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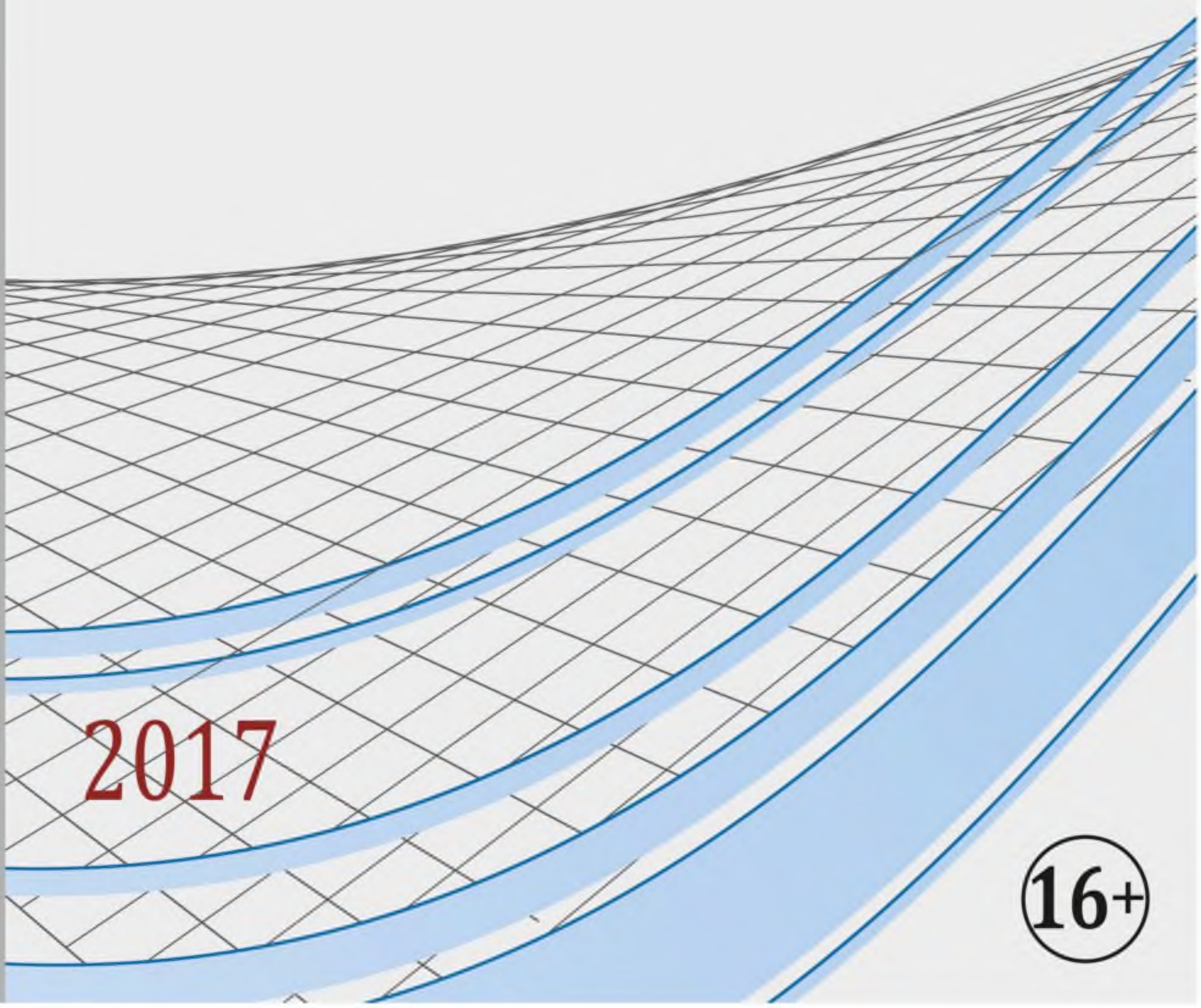

