RESEARCH OF COMBINED ROLLING-EXTRUSION PROCESS FOR PRODUCTION OF LONG DEFORMED SEMI-FINISHED PRODUCTS FROM ALUMINIUM ALLOYS OF VARIOUS ALLOYING SYSTEMS

TABLE OF CONTENTS

INTRODUCTION

High production volumes of long-length deformed semi-finished products of relatively small cross-section made of aluminum and its alloys (wire rods, bars and wire) have conditioned the creation of new technologies of combined processing with the use of continuous methods of casting and basic metal-forming operations which for production of the above-mentioned products are advisable to be applied as rolling and extrusion [1-4]. Such technology is implemented for example when a cast bar is produced with a rotary mold and then rolled on rolling and casting plants, or continuously extruded on Conform plants [5, 6]. In this case the metal processing stages are arranged sequentially, that is only after completion of one stage the following stage starts. The combined process is more complicated and is characterized by separation of the basic operations in time or space [1]. At the same time a combination of two or more basic operations is possible at one stage of processing, whereby integral application of stresses occurs within one deformation zone, and sometimes with a change of the direction of metal flow. Combined rolling-extrusion (CRE) can be considered as an example of such process where metal of a cast bar is reduced in the closed roll pass, pressed down before entering a die which covers the pass at the exit of the rolls, and due to active forces of friction metal is extruded through the opening of the die in the form of a product with determined shape and size [1]. The process is implemented continuously, and a semi-finished product is coiled by a winding machine (coiler). The use of shape rolling operation allows for continuous processing and active forces of friction for extrusion of a finished product. The extrusion allows to obtain configuration and sizes of products preset by a die at high degrees of reduction [7-10] which enables to produce them on one roll mill stand in one processing cycle.

Analysis of research results for of the behavior of aluminum alloys of different alloying systems during casting, deformation and heat treatment [11 - 30] allows to conclude that for efficient processing of such alloys it is required to apply all-around non-uniform compression pattern. Such pattern is implemented in pressing, in this case the metal has maximum ductility and is not susceptible to defects (cracks) which are typical for example for rolling. However rolling is probably the only practically used method of metal forming in which it is possible to arrange a continuous cycle of metal processing and to achieve maximum performance.

Thus, combination of these operations with continuous casting allows to significantly decrease the number of technological conversions and reduce labor and energy intensity of the technological process. This is particularly relevant for low-ductile and low-tech alloys that are difficult to deform using conventional processing methods. That is why in practice, for manufacturing of semi-finished products from these alloys, one has to apply discrete pressing methods to make products of limited length with the use of heavy draw presses. The existing high-performance casting and rolling plants are mainly targeted at production of wire rod with circular cross section of aluminium grades 1020 and 1350 or 6151 (AVE) alloy because the casting and rolling mill (CRE) is not designed for rolling of aluminum alloys with higher strength properties.

With implementation of combined technologies for production of long products, a number of technical and economic advantages are provided, the main of which are the following.

1. Continuity. In order to achieve maximum performance, the equipment and the metal processing must ensure continuity of the process chain, from preparation of the melt till winding of finished products. Performance of one plant of combined processing can reach 2.5 - 4 tons per hour.

2. Highest degrees of reduction at one processing stage. Practically all types of metal forming (besides pressing) are characterized by multistageness, that is in order to achieve total deformation (reduction) during production of final products of small cross sections it is necessary to split the deformation process. When producing rods by shape rolling methods including production on casting and rolling mills the degrees of reduction at one stage are so low in comparison to pressing, that the number of mill stands and passes during rolling even on continuous mills is 15–20 and more. In combined processing, the reduction of metal is carried out in one reduction component of rolling-extrusion process during one pass.

3. Low power consumption of the process. Practically all metal-processing equipment is characterized by high energy consumption. It concerns both hydraulic horizontal presses that use pump-and-accumulator stations for their drives, and multi-stand rolling mills with

common drive or individual drive. Due to the use of active friction forces, energy consumption of the combined processing is lowered by 5-10 times as compared to conventional forms of production.

4. Dimensions of the equipment. Should be minimum and it should allow for all the necessary technological operations. For press equipment and casting and rolling mills the length of the equipment line is 50-70 meters. The size of a combined processing plant can be reduced by 2-5 times where the maximum overall length can be 12 meters.

5. Quick changeover of the equipment and flexibility to switch from one standard shape of products to another. High-performance methods of manufacturing of products with small cross section of aluminum alloys using casting and rolling mills, it would seem, solved in their time all problems of making integrated processing lines. However, a casting and rolling mill can give cost-effective results for mini-production only at high volumes. At the same time a slight change of extrusion shape leads to the necessity to change the design of the roll pass and make a new production tool (rolls) with a different pass. Combined processing can be applied for small lots. And the transition from one standard shape to another is conducted by changing only the die.

6. High metal yield. Metal yield should be maximum, since the more technological conversions, the higher the loss of metal yield. The total yield from the combined processing can achieve 90-95% due to decrease of losses on cut-offs and extrusion discards.

7. Possibility to process different aluminium alloys. Practically all types of casting and rolling mills currently being in operation are designed to produce wire rod of electrical aluminium 1020, 1350. The combined processing technologies due to the use of a favorable pattern of strain-stress state and alternating deformation allow to make high-quality semi-finished products of technologically unfeasible (low-tech) and low-ductile alloys.

The target of this paper is therefore to increase production efficiency of long-length extruded products of aluminium and its alloys on the basis of combined rolling-extrusion method. The following tasks are formulated to achieve this target:

- to create an experimental plant for combined rolling-extrusion (CRE) that will enable to study geometrical deformation zone and conduct experimental research of power parameters of the process;

– to establish analytical dependences for calculation of temperature conditions and power characteristics of the studied process;
– to develop technical and technological conditions for design of technology and equipment;
– to conduct studies of properties of aluminium semis produced by CRE method;
– to create a semi-production experimental plant for manufacturing of long-length extrusion products of aluminium and follow up operating practices in production of aluminium rods using the plant.

1 CURRENT STATUS AND DEVELOPMENT TRENDS OF TECHNOLOGIES AND EQUIPMENT FOR COMBINED PROCESSING OF ALUMINIUM ALLOYS

High production volumes of long-length deformed semi-finished products from aluminum and its alloys have conditioned the creation of new technologies of combined processing with the use of casting and metal-forming operations. This is particularly relevant for low-ductile and low-tech alloys that are difficult to deform using conventional processing methods. That is why in practice for manufacturing of semi-finished products of these alloys, one has to use discrete methods of pressing, making products of limited length. Alloys 1xxx, 3xxx, 5xxx, 6xxx, 8xxx and others can be considered as examples of such alloys. The existing high-performance casting and rolling units are designed mainly for production of wire rod with circular cross section from aluminium grades 1350 and 1020 or soft aluminium alloy 6151.

In this regard, development and implementation of new technologies for production of long semi-finished products of aluminum alloys is an important issue for metallurgical industry. In order to solve this issue, the scientists of Institute of Non-Ferrous Metals and Material Science of Siberian Federal University (SFU) proposed methods and devices for combined processing that include casting into two-roller mold, rolling and extrusion as basic operations [1]. Moreover, the operations of casting and rolling-extrusion can be separated in time or combined in one reduction component. This enables to vary methods of processing depending on the properties and rheological characteristics of aluminium alloys. In addition to that there is an option of using a plant with an electromagnetic mold as a casting unit which allows to significantly improve the structure of cast bar, increase mechanical properties and reduce power parameters for its subsequent processing. Application of shape rolling allows to create continuity of processing and active friction forces required for extrusion of finished products. The extrusion allows to obtain configuration and sizes of products preset with a die at high degrees of reduction. It enables to produce them on one mill stand during one processing cycle.

Technical solutions on the above methods of combined processing and the equipment for their implementation are protected by numerous RF (Russian Federation) patents. On their basis, laboratory and semi-production experimental units of combined processing are made in Siberian Federal University and at a number of metallurgical plants. Deformation, stress-strain state of metal and power parameters of the new processes as well as structure and properties of metal are comprehensively studied with those units.

1.1. METHODS AND TECHNOLOGIES FOR CONTINUOUS PROCESSING OF ALUMINIUM ALLOYS

Processing of non-ferrous metals and alloys mainly include such metal conversions as casting and metal forming as well as operations aimed at producing bars from powder materials (compacting) and formation of structure and properties of products (heat treatment). One of the main development trends of metallurgical industry is combination of the processes of casting, metal forming and thermal treatment. This trend has led to implementation of new processes intensifying production for various purposes. They allow to increase productivity by excluding numerous time-consuming and unproductive operations from the process cycle, to reduce production areas and inter-operational transportations, and to use thermal energy that is released during solidification and reduction of a cast bar at subsequent stages of processing.

A particular importance in industry has been recently given to development of processes of metal forming when several operations are performed within one deformation zone, for example, rolling-drawing, rolling-forging, rolling-extrusion etc. These combined processing methods are used for efficient deformation of non-ferrous metals including aluminium and its alloys.

Despite a relatively short development period of combined processing of non-ferrous metals (mid-twentieth century) and especially of aluminum alloys, scientific papers of many domestic and foreign scientists have been devoted to this area. In the first place those are studies of action of friction forces in extrusion and their use for deformation of non-ferrous metals and alloys [31-33], studies of continuous casting processes, rolling and extrusion [34-41] and development in the area of algorithms and computer-aided design systems of metal forming processes [42-46].

The operation of rolling is used practically in all types of combined methods of processing. The main advantage of the latter is the possibility to use rotating rolls for continuous deformation process [47]. In addition, the forces of friction usually impeding metal processing in many operations and requiring additional energy costs, are active in rolling due to which reduction occurs. However, rolling does not allow to get high single values of reduction in one processing cycle. Along with that it is known that maximum degrees of reduction can be achieved by application of direct extrusion. Its implementation makes the process circular, and about two thirds of the effort is spent for overcoming the forces of contact friction on the tool. Let us review some types of combined processing of non-ferrous metals that have recently received predominant development in production of extruded products of aluminium alloys.

