ECAP is an innovative process capable of producing uniform plastic deformation in a variety of materials, without causing significant change in geometric shape or cross section. Multiple extrusions of billets by ECAP permit us severe plastic deformation in bulk materials associated with significant grain refinement down to the nanometric scale. Many advantages were found with ECAP in an attempt to develop different structures with the same chemical composition; a variety of microstructures with equiaxed, laminar, and fibrous textures can be created.

Key Words: nanostructure, nanomaterial, nanotechnology, extrusion, plastic forming, ECAP, SPD, grain boundary, ultra-fine grain, fatigue, Titanium, die, simple shear

1. Introduction

The ECAP (Equal Channel Angular Pressing) method is a state-of-the-art plastic processing method that enables a relatively large piece of material to have such uniform severe plastic deformation that refines the grain size from the submicron to nanometric order while enabling the pre-process cross-sectional form to be maintained after the process. Another feature of this process is that it facilitates rearrangement of the microstructure to create an equiaxial, laminar or fibrous texture. Beginning with a brief review on current recognition concerning nanomaterials, this paper will discuss the principles, problems and future potentials of the ECAP method.

2. Study of Nanomaterials in Nanotechnology

In November 1993, then U.S. President Bill Clinton established the National Science and Technology Council (NSTC) as a "virtual" governmental organization to orchestrate government policies in the areas of science, space development and technology. Establishing and chairing it himself, he is said to have contributed much to collaboration between the research and development facilities in the United States. The "Interagency Working Group on Nanoscience, Engineering and Technology" was one of the subdivision of this organization and they published a paper describing the "Nanotechnology Research Directions for Coming 10 Years". The first paragraph of the Executive Summary of this publication, shown below, succinctly describes "Nanotechnology" and "Nanostructures."

"Nanotechnology is the creation and utilization of materials, devices, and systems throughout the control of matter on the nanometer-length scale, that is, at the level of atoms, molecules, and supramolecular structures. The essence of nanotechnology is the ability to work at these levels to generate larger structures with fundamentally new molecular organization. These "nanostructures," made with building blocks understood from first principles, are the smallest human-made objects, and they exhibit novel physical, chemical, and biological properties and phenomena. The aim of nanotechnology is to learn to exploit these properties and efficiently manufacture and employ the structures."

This implies that if nanotechnology is applied to materials, it is feasible to control the material structure on the nanometer-length scale, or at the level of atoms and molecules, and thereby to create unprecedented material properties and radical improvement in material function. In this paper, discussion will be focused on the mechanical properties of nanomaterials.

3. Grain Refining Methods and Nanomaterial

Before discussing ECAP, the author would like to assert the importance of grain refinement in "nanostructurization" of metallic materials.

3. 1 Strength Enhancement by Grain Refinement

3. 1. 1 Mechanical Properties of Refined Polycrystalline Materials

In the development of a new metallic material, it is required to provide it with high functionality. It is a matter of course that, for the sake of safe, reliable life and ecology, recycling of resources, energy saving and efficient production of material are imperative. That is to say, "using minimum necessary amount of material" is most important. Given the task of
ensuring material strength and safety while using a small amount of material, the only answer is to improve the mechanical properties of the material.

In order to strengthen a metallic material, the first approach commonly taken is "chemical structural improvement," by such methods as making solid solutions by alloying, precipitation and dispersion hardening, that is then improved by further refinement of the grain through variously contrived work-hardening and heat-treatment methods. The strength of polycrystalline material increases with the reduction of grain size. In many materials, the following relationship between the yield stress, \( \sigma \), and the average grain diameter, \( d \), stands,

\[
\sigma = \sigma_0 + k d^{1/2},
\]

where, \( \sigma_0 \) and \( k \) are constants depending on materials. This equation is referred to as "Hall-Petch equation." The reason why the smaller grain size makes the material stronger is that a smaller unit of sliding deformation required more intensive external stress to movement and multiplication of dislocations, as well as that more intensive resistance is provided from the grain boundary.