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RECENT PROGRESS OF EXTERNAL FIELD PROCESSING TECHNOLOGY IN CHINA*

1. Introduction

The properties of materials and plastic deformation usually can be modified when it is exposed to a specific field. The common external field is composed of electric field [1], magnetic field [2], and ultrasonic field [3], as well as combinations, etc. For example, electropulsing, as an instantaneous high-energy input method, has been applied for enhancement of the plasticity of metallic materials. It not only can reduce the deformation resistance, but also can reduce a large number of defects to improve the surface quality of metals, which is especially applicable to the materials that are difficult to deform. In the early 1960's, a number of investigations have shown that except electronic properties, mechanical properties such as the flow stress, creep rate and stress relaxation also undergo a change, a decrease in the flow stress and an increase in the creep rate and stress relaxation, occurring upon going from the normal to the superconducting state [4].

In China, most of researchers focused on the electromagnetic casting in the liquid forming and electric-pulse assisted plastic deformation in the solid forming. The direct chill casting with electromagnetic stirring has been a main method for producing the semi-solid billets on a commercial scale due to its non-pollution, easy control and continuous production [5, 6]. Low frequency electromagnetic casting (LFEC) is the attracted one among electromagnetic casting compared to conventional casting methods. LFEC was developed by Cui et al [7, 8], in which the low skin effect of low frequency electromagnetic field is used to control the macro-physical fields in the casting process. External field has long been employed to assist the deformation and control the microstructure of metallic materials since the discovery of electroplastic effect [9]. In the past several decades, researches on the influence of external field on the homogenization [10], solid solution [11], aging [12], recovery and recrystallization [13-15] behavior of metals and alloys have been carried out by many scientists. Recently, Tang et al have dedicated to apply the complex external fields to improve the surface quality and enhance the mechanical properties by means of surface modification. This is greatly expanded the application of external field processing in manufacturing.

In the following a review about the external field processing is presented. After a description of the process principle and process variants mentioned in the literature (see Section 2), information about basic research considering the process analysis and examples is given in Section 3.

2. Principle of the external field processing

Electromagnetic casting

Electromagnetic casting (EMC) is a special semi-continuous process. The absence of contact with the mold eliminates mechanical defects on the surface of the ingot, so the EMC ingots have a very smooth and uniform surface irrespective of the dimensions and the alloys. During the EMC process, the Joule heating produced by the induced currents will heat the metal and obviously influence the temperature field of EMC. There are main two reasons: heat transport and solidification in electromagnetic casters. The function of shape control is based on the magnetic pressure given as $P_m = B^2/2\mu$.The function of fluid driving is induced by imposing a direct electric current and a magnetic field, $F = JB$, or by imposing a traveling

* **Acknowledgements.** GT acknowledges to the financial support from the National Science Foundation of China (Grant No. 50571048).

magnetic field (TMF) [16]. The function of flow suppression appears when applying a direct magnetic field on moving molten metal, based on the principle of $F = \sigma(v\mathrm{B})B$. The function of levitation appears when the gravity force balances with the electromagnetic force, $JB = \rho g$. When electromagnetic force is much larger than the gravity force or the adhesion force due to surface tension, $JB > \max\{|\rho g|, 6\sigma/a^2\}$, the function of splashing takes places. The Joule heat, $q = |J|^2/\sigma$, indicates the function of heat generation. Regarding a magnetization force given as $(\chi/\mu)(B\cdot\nabla)B$ and MB, which is familiar to us as the force to attract iron to a magnet, the functions of crystal orientation and alignment of solidified structures are useful in the materials processing.

The geometry of the solidification front, along with the thermal gradient, determines ingot structure, including the microstructure and segregation, in this technology, as in other casting technologies. From electromagnetic theory [17], the skin depth of the induced currents can be calculated by means of Eq. (1):

$$\delta = \sqrt{2/\mu\sigma\omega}\,, \qquad (1)$$

where μ is the magnetic permeability, σ, the electric conductivity, and $\omega = 2\pi f$, where f is frequency applied in the process. In addition, the relationship between the induced currents and the skin depth is derived from the following equation:

$$I = \mathrm{e}^{-\frac{y}{\delta}} I_0\,, \qquad (2)$$

where I is the induced current inside the ingot, y, the distance from the surface to the center of the ingot, δ, the skin depth, and I_0, the maximum induced current on the surface of the ingot.