Semi-continuous extrusion is currently one of the main flowcharts for extrusion of products of aluminium alloys. Its characteristic feature is the use of a pre-chamber tool which allows for extrusion with butt welding and tension.

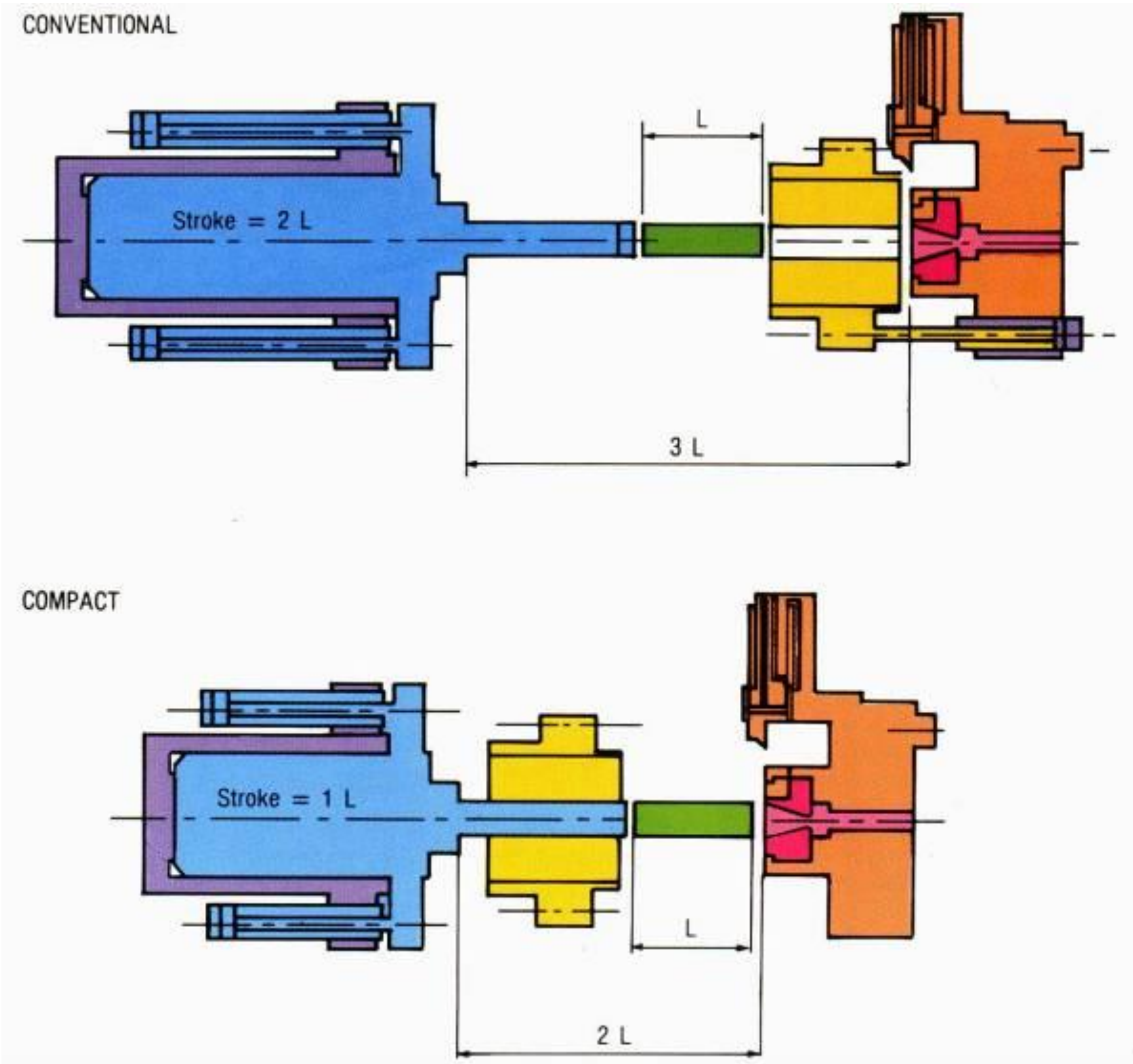
The characteristic feature of such process is the decrease of high degree of reduction due to its fragmentation in progressive extrusion of metal first from the main container into an intermediate tool block, and then from the intermediate block into a die. In the process of direct pressing on hydraulic press, in most cases, a special tool called a pre-chamber plays a role of an intermediate tool block.

The main advantage of this process is preliminary redistribution of metal flows of a cast bar so that before entering into the die mouth uneven deformation of metal would be decreased. In addition, the stress on the extrusion tool is significantly lowered resulting in increased dimensional accuracy of the extruded shape. Depending on the size and type of extruded shape the design of the pre-chamber can vary: it can be a recess in the body of the die from at the side of the face or the pressure pad in which dedicated cavities are made for metal to be pressed. Expanding pre-chamber allows to extrude profiles that are dimensionally larger than the inner wall of the container. After completion of extrusion through a die with pre-chambers and detachment of extruded discards which requires slightly higher effort because you has to additionally cut off the section of metal that remains in the pre-chambers, the following cast bar would push the remaining metal. Since the metal remains in the pre-chamber it is notable in addition to the above advantages of this method that there is a possibility of semi-continuous extrusion with tension followed by butt welding of the produced shapes. Currently the leading metallurgical plants in Russia and in foreign countries use this technology in production of aluminum structural shapes of soft wrought alloys. However, the issues of studying the strength of the weld seam, its length and colour variation in subsequent anodizing, require science-based design methods and modern technologies of manufacturing of extrusion tool. That is why this technological process does not allow to produce long-length products because the welding should be cut out in most cases, and that will reduce extrusion yield.

Horizontal presses of nominal force from 5 to 200 MN with the size of containers specified by product mix, length and alloy grade of extruded products, reduction ratio, extrusion method etc., are used as the main equipment for implementation of such technologies (picture 1.1).

Picture 1.1 – Horizontal hydraulic press for direct extrusion of semis of aluminium alloys

The main parameters of these presses are nominal force, dimensions of the container, stroke and speed of the extrusion crosshead. The development trend of hydraulic forging equipment is the use of automated production lines equipped with drawing devices, new systems of products transition and its finishing. In recent times, modern short-stroke horizontal hydraulic presses are used for extrusion technologies (pic. 1.2).



Picture 1.2 – Layouts of modern short-stroke horizontal presses for direct extrusion of semis of aluminium alloys

Analysis of possible flowcharts of extrusion showed that nowadays direct extrusion on hydraulic presses is the most commonly used flowchart because it is relatively simple and it allows to produce profiles, panels, rods and pipes practically any shape with high surface quality. However due to significant resisting forces of friction the process is characterized by considerable unhomogeneity of metal flow which limits maximum extrusion speed, leads to decrease in performance of extrusion plants, causes heterogene structure in products and lowers the yield [32].

The use of technologies of casting and rolling on casting-and-rolling mills in contrast to extrusion are characterized by continuity of technological cycle, so in comparison to extrusion they have higher productivity and product yield. However at present, in industrial production, these technologies are used mainly for production of wire rod, chiefly of aluminium 1020 and 1350 grades, and to a lesser extent of 6151 (AVE) alloy [11].

Table 1.1 shows comparative performance indicators of extrusion technology, continuous casting-rolling technology on casting-and-rolling mills and combined continuous rolling-extrusion (CRE) technology. It is obvious that on many indicators conventional technologies are inferior to combined processing technology.

Thus, the existing production technologies of extrusion on horizontal hydraulic presses have several disadvantages the main of which are associated with discreteness (discontinuity) of the process and implementation of extrusion flowchart which has reactive friction forces at the point of metal contact with container. This leads to limited length of extruded products, their low quality because of unhomogeneity of reduction, and high energy intensity of extrusion process. These disadvantages can be removed by way of continuous casting application.

The technologies and equipment for continuous extrusion that have been recently developed [34] allow to solve the above problems by concentrating of deformation to the required degree in one unit – that is in the unit of continuous extrusion. At the same time, along with the main type of processing – extrusion, depending on the type of continuous extrusion, such operations as rolling, drawing, sinking strain, expansion and others can be combined in one reduction area. The main forms of continuous extrusion are Conform, Linex and Extrollong.

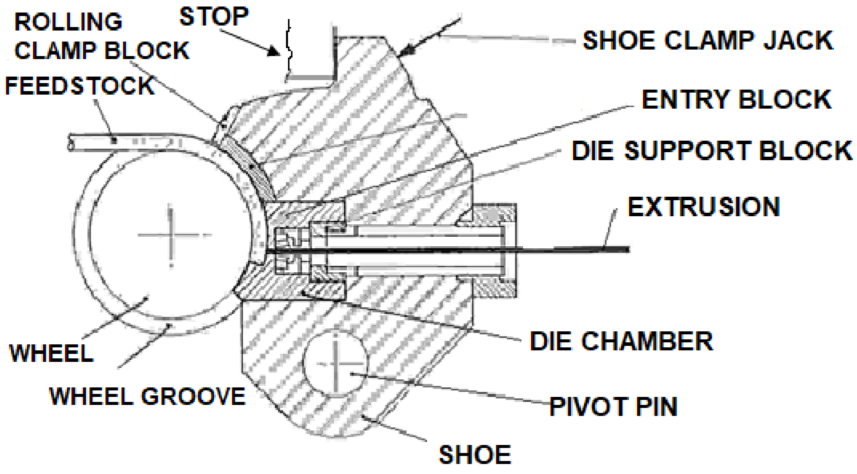
Table 1.1 – Comparative performance indicators of technologies for production of long-length products of aluminium alloys

Indicators	Technology		
	Extrusion	(CCR) Continuous casting and rolling	CRE (combined rolling-extrusion)
Continuity	Provides only semi-continuous extrusion with butt welding of shapes	Provided	Provided
Content of equipment	Line with horizontal hydraulic press, 16-20 MN	15-20 and more mill stands	One mill stand
Length of equipment	Up to 80 meters	50-70 meters	10-15 meters
Energy intensity	Individual drive for hydraulic press and pump-and-accumulator station	Common drive for 15-20 mill stands and casting machine	Individual drive for 1 mill stand
Flexibility of switching from one type of shape to another	Provided by quick change of extrusion tool	Only wire rod of circular cross-section, dia 9-15 mm	Provided by quick change of extrusion tool
Yield	75-77%	80-90%	90-95%
Possibility to process aluminium alloys	All deformed alloys	Only 6151	All deformed alloys
Productivity	up to 1 ton per hour	from 2,5 to 8 ton per hour	from 2,5 to 8 ton per hour

Among the listed methods a special place is taken by Conform that was proposed by Green D. [49] in 1970. It has a number of technical and economic benefits and widespread application, and it seems particularly promising in non-ferrous metallurgy. The papers [33-35, 38, 41, 49-53] contain analysis of the technology and equipment for continuous extrusion as well as the results of research in this area.