Refinement of grain not only brings about the effect of increasing strength, it also gives rise to significant collateral improvement in the areas of corrosion, and stress-corrosion cracking as well as in fatigue strength, or crack propagation and rapture. This can easily be explained by the fact that, in many metallic materials wherein generation and propagation of corrosion and cracks are localized at the grain boundary, dispersion from localization of these defects is more likely with smaller grain sizes. Traditionally, grains have been normally refined through repetition of plastic process and recrystallization. It has generally been difficult to generate grain sizes smaller than 1 micron, hence there have been difficulties to produce nano region materials in bulk form (Note 1).

### 3.1.2 Volume Ratio of Grain Boundary in Nanostructured Materials

There exists a disordered region ("grain boundary") between crystalline grains. While the thickness of this region depends on its structure, it has been known that a grain boundary with a large misorientation is generally equivalent to 3~4 atoms. Figure 1 shows the babble raft model of a crystalline grain boundary that the author worked out, a quarter of a century ago, with the use of soapy water. Incidentally, the inventor of the babble raft model was Sir Laurence Bragg, who upgraded the babble raft model up to the atomic arrangement model of metal crystals and won the Nobel Prize with his father, Henry, for formulating the Bragg conditions concerning X-ray interference. Sixty years ago, ten years before an announcement of direct observation of dislocation by means of a transmission electron microscope, this babble raft model played an important role in structural analysis of crystal lattice defects, dislocations, stacking faults and grain boundaries. Since the interpair potential of babble is approximately the same as that of a metal, the babble model has subsequently been actively used more often than before in the study on the structure of grain boundaries, being found useful in predicting atomic arrangement therein. Nowadays, that predicted atomic arrangement has been found to be not substantially different from that observed by the high-resolution transmission electron microscope (HRTEM). Therefore, the reader may reliably observe this babble raft model that simulates the world of nanometers in one million times magnification. If you have a careful look at it tilting the page, you can identify the grain boundary formed by bending of the raft and imperfect portions (Note 2).

![Fig. 1 Crystalline grain boundary & triple points by means of babble raft model](image)

Actually, in the polycrystalline substance, there exist, besides this grain boundary, "boundary triplet" which is an intersection of boundaries and a quadruple point which is an integration of four boundary triplets. With reduction of grain size, the volume ratio of boundary defects, grain boundary, grain boundary triplets and quadruple points to total volume increases. For example, supposing that the grain sizes are 1 000 nm, 100 nm and 10 nm, with the grain boundary as thick as 1 nm, the volume ratio of boundary defects are 0.3%, 3%, and 20%, respectively. In case of the grain size 5 nm, the ration reaches even 50%. That is the very reason why properties of the bulk material with nanostructures are governed to a large extent by diffusion of atoms along the grain boundary as well as by the growth behavior of the grain. Taking hardness for example, its increasing tendency with reduction of grain size subsides (saturate) in the vicinity of 10 nm, and below that grain size level, the tendency represented by the Hall-Petch equation has been observed to be reversed. This phenomenon has been explained by the boundary sliding and rotation of the grains.

---

Note 1: Generally, the nanostructured material refers to the material in which crystal grain size is approximately 2 nm~100 nm. Remember that 1 nm corresponds to a low of 4 atoms based on the lattice constants of metals. On the other hand, the submicron material refers to those having polycrystalline grain of several hundred mm to 1 \( \mu \) m. Sometimes, the material with grain size of 200 nm~300 nm is referred to as the "nano region material."
In addition, it has been known that when the grain size is reduced to a nanometer level, the dislocation is sucked into the grain boundary, leaving the grain free of dislocation. In this sense, each individual grain is a perfect crystal. Strength of the perfect crystal is approximately one-tenth of shear modulus (G) and in the order of 10 GPa depending on the metal. Thus, the bulk material having crystalline grain of several nanometers is analogous to “a box in which hard glass balls are packed up with amorphous fillers.”