Electroplastic forming

The idea that the electrons in a metal exert a drag on dislocations, is now generally accepted [1]. The electron drag coefficient B_e is given by the following expression:

$$(f/l) = \tau b = B_e v_d, \qquad (3)$$

where (f/l) is the force per unit length acting on the dislocation, τ is the resolved shear stress, b the Burgers vector and v_d the dislocation velocity.

The other is that drift electrons in a metal may assist dislocations in overcoming obstacles to their motion; i.e. that drift electrons can exert a push or «wind» dislocations, in contrast to drag. That moving electrons in a metal crystal may interact with the dislocations therein was first reported by Troitskii and Lichtman [18].

Theoretical considerations of the force exerted by drift electrons on dislocations are put forward by Kravchenko [19] and Klimov [20] et al. In these considerations, the force due to drift electrons is proportional to the difference between the drift electron velocity v_e and the dislocation velocity v_d. Further, the theory indicates that the electron wind force f_{ew}/l is proportional to the current density, i.e.

$$\tau_{ew} b = K_{ew} J, \qquad (4)$$

where τ_{ew} is the stress acting on the dislocation due to an electron wind, b the Burgers vector, K_{ew} the electron force coefficient and J the current density.

The value of the electron push (drag) coefficient B_{ew} given by:

$$B_{ew} = \tau_{ew} b / v_e = K_{ew} en, \qquad (5)$$

where e is the electron charge and n the electron density. Computer calculations indicated that the plastic flow associated with the stress drop could be explained by assuming the existence of an electron-dislocation interaction stress with added to the applied thermal component of the flow stress in providing thermally-activated plastic flow. Therefore, in addition to the force exerted on the dislocations by an electron wind, the drift electrons also had an effect on one or more of the other parameters of the thermally-activated rate equation.

3. Process analysis

Electromagnetic casting

A comprehensive mathematic model was developed by Tang [6] et al, to describe the interaction of the multiple physics fields (electromagnetic field, fluid flow, heat transfer and solidification) during the electromagnetic stirring process. Fig. 1 shows a sketch of the EMDC installation. The annulus gap is advantageous to increasing circular flow, reducing the temperature gradient as well as hallowing liquid sump depth in the EMDC. In terms of the thermal boundary condition, the heat transfer coefficient at annulus graphite is 2000 W/(m$^2\cdot$K). The secondary cooling boundary is divided into two zones, impingement zone and streaming zone. There are also Cauchy-type boundary conditions, which are formulated according to Eq. (6) and Eq. (7),

$$h = Q^{0.33}[352(\mathrm{T_s} + \mathrm{T_w}) - 167000] + \\ + 20{,}8(\mathrm{T_s} - 273)^3 \qquad (6)$$

where h is the heat transfer coefficient at impingement zone; T_s is the ingot surface temperature; T_w is the saturation temperature of water; Q is the cooling water flow rate per unit width of film;

$$h_c = (-1{,}67\cdot10^5+704T)Q^{1/3}\ , \qquad (7)$$

where h_c is the heat transfer coefficient at streaming zone; T is the average of bulk temperature and wall temperature; Q is the cooling water flow rate per unit width of film.

The numerical magnetic flux density and temperature are in good qualitative agreement with the measurements. With increasing annulus gap width, the vortexes would decrease, and move somewhat upward. But too narrow gap is not in favor of operating. With increasing center pipe depth, the circular flow would decrease due to the dislocation of center pipe. When annulus gap is at periphery of the billet, there are two large vor texes under the center pipe. And the temperature gradient of the longitudinal direction in the solidification region falls and the depth of liquid sump shallows evidently.