Conform method is based on the use of a stationary tool called Shoe, and a movable rotating tool like a wheel with a groove around its periphery. At the end of the Shoe, a die is installed which covers the groove of the wheel. The process flow is shown in picture 1.3.

A rod 7 is used as a feedstock. The rod is driven into a pass 2 made in the form of a annular groove on the working wheel. From the external side the groove is covered by the Shoe which has on its internal side a pass enclosing the feedstock. In the Shoe there is tool block with an extrusion die.



Picture 1.3 - Conform flowchart

When feeding the rod into the gap between the Shoe and the wheel, it (the rod) travels into the pressing chamber formed by the surfaces of the Shoe and the groove. Driven by friction forces on the surface contact with the rotating wheel, the feedstock finally reaches the die. In the area immediately before the die the rod undergoes intensive plastic deformation ("squashing") and fills the entire cross section of the groove (gripping area during extrusion); this contributes to the increase of frictional forces between the surface of the groove and the rod. As the wheel turns, a compressive force applied to the feedstock rod, grows, and the force required to extrude the feedstock material through the hole in the die, is achieved. Thus, extrusion process starts. The area of incomplete contact of the feedstock with the surface of the groove (the area of primary gripping) serves to develop the pressure needed for plastic deformation of the material and filling in the area before the die. A usual wire can be used as a feedstock, and the process of its deformation, i.e. pulling of the wire into the pressing chamber in the course of rotation of the wheel, preliminary shaping and filling in the wheel groove, creation of working force, and finally extrusion, occurs continuously. Thus, the technology of continuous extrusion is implemented. This method allows to extrude products not only in the direction of rotation of the working wheel but also in directions parallel to the axis of the working wheel, including radial direction.

For optimization of kinematics flow of deformed metal, for decrease of extrusion force and for simplification of the design of the extrusion tools for production of pipes and hollow profiles, a double-pass flowchart can be used. And for production of thin-walled pipes, profiles, wire and clad products, a two-wheeled option of Conform flowchart is particularly effective. The extrusion tools are characterized by separate installation of the extrusion die and the mandrel, the level of required pressures and extrusion temperature is lower which contributes to the productivity growth of the process.

Based on the above technical solutions, experts from Springfilds laboratory and Advanced Metal Forming Group at Atomic Energy Authority (UKAEA) in the UK have developed a line of continuous extrusion. Advantages of the line are the following: high quality of extruded products, relatively low production cost; low specific capital costs; insignificant amount of process scrap (3-7% instead of 25-45% traditionally); high operating flexibility.

Currently extrusion Conform plants are manufactured by English companies "Holton Machinery" and "Babcock Wire Equipment". The drive power of a "Holton Machinery" plant with a diameter of the wheel 400 mm is 150 kW, overall dimensions are 27250x6800x4380 mm. These plants are used to make section wires for cables with cross section 16-300 mm^2, electro-buses of various shapes and sizes, pipes of all types for cooling systems with a diameter from 4 to 8 mm with wall thickness up to 0,6 mm and other products.

Picture 1.4 – General view of Conform plant

However, insufficiency of research of metal deformation, records of interface friction forces, studies of deformation of various metals and alloys patterns has led to a number of disadvantages that severely restrict opportunities of this method of continuous extrusion. It is important to note that deformation of even soft alloys require high energy consumption because the friction on the extrusion unit is quite high. In addition to that it leads to significant heating of the extruding tools and consequently to reduction of its resistance. The properties of extruded products are characterized by heterogeneity due to non-uniform extrusion caused by reactive friction forces at the contact of the metal and an extrusion tool (Shoe). And it is not quite acceptable for example for production for electrical purposes.

A peculiarity of Linex method proposed by specialists of Western Electric Co (USA) is that the pressure required for the process is created through the use of active friction forces that arise between the flat surfaces of the links of endless chains and the upper and the lower planes of a feedstock that has rectangular cross section. Thus, the extrusion pressure level is dependent on the ratio (difference) of the friction forces on non-lubricated and lubricated planes of the feedstock. This method is used at the plants of Venscuck (USA) for production of aluminium buses and wire. The maximum value of reduction ratio does not exceed 20, i.e. it is next smaller than in production of the same extruded products by way of Conform.

Extrolling processing was proposed and patented by Avitzur B. in 1976 [5]. It consists in combining of rolling and extrusion in one deformation zone. The process is characterized by the following: due to active forces of the contact friction between the rollers and the feedstock, the extrusion is carried out through an extruding die.

For implementation of the process, initial feedstock is continuously driven into the pass, gets reduced in it which fully corresponds to the stage of rolling, and then it is extruded into the orifice area of the die installed at the exit of the pass. This method is used in cold state and in high temperatures, it has lower power losses on reactive friction, and more efficient filling of the pass with metal. The process combines low friction losses, short duration of processing that are typical for rolling, with high single values of reduction which is possible in extrusion. Disadvantages of rolling (low single reduction) and extrusion (limited length of product) in this implementation of the process can be removed.

However this method has not found a proper application in the industry because the proposed technical solution (the use of an open pass, the position of the die on common vertical axis of the rolls, etc.) did not provide a steady flow process and generation of pressures required for extruding of metal.

Thus, of all the methods of continuous casting of non-ferrous metals and alloys that started to be actively implemented in production since 1974, the most developed and the most industrially integrated method was Conform. Plants based on this method are manufactured and distributed throughout the world by Babcock Wire Equipment and Holton Machineri LTD. In our country despite numerous technical solutions protected by copyright certificates and patents, attempts to make similar domestic plants failed because of the lack of automatic system of heat removal from the working tool. As a matter of fact, a number of features of this method the main reason for which is contact forces friction of reactive action, cause high heating of the tool, so it is quite difficult to control and manage it during extrusion.

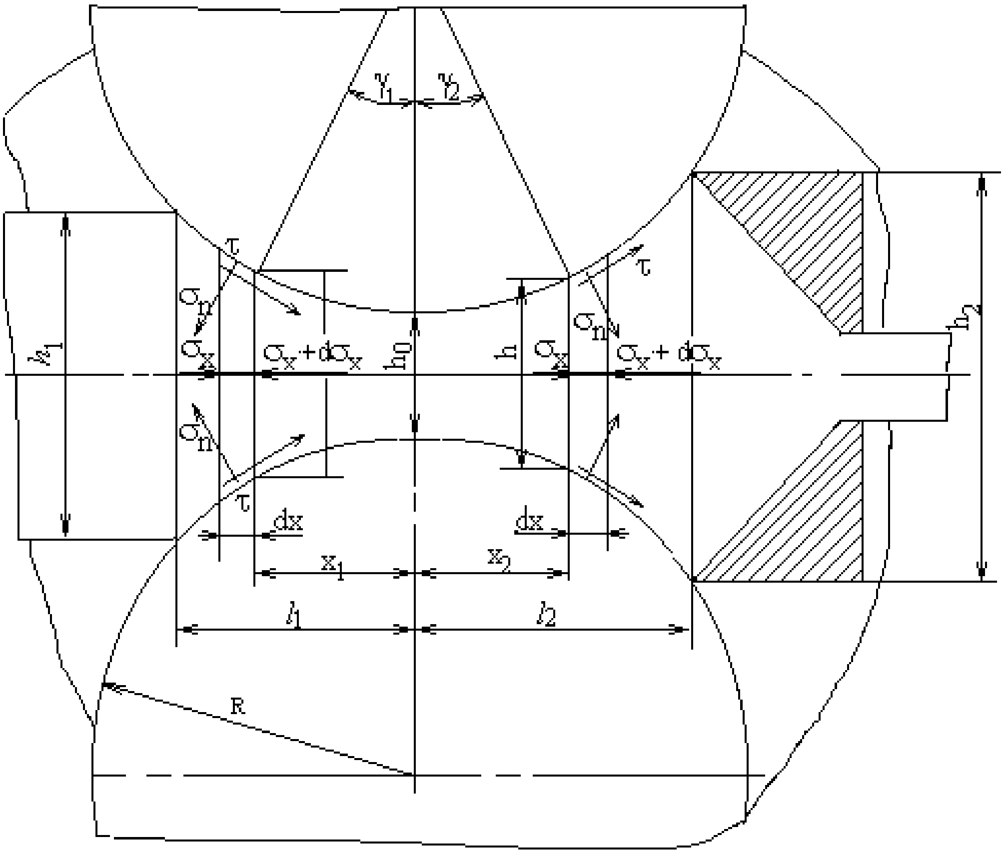
In recent times in Russia and abroad, an increasing attention is given to energy-saving technologies based not only on the combination of processing operations but also on the use of active forces of friction for extrusion. From this point of view the prevailing method is rolling-extrusion based on Extrolling in which products are extruded due to powerful active forces of friction supplied by rolls. However as noted by the author of the paper [41] this method has not found a proper application in metalworking industry because an incorrect idea that was formed in foreign and in domestic papers about the extrusion pressure generated in the pass of deformation zone during rolling-extrusion.