3.2 History of Nanomaterials

3.2.1 First Nanocrystalline Materials

(H. Gleiter 1985)

Back in 1986, at the international conference on the “Structure and Characteristics of Crystalline Grain Boundary” held at Minakami Spa in Gumma Pref., the first report of nanomaterial was announced as an invitation lecture. The principle was simple. Professor Gleiter of Saarbrucken University had vaporized metal collide on the outer wall of a vessel refrigerated by liquid nitrogen in a vacuum chamber, then the solidified and descended crystals were compressed by a small press machine equipped on the bottom of the vacuum chamber to create a button-shaped nanomaterial with crystalline grain sizes of 5 nm to several tens of nm. This method, the so-called Vapor-Solid-Inert Gas Consolidation (IGC) Method, could not avoid formation of voids in the boundary area. This problem and the difficulty of producing large-sized material combined to make it hard to apply this method to “structural material.” Nevertheless, it is still fresh in our memory that, in those days, each time a new finding of unprecedented “material physical property value” was published, it served as a shot in the arm in the field of solid-state physics. Taking that opportunity, the Nanotechnology Laboratory (http://www.fzk.de/) was founded, wherein Professor Gleiter has served as the leader in the discipline of nanostructured materials.

3.2.2 Electrochemical Plating

(U. Erb and G. Palumbo)

Erb, who was one of protégé of professor Gleiter, has a job in the Queen’s University in Canada after receiving his doctorate. As he had been annoyed by the limitation of the size of materials that could be produced by the IGC method, he had been searching for an alternative method, and finally succeeded in production of nanomaterial by means of pulse current plating. He then became the successor of Professor K. Aust of the University of Toronto, who was an authority in the study of grain boundaries. Erb and Palumbo, a protégé of Aust, worked diligently on nanomaterials by electroplating after arriving in his post in University of Toronto. In the middle of 1990s, they eventually established the technology for production of various nickel nanomaterials ranging from sheets in 0.1mm order of thickness to plates thicker than 10mm. They then founded Integran Corp. (http://www.integran.com/), with Palumbo as president, funded by Ontario Power Generation. Integran Corp. has been a successful example of a graduate-school-originated developmental venture business, which is now employing about ten researchers who received doctor degree from the University of Toronto. Although the use of electrodeposition is effective for limited kinds of material, it has created bulk material with as small grain size as several nms. Commercially, the company has succeeded in putting on the market various epoch-making products ranging from long-life drill bits with nanocrystal grain coating to on-site repair of cracked coolant pipes in nuclear power plant.

Incidentally, when we interviewed Professor Erb on industry-academy collaboration, the first words he voiced were, “Since several years ago, the Ontario State government has launched a program that allows the government to subsidize private firms that hire researchers with Ph. D. from a College. This subsidy amounts to half of the salary for the applicable researcher for certain period of time.”

3.2.3 ECAP Method

ECAP is a plastic processing method invented in 1977 in the Soviet Union by Dr. Vladimir Segal and patented in the U. S. S. R.10–14 Later on, Segal moved to the U. S. A. where he obtained numerous patents for the design of dies to apply the method to a wide variety of materials.15 The essence of the ECAP method is that an extremely high draft is attained by extruding the material through angled, parallel bore dies. Repetition of this process turns out ultrafine crystalline grains, ranging from 200~300 nm down to 50 nm. By selecting the inserting direction of the billet through the dies, either an equiaxed crystal can be created or a texture created. Moreover, this method is useful for pressure welding of powder metals, and it is also used for reinforcing plastics.