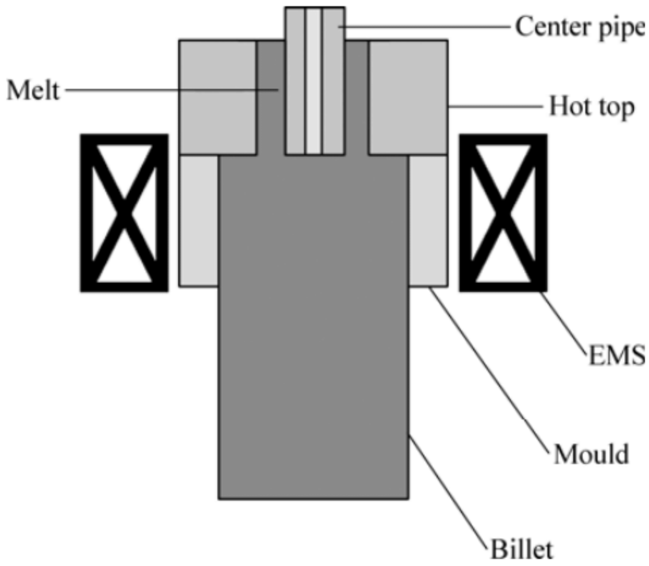

Fig. 1. Schematic diagram of EMDC casting apparatus

Wang [21] et al investigated the effect of the electro-magnetic level stabilizer (EMLS) on the molten steel flow. Simulation results indicate that, due to the electromagnetic force, the molten steel is forced to flow toward the magnetic field traveling direction in the region where the magnetic field imposed. The molten steel flow is decelerated in proportion to the imposed electromagnetic force. Consequently, the molten steel flows toward the mold center near the free surface with a smaller imposed electromagnetic force, and it flows toward the nozzle at the nozzle at the nozzle side and toward the narrow face at the narrow face side with a larger imposed electromagnetic force. However, the magnitude of the electromagnetic force is decided by the current intensity and frequency, a suitable imposed electric current can be chosen to minimize the flow velocity and also the amount of mold powder entrapments.

Zhang [22] et al reported that the effects of low frequency electromagnetic field on the macro-physical fields in the semi-continuous casting process of aluminum alloys. Comparison of the results for the macro-physical fields in the low frequency electromagnetic casting process with the conventional DC casting process indicates the following characteristics due to the application of electromagnetic field: an entirely changed direction and remarkably increased velocity of melt flow; a uniform distribution and a decreased gradient of temperature; elevated isothermal lines; a reduced sump depth; decreased stress and plastic deformation.

Electroplastic rolling

Li [23] et al investigated the effect of current frequency on the electroplastic rolling in AZ31 magnesium alloy. It is shown that the mechanical properties, microstructure, and texture are highly current frequency-dependent. Best mechanical properties are obtained from 500 Hz ER specimen by carrying out tensile tests for all the rolled strips. Besides, the frequencies of twin boundaries, which are reduced to the minimum at 500 Hz, vary with the current frequency.

The schematic view of the ER equipment is shown in Fig. 2. Multiple current pulses were applied to the strip directly between the anode and the cathode (two rolls of mill) at a distance of 225 mm on-line continuously when the strip was rolled with the speed of 1.5 m/min. When the activated slip modes are insufficient to accommodate strain along a specific direction, twinning would become a supplement as another deformation mode. Whereas once the CRSSs for certain slip systems are reduced to relatively low values or enough driving force is provided to facilitate the motion of dislocations, slip is supposed to be the dominant deformation mode, vice versa, twinning will be suppressed at the same time. Electroplastic effect is a combination of thermal and athermal effect. Athermal effect is weakened as current frequency rises, and the thermal effect is strengthened. Since the two components behave conversely as current frequency rises, a balance point should exist to maximize this effect. The point is supposed to be at 500 Hz. During ER, the thermal effect mainly contributes to reducing the CRSSs for non-basal slip systems, while the athermal effect is more responsible for the dragging force that is directly exerted on dislocations.