1.2 ANALYSIS OF RESEARCH RESULTS FOR IDENTIFICATION OF DEFORMATION AND POWER PARAMETERS IN COMBINATION OF ROLLING AND EXTRUSION

A great number of papers [41, 54-64] in the national press is devoted to research in this area mostly aimed at the study of distribution pattern of stresses and forces acting in deformation zone. Moreover, in scientific and technical literature there are publications which studied the possibility of using this pattern for production of extruded products of ferrous metals and alloys.

In the paper of Kornilov V. N. [41] where most of the focus is on the study of continuous extrusion processes for powder and granular materials, possible technical solutions allowing to increase the stability of Extolling are given, and also the results of a theoretical solution for identification of extrusion in the die. In addition, the research results of deformation obtained with the use of a laboratory plant are provided for various standard sizes. Moreover, the study of processing of aluminum alloys granules, their intensive setting, welding and deformation is emphasized. The efficiency of using rolling-extrusion method for deformation of aluminum alloys is shown. The results of research allow for initial assessment of effectiveness of the proposed methods of rolling-extrusion and upper-bound estimate of the power parameters of the process. However, the design of rolling-extrusion plants requires information about feasibility (stability) of the process, it is also necessary to determine the forces and torques affecting the tools (rolls and die). In this regard, fundamental studies for better understanding of rolling-extrusion processing of compact products of metals and alloys are needed.

In deriving the formulas for calculation of pressures in a scientific paper of Kornilov V. N. [41], the method of thin sections is used. At the same time the deformation zone (pic. 1.5) is divided into two zones: a deformation zone during rolling and a deformation zone during pressing-out of metal before entering the die. When setting up this problem the following assumptions are taken: the radii of the rolls are accepted as identical and equal to R; the ambient is taken as incompressible and rigid-ductile; normal stresses and friction stresses following Siebel's friction law affect at the contact of a feedstock with the pass; resistances to deformation in the zone of rolling and zone of pressing-out are equal.



Picture 1.5 – Calculation scheme of longitudinal pressures

As a result of solution of a theoretical problem the author obtained the following relation:

$$\sigma_x = \frac{\sigma_S l_2^{\,2}}{R\Delta h_2} ln\frac{h_2}{h_0} - \frac{\sigma_S\, l_1^{\,2}}{R\,\Delta h_1}\times \ln\frac{h_1}{h_0} + \frac{2m\sigma_S}{b} l_1 + \frac{2m\sigma_S}{b} l_2 +$$
$$+ \frac{2m\sigma_S l_1}{\sqrt{h_0\,\Delta h_1}} \mathrm{arctg}\sqrt{\frac{\Delta h_1}{h_0}} + \frac{2m\sigma_S l_2}{\sqrt{h_0\,\Delta h_2}} \mathrm{arctg}\sqrt{\frac{\Delta h_2}{h_0}}, \qquad (1.1)$$

where Δh_1 – value of reduction in thickness of initial feedstock in the rolling zone; h_0 – minimum gap between the flange and the bottom of groove; h_1 – height of initial feedstock;

h_2 - height of the die; m - coefficient of friction by Siebel; $\Delta h_2 = h_2 - h_0$; σ_s - plastic resistance of material; l_1 и l_2 - lengths of rolling and pressing-out areas respectively.

Analysis of this formula shows that the pressure of metal on the die depends on geometrical parameters of the pass and distances that characterize the area of metal gripping by rollers and the area of pressing-out. By changing these parameters you can make different pressures of extrusion. However, a more precise analysis of this formula shows that when setting up this problem and consequently when solving it, it was not taken into account that besides the area of pressing out the value of pressure is influenced also by deformations that occur in the area of immediate extrusion. Therefore, knowing the cross-sectional area of the die this formula allows to identify the force that affects the die, however, the deformation of extrusion estimated as value **μ** is not taken into account.

In the paper [45] it is proposed to calculate the force of extrusion according to the formula of Perlin I. L. for which reason the stress component used for friction on the container is excluded from it. Based on the above the force is determined as:

$$P_{пр} = R_м + T_м + T_п \qquad (1.2)$$

Force required for deformation of metal during extrusion is:

$$R_м = \frac{1}{\cos^2(0{,}5\beta)} \times F_м \times \sigma_{вмс} \times i \qquad (1.3)$$

where β - die angle; i – integrated deformation indicator; $F_м$ – area of pressed-out feedstock before die face; $\sigma_{вмс}$ – average tensile strength in static testing, can be found by formula:

$$\sigma_{вмс} = \sqrt{\sigma_{вмн} \times \sigma_{вмк}}\,, \qquad (1.4)$$

where $\sigma_{вмн}$ and $\sigma_{вмк}$ – respectively, tensile strength in static testing of extruded metal at start and at end of process.

Force required to overcome friction forces on lateral surface of reduced part of deformation zone would be:

$$T_м = 0{,}5\, f_{км} \sigma_{вмс} \frac{F_м}{\sin\beta} i\,, \qquad (1.5)$$

where $f_{км}$ – averaged coefficient of friction on flow shear stress.

And the force required to overcome friction forces on the surface of parallel land of the die can be identified by formula:

$$T_n = \mu\ f_{кп}\ K_{мк}\ F_n\ , \qquad (1.6)$$

where μ - extrusion coefficient; $f_{кп}$ - averaged coefficient of friction on maximum shearing stress $K_{мк}$ on the parallel land ($f_{кп}$ =0,5, because extrusion is without lubrication); $K_{мк}$ - flow shear stress of extruded metal at the end reduced part of plastic zone ($K_{мк}$=0,5*$\sigma_{ВМК}$); $F_п$ – area of contact surface along the parallel land.

After the transformations we have a formula for calculation of the force that affects the die during extrusion of metal by rollers:

$$P_{матр} = 2{,}57\ \sigma_{вмс}\ F_м\ ln\mu + \sigma_{вмк}\ f_S\ \mu\ \pi\ r_м\ l_n, \qquad (1.7)$$

where $r_м$ – radius of orifice area; l_n – value for the operating parallel land.

This formula allows to calculate the force affecting the die that has an orifice area, however a change of the pass dimensions does not affect its value.

Dovzhenko N.N., Sidelnikov S.B. and co-authors [1, 61-64] in their papers suggested investigations of deformations and power parameters of rolling-extrusion process. And by means of video-plasticity method on unfinished sections they studied conditions of deformation of lead and aluminium feedstocks, mathematically they solved the problem of estimation of power parameters, and made diagrams for identification of possible deformation stages depending on various factors of the process. For the first time they obtained experimental data and the results of theoretical research of power parameters and conditions of basic feasibility and sustainability of rolling-extrusion process. Developed a process model which allows to calculate design parameters and generating extrusion pressures depending on diameters of the rolls and their ratio, size of the pass, distance of the die from a plane that goes through the axis of rolls, the size of feedstock and friction conditions.

For analysis of metal deformation and power parameters of combined processing the authors developed a mathematical model of rolling–extrusion in closed box-passes [1] using the system of equations comprising the equation of power balance and variational equation of principle of minimum full-power

$$\delta(N_{вн} + N_{ср} – N_{ск} – N_{вал}) = 0, \qquad (1.8)$$

where $N_{вн}$ – power of internal forces; $N_{ср}$ – power of shearing forces; $N_{ск}$ – power of friction stresses on sliding speeds; $N_{вал}$ – power delivered from rolls.

To determine the components of full power the following formulas were used

$$N_{вн} = \int\limits_{V} 0,58\sigma_S H dV,\ N_{ср} = \int\limits_{F_{ср}} 0,58\sigma_S \left|V^+ - V^-\right| dF,\ N_{ск} = -\int\limits_{F_к} \tau_{тр} v_{ск} dF,\ N_{вал} = \int\limits_{F_к} \tau^*_{тр} v_в dF, \qquad (1.9)$$

where H – intensity of shear-strain rates; σ_S – resistance of metal to deformation; V^+, V^- – projections of metal flow velocity onto tangential plane to the surface of slide F_{cpj}, respectively, from internal and external sides of this surface; n – number of surfaces of slide; $\tau_{тр}$ – friction stress; $\tau^*_{тр}$ – projection of total friction stress onto tangent to a circle of a roll at any point of contact surface.

Solution of variational problem allowed the authors to obtain numeric array of data of the magnitude of forces acting on the die $P_м$ and rolls $P_в$, depending on dimensionless parameters of rolling-extrusion process and formulas to calculate sought-for values:

for the force acting on the die

$$P_м = \frac{0,12\sigma_s(A-11,5)}{\sqrt{3}}[2ln\mu(\tilde{b}+1)(L_1+L_2)h - \frac{\tilde{b}}{(A+1)}(L_1^2+L_2^2)+$$

$$\frac{ln\mu}{2h(A+1)}(L_1^3+L_2^3) - \frac{\tilde{b}h}{12(2hA+2h)^3}(L_1^4+L_2^4) + \frac{ln\mu}{30(2hA+2h)^3}(L_1^5+L_2^5)]; \qquad (1.10)$$

for the force acting on rolls

$$P_в = (1,7-0,38A)\sigma_S\frac{4\tilde{b}h}{\sqrt{3}}\left[\left(\frac{h}{12h(A+1)}-1\right)(L_1 ln(2h^2(A+1)+L_1^2)+L_2 ln(2h^2A+2h^2+L_2^2))\right.$$

$$-(L_1+L_2)\left(\frac{h}{12h(A+1)}-1\right)ln(2h^2(A+1)) + +\frac{3ln\mu}{2\tilde{b}h}(L_1^2+L_2^2) - \frac{(L_1^3+L_2^3)}{12(2hA+2h)^2} + \frac{2\tilde{b}h}{\sqrt{3}} \qquad (1.11)$$

$$\left.+\frac{ln\mu}{\tilde{b}h}\left(\frac{\tilde{b}h\sqrt{2h(A+1)}}{\sqrt{h}} - \sqrt{2h^2(A+1)}\right)\times\left(L_1 arctan\frac{L_1}{\sqrt{2h^2(A+1)}} + L_2 arctan\frac{L_2}{\sqrt{2h^2(A+1)}}\right)\right],$$

where L_1 – length of gripping area during rolling, L_2 – length of pressing-out area, μ – extrusion reduction.