Through perestroika and the collapse of the Soviet Union, Russian researchers transaction with not only Western but also Japanese research communities and universities improved dramatically. In those days, R. Valiev, an enthusiastic young researcher, who represented Russian research in the super plasticity and grain boundaries, visited Japan frequently. The laboratory in Kyoto University, to which the author belonged then, was joined by a Russian resident researcher, A. Vinogradov, under the sponsorship of the Japanese government. On his return from a short home visit, he delivered a 100mm dia. × 10 cm long copper "bar" gift from Valiev. We were amazed to see this sample, particularly when we heard the explanation about the manufacturing principle. We had been apprised of numerous Russian inventions.

Note 2: From around 1970, a study of the atomic arrangement in the crystalline grain boundary became prevalent world over, with many solid-state physicists working for solutions to succeeding problems from point defects in crystal to line defects and to this problem, or the final chapter of lattice defect conundrum. In Japan, the late Youichi Ishida, professor of Tokyo University, was the leader in crystalline grain boundary studies and the forerunner in observation of atomic arrangement and microstructure by a high-resolution electron microscope. Until the mid-1970s, there has not been a clear model for prediction and analysis of orderly/periodic atomic arrangement in grain boundary with large variation in orientation. Ishida made a big success in building such a model by resorting to the babble raft model precisely controlled and produced. In his last retirement lecture, he stated reflectively, “In the final analysis, there is no a substantial difference between the atomic arrangement observed directly by an electron microscope and that emanating from the babble raft model.”
stemming from innovative ideas that could not be found in Western Europe. In an attempt to best the free world, Russian researchers pursued the ultimate by any means, setting aside economy, market or cost. We could not help but respect the technology that had been cultivated in such circumstances.

Around that time, Valiev was invited to France by professor Baudelet, who counseled me, to visit the Institut National Polytechnique de Grenoble to introduce the ECAP method. That was ten years ago.

A nano region material can also be produced by the compression-torsion method, which applies powerful deformation to the material by a combination of compression and torsion, although it can produce only a thin disc. Such a plastic process involving intensive deformation is generally called "severe plastic deformation (SPD)." In the conferences of Japan Institute of Metals in recent years, sessions on this theme have been one of the most audience attracting ones. The first international conference was the NATO Conference in Moscow in 1999, followed by international conferences almost every year, see Appendices 1.

4. Strength of ECAP Processed Material

Table 1 shows Vickers hardness Hv, yield stress $\sigma_{0.2}$, and tensile strength $\sigma_{UTS}$ of a material refined by the ECAP process.

Compared to comparable commercial materials, those produced by the ECAP method have 2~3 times higher strength. For instance, the Au alloy shown in Table 1 is the K18 alloy most extensively produced for eyeglass frames and ornaments. Experiments in our laboratory have shown that with normal aging treatment, hardness of Hv 345 and yield stress of more than 1 GPa are attainable.\(^{21,22}\) Embrittlement can be reduced if the ECAP processing is followed by short annealing at an appropriate temperature that does not cause the grain growth. In addition, in the case of alloys that are amenable to precipitation dispersion hardening following ECAP, it is possible to enhance the thermal stability of the processed material because such after-processing can effectively preclude grain boundary movement and grain growth.\(^{23}\)

As mentioned in 3.1.1, such metal reinforcement methods as solid solution hardening, work hardening and precipitation hardening are generally accompanied by reduction of ductility and toughness. On the other hand, grain refinement allows strengthening of material while maintaining ductility and toughness to a certain extent. As to the reason for this property, various hypotheses are under discussion, such as that which supports that because grain refinement extremely increases the relative volume of the boundary atomic layer, boundary sliding, which normally takes place at high diffusion rate at high temperatures, can happen at relatively lower temperatures.