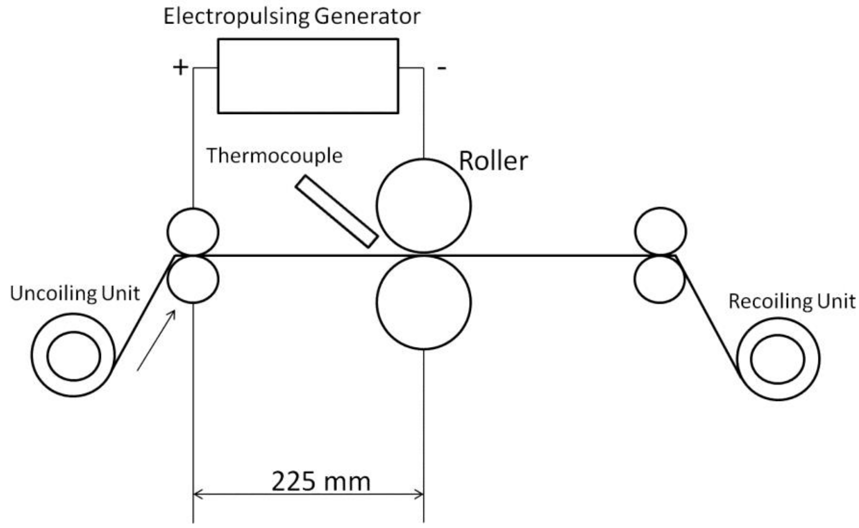

Fig. 2. Schematic drawing of electropulsing rolling (ER) process

The effect of electroplastic-differential speed rolling (EDSR) on manufacturing thin AZ31 strip was further investigated by Li [24] et al. The strips were cold rolled at room temperature with 8 % reduction per pass by symmetrical electroplastic rolling (ER) and EDSR. The ductility of rolled strip is significantly enhanced by EDSR, with an acceptable decrease of tensile strength compared to the strip by ER, which may be attributed to the fully dynamic recrystallization (DRX) and tilted basal poles in the EDSR sample. It can be found that fore the EDSR and ER samples, both the grain morphology and grain size are totally different. The ER sample exhibits equiaxial grains with relatively large grain size. In contrast, fine grains elongated along the RD are observed in the EDSR sample. It can be inferred that DRX takes place in the ER sample, promoted by the cooperation of thermal and athermal effect of current pulse. The thermal effect can be expressed by rising temperature related to the Joule law, and the athermal effect can be offered by periodic drastic impacting force between electrons and atoms. During EDSR, the deformation resistance is substantially decreased. Besides, the elongation to failure of rolled strip by EDSR increases significantly with an acceptable decrease of tensile strength, compared with the strip by ER. This is related to the microstructure and texture evolution of these two processes. During ER, a number of compression twin and double twin generate on account of limited slip modes to accommodate the strain along ND as reduction increases, resulting in serious stress concentration and premature failure in uniaxial tensile tests. Whereas for EDSR, refined grains with a tilt of basal poles towards RD about 15^o are formed as result of fully DRX promoted by the cooperation of current pulse and shearing stress induced by DSR.

Electroplastic treatment

Two magnesium alloys AZ31 and ZEK100 were subjected to cold rolling followed by electropulse treatment (EPT) for different durations in order to investigate the microstructure and texture evolution during EPT [25]. AZ31 started to recrystallize once the electropulse current was applied. The low local misorientation value in the nuclei, which is usually interpreted as the nuclei being strain free, indicates the discontinuous nature of the process. Tremendous texture weakening is achieved in both alloys when comparing the {0002} pole figures of deformed matrix and the nuclei, suggesting a significant role the nucleation stage played in the texture modification.

It is interesting to note that rather than being unique in samples subjected to EPT, the nucleation at shear bands are actually very common phenomena in conventional annealing treatment. In the latter treatment, though we will not feel surprise to obtain weak in the RE containing alloy, up till now, texture modification in the commercial alloy has not been reported yet. For AZ31 subjected to conventional annealing, unlike its EPT counterpart, strong basal texture is usually maintained during the whole process of the static recrystallization, even when only the textures corresponding to the nuclei at shear bands are considered. This suggests that the modified texture obtained in AZ31 in the present case is not appropriate to be ascribed to the special nucleation sites (shear bands) but to the selective effect brought about the electropulse current: in EPT, the nucleation of non-basal nuclei is promoted at the expense of the basal oriented ones.