These formulae can be used to determine power parameters of combined processes required for design of plant for production of long-length deformed semis of aluminium alloys.

1.3. SELECTION OF MATERIALS FOR RESEARCH

Currently in production of extruded products of aluminum alloys the main method of production is discrete pressing on horizontal hydraulic presses. Since customers of shapes, rod and pipes impose high requirements to the quality of extruded products these technologies are constantly improved in the direction of equipment automation, transition to new ways of semi-continuous extrusion and extrusion with the use of active friction forces. Aluminium alloys have high ductility which enables to produce by extrusion on horizontal hydraulic presses a variety of shapes of very complex configurations and different cross sections. Such properties of aluminum alloys like low density, high corrosion resistance, relatively high mechanical properties allow to use their products in various parts of machines, in auto industry, building constructions and architectural structures.

Among aluminum alloys one can point out those with low plasticity that are difficult in forming, so they are often used as casting alloys. In this regard, conventional technologies of production of long length deformed semi-finished products of these alloys are characterized by high labour- and energy-intensity and high economic costs.

The main consumers of solid and hollow shapes of aluminium alloys are aircraft industry, shipbuilding, refrigeration engineering, electrical engineering, radar production [11, 65-73]. In recent years the assortment of hollow shapes of aluminium alloys has significantly increased due to their use in construction for manufacturing of finishing and structural details (details for window stained glass, partitions, suspended ceilings, window frames, built-in furniture, etc.).

Aluminium alloys are often used in welded structures of various purpose, for example in heat power engineering. According the expert replacement of copper alloys for aluminum will allow to reduce the cost of pipes used in heat exchangers by almost three times while ensuring similar thermal characteristics of these devices. Until recent times semi-finished products (sheets, profiles, pipes, etc.) of wrought alloys for example thermally non-hardenable Al-Mg alloys have been used in welded structures.

Analysis of scientific and technical literature showed that at present for production of shape products of aluminum alloys and wire rod, the following groups of aluminum and wrought aluminum alloys are used:

– commercially pure aluminium A0, A5,A7, 1230 and others.;
– aluminium alloys Al-Mg-Si, grades 6063, АД33, АД35;
– alloys of system Al-Mg, grades АМг3, АМг5, 5082
– alloys of system Al-Ti-B (АТБ) used for grain refinement of bars.

Wrought aluminum alloys of different alloying systems are conditionally divided into pressure hardenable (thermally non-hardenable) and thermally hardenable, and alloys of low, medium or high strength, high ductility, heat-resisting, forging alloys etc. The most popular alloys are systematized according to the above parameters and summarized in table. 1.4. Their designation is given according to GOST 4784 – 97 and the international classification ISO 209 – 1.

In foreign countries, a four-digit designation is adopted to denote wrought alloys in which the first digit is for the series (group) and the principal alloying element in this series of alloys (table. 1.2).

Thermally hardenable alloys contains one or more elements which may be copper, magnesium, silicon or zinc as they at elevated temperatures are soluble in aluminum in large quantities. In this regard, there is a possibility to harden them using heat treatment. These include mainly alloys 2XXX, 6XXX and 7XXX. For extruded semis made of these alloys, certain limits of mechanical properties [68] (table 1.3) depending on the state are established: soft (O – annealed) and hard (T4 – hardened with subsequent aging). Thermally non-hardenable alloys include aluminum and those alloys where hardening is achieved by formation of supersaturated solid solution and by cold hardening. The difference in the properties depends on the composition of alloying elements or impurities which may be copper, chromium, iron, magnesium, manganese, silicon and zinc.

Table 1.2. Aluminium alloys

Characteristics of alloys	Labelling		Alloying system	Remarks
	in Russia	abroad		
Thermally non-hardenable				
	АД0	1050A		
	1230	1230		
	АМц	3003		
	Д12	3004		
	АМг2	5251		
	АМг3	5754		
	АМг5	5056		
	5082	5082		
Thermally hardenable				
	6063	6063		
	АД33	6061		
	АД35	6082		
	Д1	2017		
	Д16	2024		
	Д18	2117		
	1915	7005		
	1925	–		
High strength alloys	В95	–	Al-Zn-Mg-Cu	В93
	АК4-1	–	Al-Cu-Mg-Ni-Fe	АК4
	1201	2219	Al-Cu-Mn	Д20
	АК6	–		
	АК8	2014		
	АК5	–		
	АК12	–		

Table 1.3. Designation of industrial deformed alloys

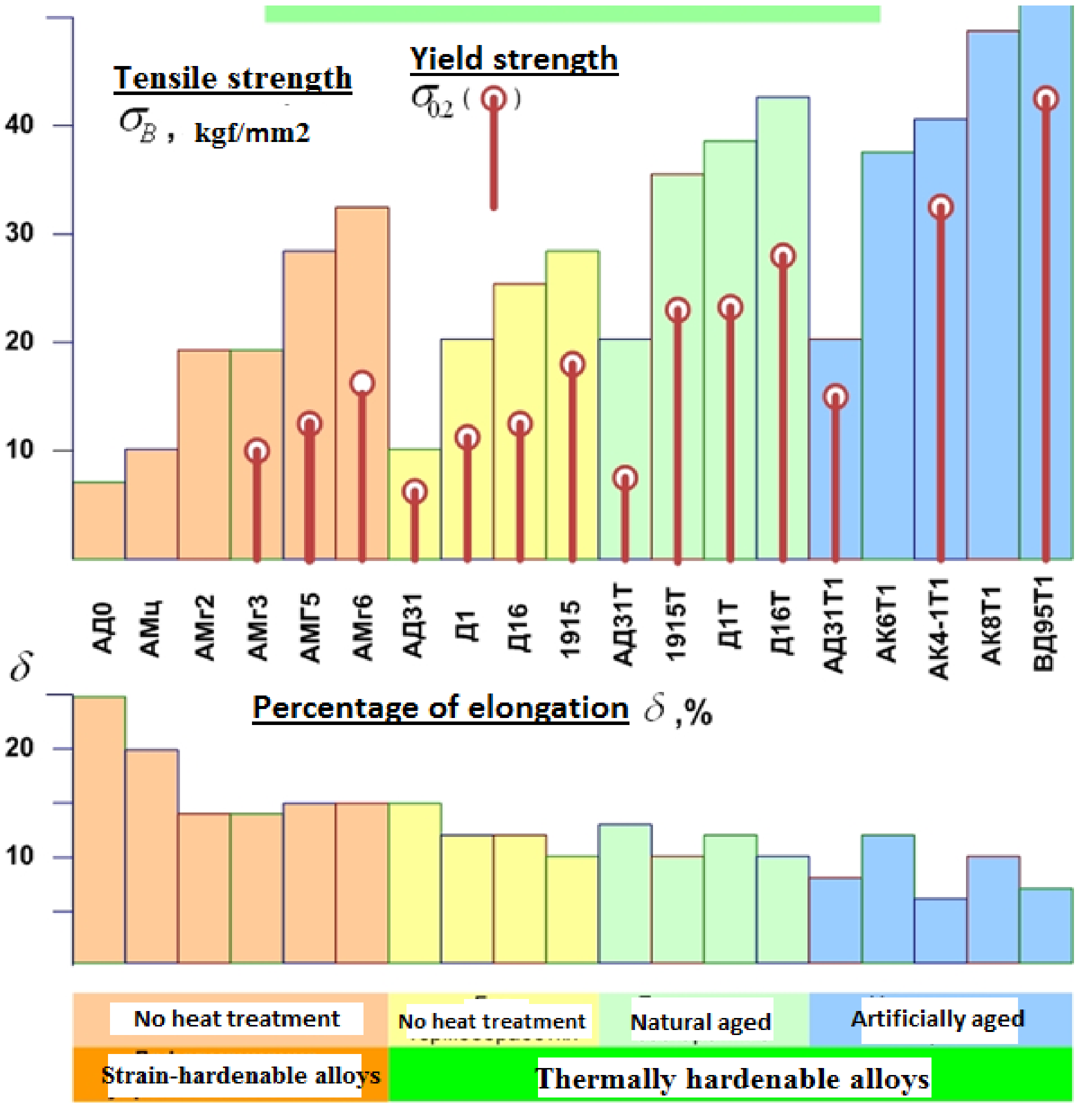
Designation	Principal alloying element
1XXX	Impurities lower than 1 %
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Magnesium and silicon
7XXX	Zinc
8XXX	Element not specified above

Table 1.4. Mechanical properties of aluminium alloys

Grade	Principal alloying elements, %	State	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	HB, kg/mm^2
Thermally hardenable aluminium alloys						
		Soft	185	95	18	45
		Hard	425	290	20	105
		Soft	180	70	22	45
		Hard	425	275	22	105
2117	2,6Cu; 0,35Mg	Hard	300	165	27	70
		Soft	180	76	20	–
		Hard	440	290	19	–
		Soft	90	50	–	25
		Hard	170	90	22	–
		Soft	125	55	25	30
		Hard	240	145	22	65
		Soft	195	80	20	–
		Hard	350	290	13	–
Thermally non-hardenable aluminium alloys						
		Soft	45	10	50	–
		Hard	115	110	5	–
		Soft	85	30	23	–
		Hard	185	165	2,5	–
		Soft	110	40	30	28
		Hard	200	185	4	55
		Soft	180	70	20	45
		Hard	295	285	2	–
		Soft	290	150	35	65
		Hard	435	405	10	105
		Soft	180	85	23	46
		Hard	285	240	5	75

Thermally non-hardenable alloys include aluminum and those alloys where hardening is achieved by formation of supersaturated solid solution and by cold hardening. The difference in the properties depends on the composition of alloying elements or impurities which may be copper, chromium, iron, magnesium, manganese, silicon and zinc.