Table 1 Strength of ECAP processed material

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Hv</th>
<th>$\sigma_{0.2}$ MPa</th>
<th>$\sigma_{UTS}$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$-Fe</td>
<td>ECAP</td>
<td>300</td>
<td>850</td>
<td>980</td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
<td>90</td>
<td>200</td>
<td>350</td>
</tr>
<tr>
<td>Cu (99, 98%)</td>
<td>ECAP</td>
<td>155</td>
<td>400</td>
<td>480</td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
<td>55</td>
<td>100</td>
<td>240</td>
</tr>
<tr>
<td>Ni (99, 86%)</td>
<td>ECAP</td>
<td>310</td>
<td>600</td>
<td>920</td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
<td>70</td>
<td>170</td>
<td>400</td>
</tr>
<tr>
<td>Pure-Ti</td>
<td>ECAP</td>
<td>280</td>
<td>650</td>
<td>810</td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
<td>180</td>
<td>250</td>
<td>380</td>
</tr>
<tr>
<td>AA5056</td>
<td>ECAP</td>
<td>148</td>
<td>392</td>
<td>440</td>
</tr>
<tr>
<td></td>
<td>O-temper</td>
<td>72</td>
<td>150</td>
<td>290</td>
</tr>
<tr>
<td>Fe-36%Ni (INVAR)</td>
<td>ECAP</td>
<td>300</td>
<td>820</td>
<td>850</td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
<td>120</td>
<td>280</td>
<td>460</td>
</tr>
<tr>
<td>Fe-45%Ni (ELINVAR)</td>
<td>ECAP</td>
<td>360</td>
<td>1 540</td>
<td>1 650</td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
<td>120</td>
<td>760</td>
<td>930</td>
</tr>
<tr>
<td>Au12.5Ag12.5Cu (K18)</td>
<td>ECAP</td>
<td>270</td>
<td>–</td>
<td>880</td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
<td>155</td>
<td>–</td>
<td>550</td>
</tr>
</tbody>
</table>

Hv: Vickers hardness, $\sigma_{0.2}$: Yield stress, $\sigma_{UTS}$: Tensile strength

5. Fatigue Strength\(^{46,47,22}\)

Our study group in 1997 became the first to investigate in the fatigue properties of ECAP-processed copper. In this study we found that ECAP-processed material is subject to remarkably greater magnitude of the Bauschinger effect in repeated deformation than ordinary material.\(^{21}\) In this paper, a brief explanation is offered on the fatigue deformation of pure titanium with average crystalline grain size of 300 nm. Figure 2 shows the microstructure of ECAP-processed material by a transmission electron microscope. Although the details are reported in a separate paper, the bright view on the left and diffraction pattern indicate dominance of a high-angle grain boundary. The dark view at the center shows some low-angle grain boundary still remaining. Inside the grain, almost no dislocation is observed, although the high magnification view on the right reveals stripe patterns inside the grain, which is characteristic of high internal stress.

Fig. 2 Observation of ECAP processed Ti by transmission electron microscope
Figure 3 shows an S-N diagram (Note 3) obtained by high cycle fatigue deformation of this material. According to the data, it is found that fatigue boundary jumped to twice as high by the ECAP process. Today, development of pure Ti, which has fatigue strength equal to Ti-6Al-4V alloy, has been carried out by cold forming after ECAP processing so that the new material is expected to be applied for medical uses in replacement of Ti alloy, which has toxicity from element addition that causes worry over possible influence on the human body.

Study on low cyclic fatigue strength such as involving plastic strain amplitude of 10^{-3}~10^{-2} was also conducted. If fatigue test data on various material are plotted on a log-log diagram with the vertical axis for strain amplitude and horizontal axis for the number of cycles until failure, straight-line relationship can be obtained on many materials. This is the law of Coffin-Manson, which stands on the ECAP-processed materials, too. With conventional structure reinforcement methods on alloys, the low cycle fatigue life will always be drastically reduced due to significant loss of ductility. When it comes to the ECAP-processed material, although its fatigue life is shorter than that of an annealed standard material, it has been ascertained that the fatigue life can be improved to the level equivalent to that of standard material by applying optimum annealing after ECAP processing.