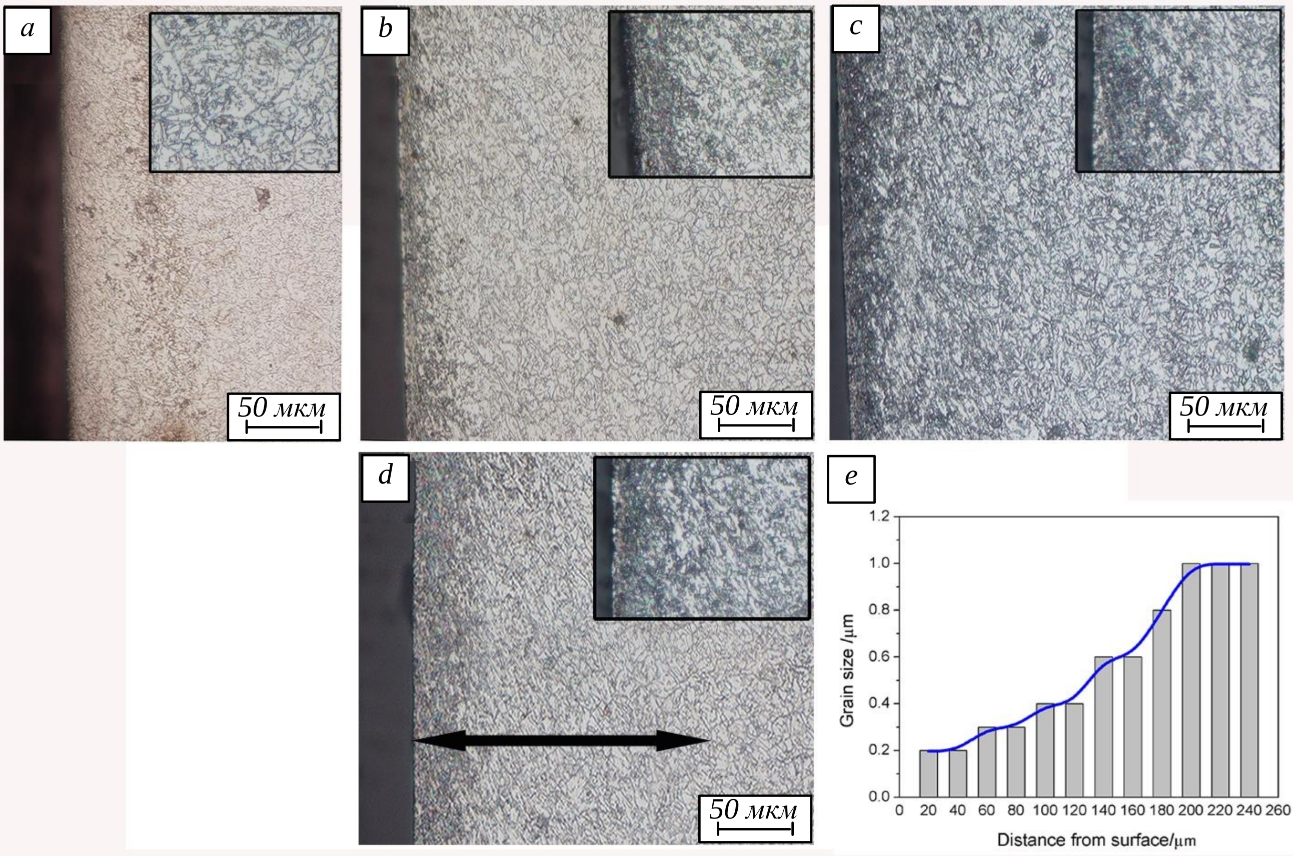

Fig. 3. 3D micrograph of cross-section specimens after treatment of conventional cutting (*a*); UESM at 2t (*b*); UESM at 4t (*c*); UESM at 6t, top right corner with higher magnification 1400X (*d*); Histogram of grain size distribution (*e*)

Ultrasonic-electric surface modification

An ultrasonic-electric surface modification (UESM) treatment, under different vibration frequencies, was employed by Liu [26] et al. to improve the surface properties of 2316 stainless steel. A grain refinement layer was formed on the specimen's surface after UESM treatment. The average grain size on the top surface was refined into the submicrometer or nanometers scales (Fig. 3). The needle-shaped martensitic phase after conventional cutting was observed in Fig. 3, *a*. After UESM at 2t and 4t, the thickness of the refined zone was about 90 μm and 180 μm, respectively. The UESM surface showed a gradient grain size distribution from the top surface to the interior (Fig. 3, *e*). The average grain size in the gradient grain layer was about 1 μm. The majority of broken grains were below 0.4 μm and a few of nanoparticles also appeared.

