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O. A. Shkoda and N. G. Kasatskii (Russia)
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9:20–9:40

G. M. Sh. Rahman and S. Itoh (Japan)
Effect of underwater shock wave on jute fiber and its characteristics

9:40–10:00

G. B. Kennedy and S. Itoh (USA/Japan)
Processing ZnS-based electroluminescent precursor powder mixtures with TNT

10:00–10:20

L. D. Dobrushin, V. G. Petushkov, A. G. Bryzgalin, J. G. Moon, and Yu. I. Fadeenko (Ukraine/Korea)
Explosion stress relieving in welded joints of metal structures

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Yu. A. Gordopolov, O. L. Pervukhina, and V. S. Trofimov (Russia)
Characterization of products formed in the Zn–S system upon combustion or detonation

10:40–11:00

S. A. Zelepugin, O. A. Shkoda, N. G. Kasatskii, and S. S. Shpakov (Russia)
Synthesis of multilayer composites and optimization of their strength properties

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11:20–12:40
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Closing Ceremony

14:00–15:00
Farewell Party

Departure of participants

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   Strength of aluminum–steel transition joints with rippled interface: Effect of thermal cycling
2. *S. N. Buravova, Yu. A. Gordopolov, I. V. Denisov, and O. L. Pervukhina* (Russia)
   Influence of internal rarefaction waves on explosive welding
3. *E. P. Carton, C. M. Wentzel, M. De Ridder, and J. Krause* (the Netherlands/Belgium)
   Biosealing of a Mars-sample container using explosive welding
4. *A. D. Chudnovskii and L. B. Pervukhin* (Russia)
   Fatigue resistance of explosion clad metals: Probabilistic aspects
5. *V. A. Chuvichilov, S. V. Kuz'min, and V. I. Lysak* (Russia)
   Three-layer composite materials by battery-type explosive welding
6. *V. V. Danilenko* (Ukraine)
   Fusion of diamond in shock waves
7. *I. V. Denisov, O. L. Pervukhina, and L. B. Pervukhin* (Russia)
   Explosive welding of large-sized sheets: Tensile deformation of base sheet
8. *N. A. Denisova, O. L. Pervukhina, L. B. Pervukhin, G. S. Doronin, V. V. Alekseev, and G. Kh. Kim* (Russia)
   Mixture of porous ammonium nitrate with diesel oil for use in industrial-scale explosive welding
9. *R. P. Didyk* (Ukraine)
   High-energy processing of materials: Technologies of the 21st century
10. *L. D. Dobrushin, V. G. Petushkov, and A. G. Bryzgalin* (Ukraine)
    Pressure and deformations formed in metal loaded with explosion of cord explosive charge
11. *O. B. Drennov, A. I. Davydov, A. L. Mikhailov, and V. A. Raevskii* (Russia)
    Shear instability at the explosion product – metal interface for sliding detonation of explosive charge

12. *O. B. Drennov, A. L. Mikhailov, P. N. Nizovtsev, and V. A. Raevskii* (Russia)
    Instability of interface between steel layers caused by oblique shock wave
13. *Y. He and R. Liu* (China)
    Production of clad metals at Baoti Group Ltd.
14. *Z. Jin, C. Dai, and N. N. Thadhani* (USA)
    Fabrication of nanocomposite permanent magnets by shock compaction of powders
15. *S. V. Khaustov, S. V. Kuz'min, and V. I. Lysak* (Russia)
    Explosive welding: Temperature profile of heat-affected zone
16. *S. Koev and R. Minev* (Bulgaria)
    Technological capabilities of BOM Ltd. in explosive forming and joining of metals
17. *A. L. Krivchenko, E. V. Petrov, and R. G. Kirsanov* (Russia)
    Impact of high-speed particles with a metallic obstacle
18. *V. I. Kuz'min, V. I. Lysak, O. V. Strokov, and V. V. Litvinov* (Russia)
    Explosive welding of steel–aluminum composites with an antidiffusion chromium layer
19. *V. N. Lashkov, A. A. Selezenev, A. V. Strikanov, A. A. Tikhonova, and V. I. Rybakov* (Russia)
    Dynamic compaction of iron disilicide powders
20. *X. J. Li, Y. X. Ou, H. H. Yan, Z. Zhao, and Y. D. Qu* (China)
    Preparation of nanostructured TiO_2 particles by gas-phase detonation
21. *A. Nobili* (France)
    Characterization of a titanium–steel explosion bond interface
22. *S. Pauley and C. Toth* (France/USA)
    Effects of heat treatment temperature and time on the properties of titanium/steel and zirconium/steel clad
23. *A. P. Peev, S. V. Kuz'min, V. I. Lysak, and S. V. Khaustov* (Russia)
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24. *A. B. Peikrishvili, L. J. Kecskes, E. Sh. Chagelishvili, and N. M. Chikhradze* (Georgia/USA)
Hot explosive jacketing and strengthening of tungsten heavy and hard alloy rods

25. *A. B. Peikrishvili, L. J. Kecskes, E. Sh. Chagelishvili, B. R. Klotz, G. I. Mamniashvili, and B. A. Godibadze* (Georgia/USA)
Structure and properties of hot shock wave consolidated Cu–W composites

26. *L. B. Pervukhin, P. A. Nikolaenko, A. V. Poletaev, A. G. Kazantsev, and A. D. Chudnovskii* (Russia)
Instrumentation for strain measurements in explosion-loaded closed vessels

27. *O. L. Pervukhina, A. A. Berdychenko, and L. B. Pervukhin* (Russia)
Method of traps for analysis of particles flying out from technological gap

28. *I. M. Peshkov* (Russia)
New model of elastic media: Numerical studies

29. *D. V. Rikhter, L. B. Pervukhin, and O. L. Pervukhina* (Russia)
Effect of initial temperature attained at contact point on explosive welding

30. *A. E. Rozen, I. S. Los', D. B. Kryukov, I. V. Denisov, A. V. Khorin, L. B. Pervukhin, and O. L. Pervukhina* (Russia)
Multilayer clad metals by explosive welding

31. *A. E. Rozen, S. G. Usatyi, and D. V. Karakozov* (Russia)
Explosive deposition of powders onto magnetron targets

32. *A. E. Rozen, S. G. Usatyi, A. V. Pryshchak, and D. V. Karakozov* (Russia)
Sintering of shock-processed powders

33. *I. V. Saikov, L. B. Pervukhin, O. L. Pervukhina, A. S. Rogachev, and H. E. Grigoryan* (Russia)
Fabrication of cermet composites by explosive welding combined with thermochemical synthesis

34. *I. V. Saikov, O. L. Pervukhina, and L. B. Pervukhin* (Russia)
Shock-assisted compaction of AlN-based ceramics

35. *A. A. Selezenev, V. N. Lashkov, A. Yu. Aleinikov, O. G. Sin'kova, and Yu. V. Yanilkin* (Russia)
    Dynamic compaction of fine iron disilicide powders:
    Numerical simulation
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    Dynamic viscosity of metals: Experimental determination
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37. *A. A. Shtertser, V. Yu. Ul'yanitsky, S. B. Zlobin, B. S. Zlobin, A. I. Popelukh, and V. A. Bataev* (Russia)
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    Cylindrical camera for explosion-driven synthesis of new materials
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40. *V. V. Sil'vestrov, A. V. Plastinin, and S. M. Karakhanov* (Russia)
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42. *V. A. Veretennikov* (Russia)
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