6. Practical ECAP Processing Technology

An outstanding feature of the ECAP process is that it makes the best use of simple shearing deformation, which makes uniform deformation possible with relatively low pressure and low load without changing the shape of billet. The principle of ECAP processing is shown in Fig. 4. While a piece of material coated with lubricant is forced through the center of dies crossing at an angle, the material is subjected to virtually uniform shear deformation at the bending. In the case of 90° bending angle of the dies, one pass of ECAP processing generates simple shear deformation by a factor of 2 (200%). Furthermore, this process can be repeated with the same dies with resultant simple shear deformation increasing in proportion to the number of repetition. In addition, it is possible to change the direction of shear deformation by rotating the billet at the time of inserting it into the dies.

Horita et al. have published a report in detail about the processing deformation and the processing channel, which is recommended for reading.

If deformation at bending is effected uniformly, the processed material remains intact. However, if deformation is uneven, the processed billet may have micro- or macro-ruptures. In order to avoid such defaults as well as to attain an ideal ECAP method, it is essential to design the dies properly. Figure 5 shows the simplest laterally split dies, while Fig. 6 is an example of vertically split right-angled dies. In the former case, the bent corner is provided with radius to avoid damage on the dies. Because of this radius, however, the billet does not have simple shear deformation in a strict sense, but suffers disturbance at both sides of the bending corner, which results in the uneven distortion as shown in Fig. 7 (b) and (c). In the latter case, an attempt was made to realize an ideal shear deformation by crossing the channels at right angle and dispensing with radius on the corner. As a result, the virtually uniform deformation shown in Fig. 8 was attained. It has also been found that an ideal shear deformation can be obtained by application of back pressure at the exit of the channel. However, this method involves the problem of cracking of the dies at the bends due to extremely high stress concentration there.

Note 3: The high cycle fatigue strength of material is normally expressed by a curve on a graph with stress, S, on the vertical axis and number of cycles to failure, N, on the horizontal axis. This curve is called the "S-N curve." In the case of steel like carbon steel, the S-N curve has a bent-up point from which it levels off, i.e. no failure is expected no matter how many cycles of that magnitude or lower stress are repeated. The maximum stress at which this S-N curve levels off is called the "fatigue limit" or "endurance limit." Normally, this bent-up point (called the critical number of cycles) is deemed to lie within the range of 10^6 to 10^7 cycles.
The above findings have shown that design of the dies at the bends is very important for efficient ECAP processing. The following are the points to be taken into account in the design of the dies:

1) Configuration and dimensions of the channel
2) Radius on the bending corner of the channel
3) The angle between the channels
4) Reverse pressure condition to assure simple shear deformation in the channel
5) Reduction of friction between the billet and the internal contact surfaces of the channel

Item 5) is particularly important in the case of such hard materials as titanium, titanium alloy and iron, to reduce energy consumption as well as to prevent the billet and the dies from being damaged. The following considerations are for reduction of friction between the billet and the dies contact surface:

6) It is important to select the die material depending on the type of channel as well as to use such lubricant that ensures smooth passage of the billet through the channel.
7) A moving dies system, like the example shown in Fig. 9, is effective. As it incorporates a mechanism that allows major parts of the dies to move along with the billet (i.e. without relative sliding movement), substantial reduction of friction between the billet and the internal contact surface of the channel is possible, and therefore it is expected to help processing with lighter load.