The effect of electropulsing assisted ultrasonic impact treatment (EUIT) on the mechanical properties and microstructure evolution of S50C steel welded components has been investigated by Ye [27] et al. They developed a relatively new post-weld treatment method to eliminate the residual stress and improve the surface mechanical properties (Fig. 4). The results show that EUIT exhibited better surface modification capability under the condition of electropulsing than using exclusively ultrasonic impact treatment (UIT). After EUIT treatment, plastic deformation layer consists of refinement grains formed on the sample surface, and residual tensile stress converted into residual compressive stress attributed to dislocation rearrangements.

The mechanism of UIT eliminate residual stress is to input vibrational energy on welding structures, make the plastic deformation happened on the surface, and change the dislocation distribution, dislocations move from high-energy state to a lower-energy state, and form stable dislocation. Microscopic stress field disappears since the appearance of stable dislocation. So the severer surface plastic deformation, the better eliminate residual stress rate. The surface microhardness depends on the size of grains and dislocation density. Hall-Petch Equation showed the relationship between microhardness H_v and grain size d. Hall-Petch Equation is useful to explain the behavior of the refined layer. The finer grain caused the greater hardness.

Conclusions. As this literature review shows external field processing technology aroused lively interest being invented in the 1960 s. Different applications ranging from the liquid forming, solid forming and materials surface modification as well as highly demanding parts in a small number of items to scale production with large lot sizes and high production rates are reported about the research and development of external field

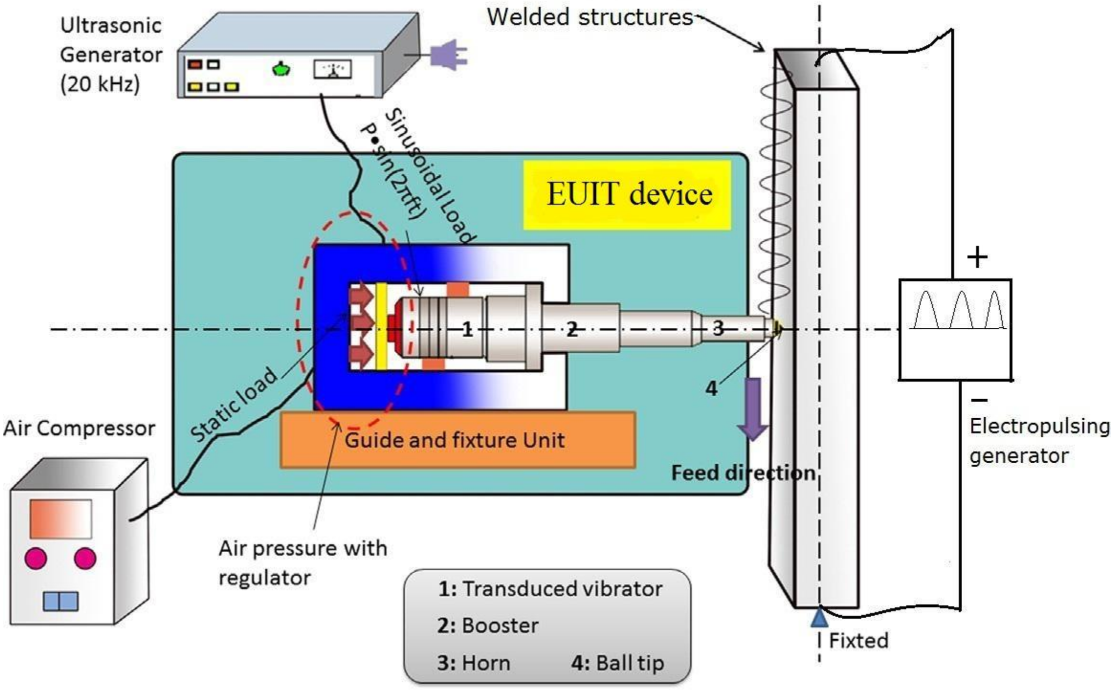

Fig. 4. The schematic diagram of the EUIT process and installation.

processing technology in China. Despite or maybe even due to this novel technology and the emphasis on the process advantages and principles without comparable mentioning the production cost, which might have led to disappointment. This might be ascribed to the following open questions and unsolved problems, which demonstrate the need for the future work.