Rods as the main form of the extruded products made on horizontal hydraulic presses have higher mechanical properties compared to hot rolled products. And they are produced both of thermally hardenable and non-hardenable alloys. Strength, ductile properties and hardness (HB) of these extruded products are shown in pic 1.6.



Picture 1.6. Guaranteed mechanical properties of extruded rods or aluminium alloys

Dependences of strength and ductile properties of products made of known aluminum alloys of various systems on temperature-and-speed and deformational parameters of processing are given in the reference. However it should be noted that the range of deformation rates during testing is not big which to some extent limits the use of existing data for design of technological processes of extrusion production.

We will give a brief evaluation of processability and machinability of aluminum alloys [70-73] from the points of their use in combined processing.

The most applicable for extrusion processing are commercially pure aluminium grades 1350, 1020, AD1 and soft alloys 6XXX. They are well-deformed in hot and cold conditions with average strength they have high corrosion resistance and high electrical conductivity [72]. Ductility and weldability of the alloys at the temperature of extrusion processing of 450-500°C are high enough, which allows to extrude them at high speeds, and apply semi-continuous extrusion and butt welding. Basic amount of profiles of various configurations and sizes are produced of these alloys including very complex thin-walled hollow extruded semi-finished products and sector and electrical wires.

Al-Ti-B alloys [73-77] are currently widely used for production of grain refiner rods with the aim of refining aluminum bars. The need for grain refiner rods is quite high as almost all aluminum alloys produced in Russia and foreign countries are modified during casting for refinement of the cast structure. Conventionally Al-Ti-B grain refiner contains 2-5% of titanium and 0,8-1,5% boron, and their ratio is from 2:1 to 5:1. Products made of these alloys are satisfactory to be pressed but difficult to be processed by methods of conventional rolling because they are prone to cracking under the action of tensile stresses.

High volume of welding wire of Al-Mg alloy system is consumed by domestic industry. Extrusion products made of these alloys are characterized by high strength and corrosion resistance together with high ductility. At the same time general corrosion resistance of naturally aged semi-finished products of alloys 5XXX is very high. Manganese, zirconium, chromium increase strength characteristics of the alloys, improves weldability and resistance to corrosion. These alloys with sufficient content of magnesium are well welded in all types of welding including fusion welding.

Based on the analysis there were selected experimental deformed alloys of various alloying systems, their chemical composition these alloys and of their counterparts is given in table. 1.5.

Table 1.5 – Chemical composition of alloys for investigation (aluminium as basis), %

Alloying system and grade of alloy	Si	Fe	Mg	Cu	Ti	Zn	Mn	B	Be
1xxx 1230	0,17	0,24	0,014	0,038	0,012	0,044	0,01	-	0,0002-0,005
5xxx 5082	до 0,4	до 0,4	5,8-6,8	0,1	0,02-0,1	до 0,2	0,5-0,8		
6xxx 6063	0,43	0,28	0,56	0,037	0,022	0,037	0,038	-	
8xxx АТВ1	0,3	0,35	-	-	5,4	-	-	0,87	
8xxx АТВ2	0,3	0,35	-	-	3,2	-	-	0,40	

Thus, review of scientific and technical literature showed that the available data on mechanical properties of aluminum alloys is insufficient, further research is required, first all all for processes characterized by high degrees and rates of deformation such as extrusion. Creation of new aluminium alloys [78-80] of various alloying systems also necessitates the study of their properties. In connection, it must be considered relevant to conduct research of strength and ductile properties of these aluminum alloys in a wide range of changes in temperature-and-velocity and strain parameters of metal forming.

1.4 CONCLUSIONS AND SETTING OF RESEARCH OBJECTIVES

Analysis of scientific and patent literature allowed to make the following conclusions and formulate research objectives:

1.One of the main development trends in industrial production of long products of non-ferrous metals and alloys and especially of aluminum alloys is the application of combined metal processing which allows to obtain technical and economic advantages by eliminating excess operations from production process and allows for reduction of energy consumption.

2.As a basis for development of such new technological processes, combination of shape rolling with extrusion is considered to be promising. It gives opportunity to use their advantages in the most efficient way.

3.As basic materials it is advisable to use deformed aluminum alloys of different alloying systems in research of new combined processes because they are characterized by high processability and machinability, relatively low melting temperatures and comparatively high mechanical properties.

4.Since scientific and technical literature has only scattered data for power parameters of combined rolling-extrusion it is necessary to research the parameters.

5.Issues related to formation and changes of properties of aluminum semi-finished products produced according to technologies of combination of various deformation patterns in one component, are not sufficiently studied, so metallographic examinations of the structure and properties of extruded products are required.

6.For practical implementation of the new continuous extrusion processes it is necessary to prepare technical specifications for design of plants for combined processing of aluminum alloys, to develop their design and conduct pilot testing.

2. SIMULATION AND ANALYTICAL STUDIES OF COMBINED ROLLING-EXTRUSION PROCESSING OF ALLUMINIUM ALLOYS

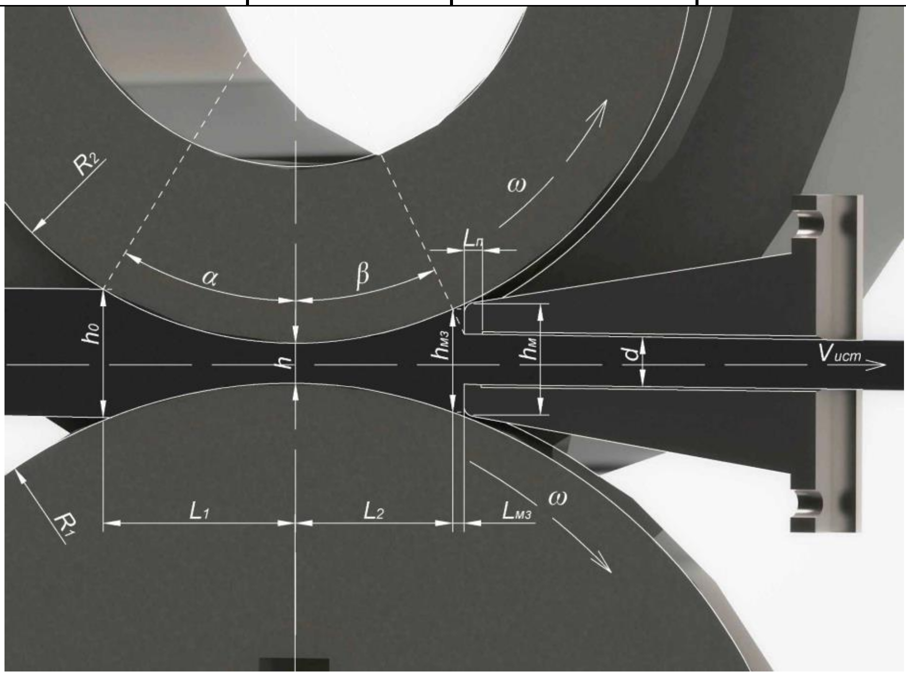
This paper shows the results of studies of the form of deformation zone, practicability and power parameters of rolling-extrusion taking into account rheological properties of experimental alloys.

The diagram shown in picture 2.1 and dimensionless and geometrical parameters (table 2.1) of the process for currently available combined processing plants were used during analysis of the process. Dimensionless parameters were used for single-valued description of the shape and size of deformation zone and with their help the shape of the pass, die, feedstock and extruded products was characterized [1]. The rotation frequency of the rolls varied in a range 4-14 rpm.

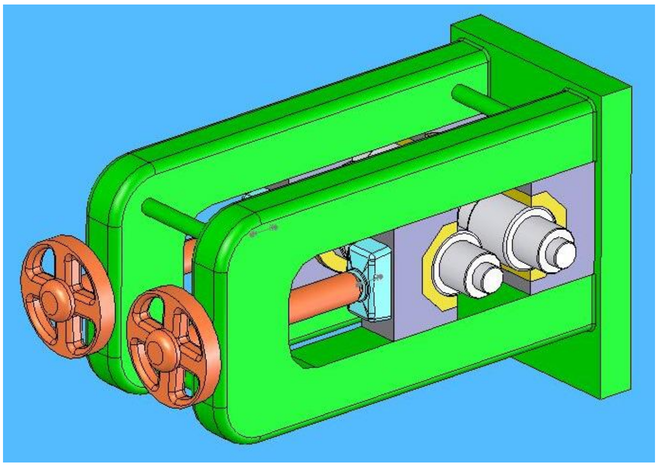
Alloys given in table 1.5 were used for simulation and studies.