Besides these, it should also be noted that some materials are amenable to ECAP processing at high temperatures, and that easiness in removing processed billet from the channel should be taken into consideration. For industrial application of ECAP technology in prospect, there still remain many technological problems yet to be solved. As a matter of fact, however, there has been an example of commercial use of ECAP in Russia, as shown in Fig. 10. This is a principle diagram of continuous ECAP processing that can apply simple shear process to a long material.
great assistance in preparation for this paper.

express gratitude to associate professor A. Vinogradov for his

subject of technological research. Finally, the author wishes to

collaborative study with Koyo Seiko, would be an interesting

surface hardening by multi-layer-nanoplating, which is under

mentioned in

the same time, combination with those other nanotechnologies

higher processing speed, higher reliability and lower cost. At

technology through development of simpler dies designs,

automotive components, have not yet been considered. It is

applications of ECAP for high-volume production, like

moment, R & D efforts have been concentrated on high-value

processing, ultrafine grain materials can be obtained. At this

for condensing powder metals. By recrystalizing after ECAP

functionality components. Furthermore, ECAP is instrumental

components as well as in aircraft and ships demanding high

Titanium alloys, on the other hand, have numerous potential

instance, commonly used biomedical titanium alloy Ti-6Al-

4V is being replaced by ECAP-processed pure titanium.

A wide variety of applications are being considered for

ECAP-processed metals and alloys. In the medical fields, for

instance, commonly used biomedical titanium alloy Ti-6Al-

4V is being replaced by ECAP-processed pure titanium.

Titanium alloys, on the other hand, have numerous potential

applications in racing cars which require light and strong

components as well as in aircraft and ships demanding high

functionality components. Furthermore, ECAP is instrumental

for condensing powder metals. By recrystalizing after ECAP

processing, ultrafine grain materials can be obtained. At this

moment, R & D efforts have been concentrated on high-value

added applications without much cost constraint, whereas

applications of ECAP for high-volume production, like

automotive components, have not yet been considered. It is

hoped that this process will evolve into more refined

technology through development of simpler dies designs,

higher processing speed, higher reliability and lower cost. At

the same time, combination with those other nanotechnologies

mentioned in 3, 2, 2, such as electrochemical nano-plating and

surface hardening by multi-layer-nanoplating, which is under

collaborative study with Koyo Seiko, would be an interesting

subject of technological research. Finally, the author wishes to

express gratitude to associate professor A. Vinogradov for his

great assistance in preparation for this paper.

References

1) “Nanotechnology Research Directions”, eds. M. C. Roco et


2) A. Vinogradov, T. Mimaki, S. Hashimoto, and R. Z. Valiev,


3) H. Miyamoto, T. Mimaki, A. Vinogradov and S.


4) S. R. Agnew, A. Vinogradov, S. Hashimoto and J. R.


5) A. Vinogradov and S. Hashimoto, Mater. Trans. JIM, 42


(1986) 43.


10) V. M. Segal, V. I. Reznikov, A. E. Drobotsevskiy, and V. I.


11) V. M. Segal, V. I. Reznikov, V. I. Kopylov, D. A. Pavlik,

V. F. Malyshiev, Processes of Plastic Structure Formation of


15) V. M. Segal, R. E. Goforth, and K. T. Hartwig, US. Patent


16) R. Z. Valiev, R. K. Islamgaliev and I. V. Alexandrov,


17) T. Suzuki, A. Vinogradov and S. Hashimoto: Journal of


18) T. Suzuki, A. Vinogradov and S. Hashimoto, Mater. Trans.,


19) A. Vinogradov, V. Patlan, Y. Suzuki, K. Kitagawa and V. I.


20) A. Vinogradov and S. R. Agnew, “Nanocrystalline

Materials: Fatigue, DekkerEncyclopedia of Nanoscience


21) A. Vinogradov, Y. Kaneko, K. Kitagawa, S. Hashimoto, V.


22) A. Vinogradov, V. Stolyarov, S. Hashimoto, R. Valiev,


23) V. Patlan, A. Vinogradov, K. Higashi and K. Kitagawa,


24) Z. Horita, M. Furukawa, T. G. Langdon and M. Nemoto:


25) V. I. Kopylov, Application of ECAP-technology for

producing nano-and microcrystalline materials, in

Investigations and Applications of Severe Plastic

Deformation, eds. T. C. Lowe and R. Z. Valiev, NATO ASI


Supplement 1) Conferences

2) NANO-2000, Orlando, USA.
10) 2nd International Conference on Nanomaterials and Nanotechnologies, June 14-18, 2005, Crete, Greece.
12) The Joint Conference of HSLA Steels’05 and ISUGS 2005, including a symposium: Ultrafine Grained Steel, November 8-10, 2005, Sanya, China.