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ВОЗДЕЙСТВИЕ ДЕФОРМАЦИИ НА СТРУКТУРУ И СВОЙСТВА СИЛУМИНОВ*

В настоящее время некоторые металлические материалы не могут быть использованы в промышленности для получения изделий путем обработки давлением из-за их низкой пластичности или полного ее отсутствия. К таким материалам можно отнести заэвтектические силумины. Первые работы по деформации таких силуминов появились сравнительно недавно – в конце XX века, хотя еще в 1930-ые годы С.М. Воронов установил возможность обработки давлением сплавов, содержащих до 20 % rhtvybz [1]. В последние несколько десятилетий появились работы, посвященные различного вида пластической деформации высококремнистых силуминов. Так, в работах [2 – 6] показана связь химического состава заэвтектических силуминов с ресурсом пластичности и с энергосиловыми и термоскоростными параметрами процессов горячего прессования и прокатки, осуществляемых различными способами. В работах, посвященных технологиям изготовления заготовок и поршней двигателей обработкой давлением из легированных заэвтектических силуминов [7 – 12], результаты получены в промышленных условиях. Однако работ, выполненных по этой тематике в области заэвтектических силуминов, недостаточно. Кроме того, необходимо учитывать присутствие в алюминиевых сплавах водорода (объем которого составляет 60 – 90 % от общего объема газов), который способен взаимодействовать с металлом в процессе его деформирования [13]. Сведения, приводимые в литературе, в основном носят отрывочный характер и, в подавляющем большинстве, не учитывают связь содержания водорода со структурой и механическими свойствами при деформации силуминов.

В настоящей работе проведено исследование влияния деформации на микроструктуру, содержание водорода и механические свойства силуминов, содержащих 11 – 30 % кремния.

В работе исследовали бинарные эвтектические и заэвтектические силумины, содержащие 11, 15, 20, 25 и 30 % кремния. Сплавы готовили в электрической печи сопротивления с карбидокремниевыми нагревателями из технически чистого алюминия А6 и кремния Кр0. Силумины, содержащие 15 – 30 % крмения, модифицировали фосфористой медью МФ-1 (содержание фосфора составляло примерно 10 %) в количестве 0,1 % от массы расплава. Содержание фосфора в сплавах составляло 0,008 – 0,0011 % по показаниям эмиссионного спектрометра ARL 4460. При выплавке силумина эвтектического состава модифицирования не проводили. Заливку проводили в алюминиевую форму квадратного сечения с размером стороны 80 мм и высотой 250 мм. Для получения заготовок под деформацию от слитка отрезали донную (высотой 15 мм) и прибыльную (высотой 50 мм) части. Масса заготовки составляла 3,20 – 0,05 кг. Заготовки перед деформацией подвергали гомогенизирующему отжигу при температуре 500 ± 10 ºС в течение 2 ч. Температура нагрева заготовок под ковку, которую проводили на пневматическом молоте МВ 412 с массой падающих частей 150 кг, составляла 510 – 550 ºС в зависимости от содержания кремния в силумине. Заготовки из сплавов, содержащих 11 – 15 % кремния, благодаря достаточной пластичности были прокованы на пруток сечением 15×15 мм без промежуточных отжигов. Температура окончания ковки составляла 350 – 400 ºС. Для сплавов, содержащих 20 – 30 % кремния, в процессе ковки проводили промежуточные отжиги при температуре 510 – 550 ºС в течение 1,0 – 1,5 часа. Сечение прутка 15×15 мм было получено после 3 – 5 циклов ковки. Величина общего коэффициента укова ($K_{общ.}$) для прутков из всех исследуемых сплавов составляла 28. Постдеформационный отпуск поковок проводили при температуре 520 ± 10 ºС в течение 2 ч.

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