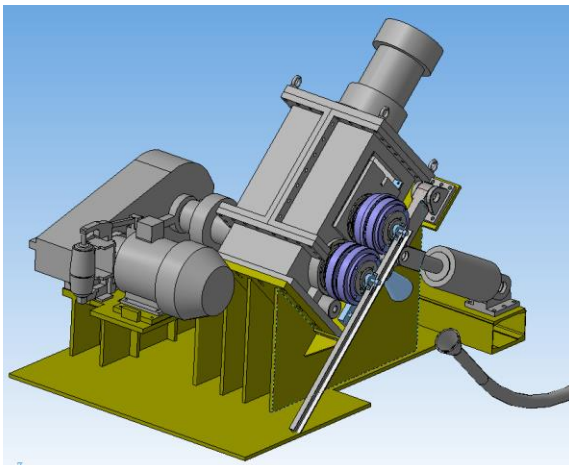
Table 2.1 – Data for calculation of combined rolling-extrusion

Value	Name of plant			Dimension-less parameter
	Combined rolling-extrusion (CRE-200)	Combined casting and rolling-extrusion (CCRE-2,5)	Combined casting and rolling-extrusion (CCRE-4)	
Diameter of roll with tongue D_1, mm	214	462	428	-
Diameter of roll with groove D_2, mm	164	394	428	-
Minimum pass height h, mm	7	10	19	-
Average diameter of rolls D_0, mm	189	428	428	$A = \frac{D_0 - h}{h}$
Pass width b, mm	15	22	42	$\tilde{b} = \frac{b}{h}$
Initial height of feedstock h_0, mm	14	20	42	$\tilde{h}_0 = \frac{h_0}{h}$
Initial width of feedstock b_0, mm	14	20	40	$\tilde{b}_0 = \frac{b_0}{h}$
Height of face $h_м$, mm	20	25	31	$\tilde{h}_м = \frac{h_м}{h}$
Diameter of extrude product d, mm	7-9	9-12	9-15	$\tilde{h}_1 = \frac{d}{h}$

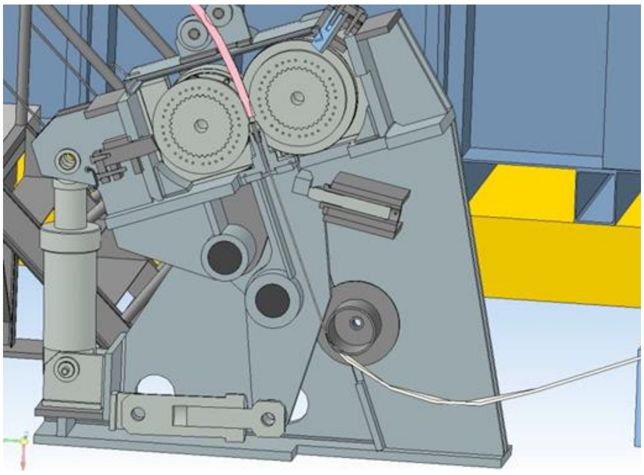


Picture 2.1. Flowchart of combined rolling-extrusion process





а б



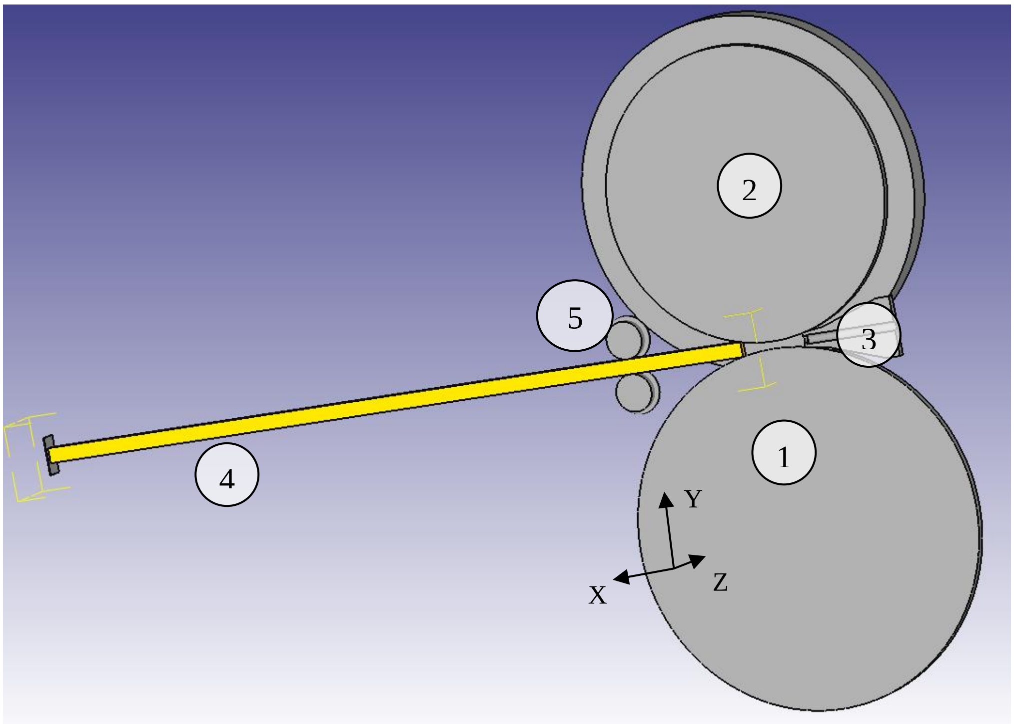
в

Picture 2.2 - 3D models of plants for combined rolling-extrusion (CRE)
СПП-200 (а); СЛИПП-2,5 (б); СЛИПП-4 (в)

2.1. SIMULATION OF COMBINED ROLLING-EXTRUSION PROCESS

On the basis of FE analysis for the process of combined rolling-extrusion of a rod with a diameter of 9.5 mm of alloy АТБ1, change of stress-strain state, forces on the tools and torques of the rolls depending on the temperature of the tool and rotation speed of the rolls were calculated. A software package DEFORM™-3D was used for 3D simulation. Data of deformation resistance of alloy АТБ1 (see part 2.3) was imported to a software package DEFORM™-3D.

Building of geometric three-dimensional models of extrusion components of a CRE plant and feedstock of were made with a software package SolidWorks® (picture 2.3). Then these geometries were imported in the format *.stl to the software package DEFORM™-3D.



Picture 2.3 - 3D model of combined rolling-extrusion (CRE) СПП:
1 – roll with tongue; 2 – roll with groove; 3 – die; 4 – feedstock;
5 – feed rolls

The following parameters are selected as simulation input data.

1. Material of feedstock – aluminium alloy АТВ1 (see table 1.5), material of rolls and die – tool steel 5ХНМ;

2. End product is extruded product with a diameter 9,5 mm;

3. Parameters of rolls and die:

- pass width – 22 mm;
- product dimensions – 20x20x500 mm;
- size of die face – 20x21 mm;
- reduction ratio during extrusion – 6.2;
- diameter of roll with tongue – 462 mm;
- diameter of roll with groove – 394 mm.

4. Rotation frequency of rolls from 4 to 14 rpm.

5. The conditions of contact interaction of feedstock and rolls were accepted according friction law of Siebel with index of friction during metal deformation ψ=0,5 and for die face ψ=0,2.

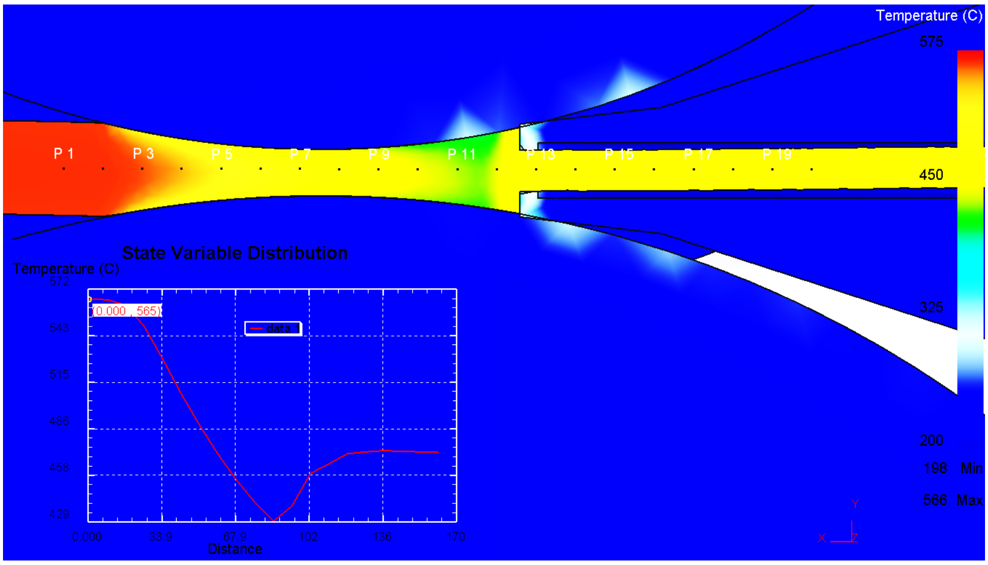
6. Percent reduction during rolling ε=50%.

7. Initial temperature of feedstock $T_{заг}$= 575°C, heat exchange with environment and the tools;

8. Initial temperatures of die $T_м$ and rolls $T_в$ were measured from 100 to 300°C, heat exchange with environment and feedstock occurs respectively.

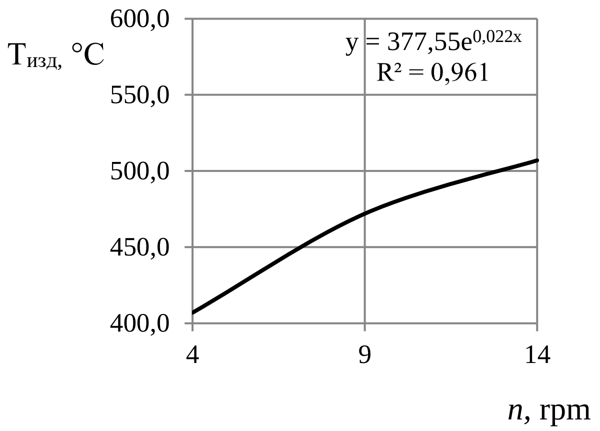
An important factor affecting the value of stress state and stable conditions of rolling-extrusion process is the temperature in plastic deformation zone and the temperature of extruded rod.