Supplement 2) Books and Reviews on SPD


Supplement 3) Commercialized Applications

1) Al, Au, Co, Cu, Mo, etc., targets for ion sputtering. Johnson Matthey Electronics.

Supplement 4) R&D Groups

<table>
<thead>
<tr>
<th>Institution</th>
<th>Investigator(s)</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC Seibersdorf research GmbH</td>
<td>Leonhard Zeipper, Georg Korb, Wolfgang Lacom</td>
<td>Austria</td>
</tr>
<tr>
<td>Chungnam National University</td>
<td>Hyoong Seop Kim</td>
<td>Korea</td>
</tr>
<tr>
<td>Clausthal University of Technology</td>
<td>Y. Estrin</td>
<td>Germany</td>
</tr>
<tr>
<td>Dresden Technical University</td>
<td>E. Thiele, D. Skrotski</td>
<td>Germany</td>
</tr>
<tr>
<td>Hanbat National University</td>
<td>Kyung-Tae Park</td>
<td>Korea</td>
</tr>
<tr>
<td>Hanyang University</td>
<td>Dong Hyuk Shin</td>
<td>Korea</td>
</tr>
<tr>
<td>Kyushu University</td>
<td>Zenji Horita</td>
<td>Japan</td>
</tr>
<tr>
<td>Los Alamos National Laboratory</td>
<td>T. C. Lowe, Yuntian T. Zhu</td>
<td>USA</td>
</tr>
<tr>
<td>Monash University</td>
<td>Rimma Lapovok</td>
<td>Australia</td>
</tr>
<tr>
<td>Nanjing University of Science and Technology</td>
<td>Jingtao Wang</td>
<td>China</td>
</tr>
<tr>
<td>Ufa State Aviation Technical University</td>
<td>Ruslan Z. Valiev, Igor Alexandrov, Vladimir Stolyarov, Georgy Raab</td>
<td>Russia</td>
</tr>
<tr>
<td>Moscow Institute of Metals</td>
<td>S. Dobatkin</td>
<td>Russia</td>
</tr>
<tr>
<td>Tomsk University</td>
<td>E. Kozlov, N. Koneva</td>
<td>Russia</td>
</tr>
<tr>
<td>Togliatti University</td>
<td>A. Vikarchuk</td>
<td>Russia</td>
</tr>
<tr>
<td>Institute for Superplasticity Problems</td>
<td>R. Kaibyshev, A. Markushev</td>
<td>Russia</td>
</tr>
<tr>
<td>University of Southern California</td>
<td>Terence G. Langdon</td>
<td>USA</td>
</tr>
<tr>
<td>University Wien</td>
<td>Michael Zehetbauer</td>
<td>Austria</td>
</tr>
<tr>
<td>Doshisha University</td>
<td>Takuro Mimaki, Hiroaki Miyamoto</td>
<td>Japan</td>
</tr>
<tr>
<td>Kanazawa University</td>
<td>Kazuo Kitagawa</td>
<td>Japan</td>
</tr>
<tr>
<td>Osaka Prefecture University</td>
<td>Kenji Higashi</td>
<td>Japan</td>
</tr>
<tr>
<td>Tokyo University of Electric Communication</td>
<td>Hiromi Miura</td>
<td>Japan</td>
</tr>
<tr>
<td>Osaka City University</td>
<td>S. Hashimoto, A. Vinogradov, Y. Kaneko</td>
<td>Japan</td>
</tr>
</tbody>
</table>