Picture 2.4 shows temperature behavior in deformation zone under the following conditions: $T_в = T_м$ = 200 °C, $T_{заг}$ = 575 °C, rotation speed of rolls – 9 rpm. As can be seen from picture. 2.4, there is an intensive temperature drop from 566°C down to 429 °C in the area of rolling, then the temperature slightly increases due to deformational heating. Such temperature pattern has a significant influence on stress state, as will be illustrated below.

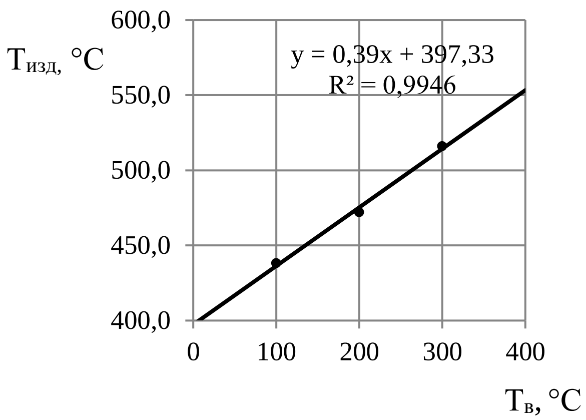


Picture 2.4 – Metal temperature behavior in deformation zone

Picture 2.5 shows temperature change of an extruded product $T_{изд}$ at the exit of the die mouth caused by rotation frequency (picture 2.5 a) and the roll temparature (picture 2.5 б). It is seen that with increase of rotation frequency of the rolls the temperature of product at the outlet of the die grows because rate of deformation increases (pic. 2.6), resistance to deformation grows, and therefore heat dissipation as well, the time for heat transfer between metal and rolls decreases, consequently the temperature drop of the feedstock in the area of rolling and pressing-out decreases.

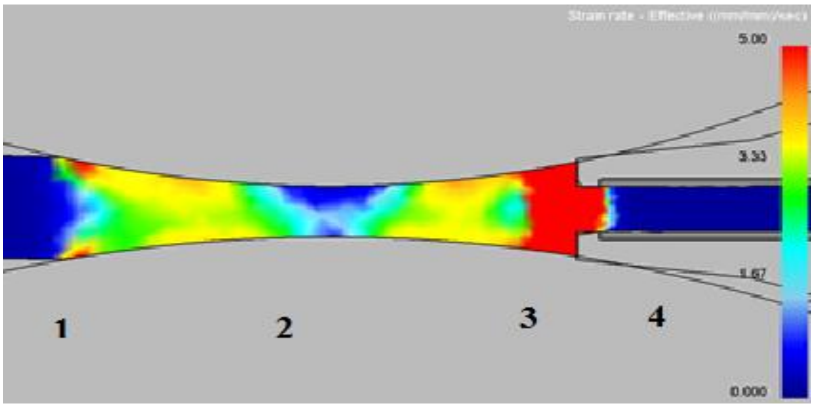


a



б

Picture 2.5 – Influence of rotation frequency of rolls (a) and temperature of tool (б) on temperature of extruded product



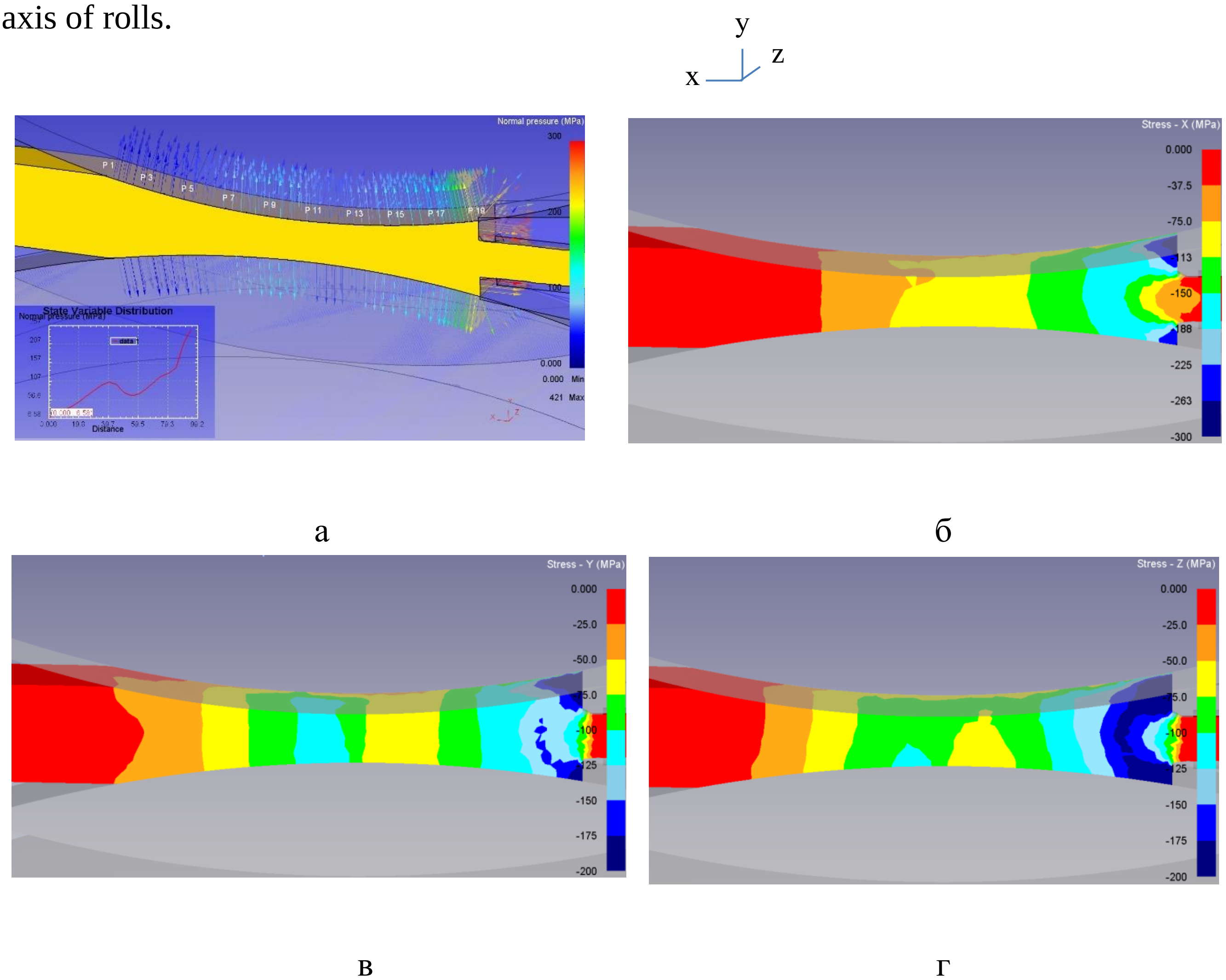
Picture 2.6 - Deformation rate behavior during CRE:

1 – area of feedstock gripping, 2 – rolling area, 3 – pressing-out area, 4 – extrusion area

Analysis of the dependences shows it is possible to control thermal conditions by regulating the temperature of the rolls and the die thanks to their initial heating and subsequent cooling during combined rolling-extrusion. In addition the product temperature can be reduced by reducing rotation frequency of the rolls.

Analysis of the deformation rate at $T_в = T_м$ =200°C, $T_{заг}$ = 575 °C and rotation frequency of the rolls 9 rpm shows that in the areas of gripping and rolling the deforamtion rate is not higher than 2,5 s^{-1}, in section of the cnters of rolls the defromation rate decreases down to 0.1-0.3 s^{-1}, further in the area of pressing-out the rate has a slight increase, and then suddenly reaches maximum values up to 130 s^{-1} in the area of pressing.

The behavior of deformation rates and temperature under the same parameters influence the distribution of both contact stresses (picture 2.7 a) affecting on the rolls and die, and internal stresses in metal (pic. 2.7 б, в, г). Analysing the data you can note that in the areas of gripping and rolling of feedstock, an increase of normal contact stresses is observed, and they reach their maximum values in the plane passing through the common axis of rolls.

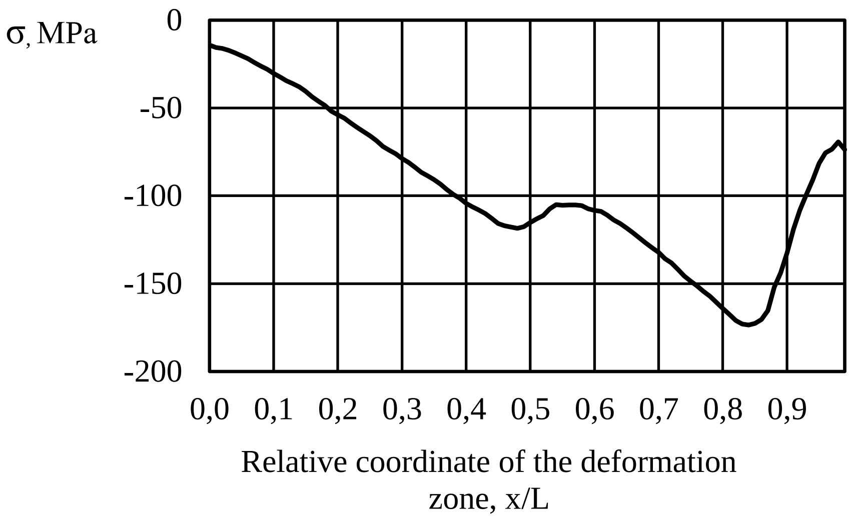


Picture 2.7 – Distribution of normal contact stresses on tool (a) and internal stresses in metal along axes X (б), Y (в), Z (г)

In the area of pressing-out normal contact stresses at first decrease and then increase, thus significantly non-monotone character of their change along the deformation zone is observed. This can be explained by non-monotone character of deformation along the deformation zone, and also by the fact that in the area of pressing-out the effect of active and reactive friction forces increases. In the area of pressing-out the stresses reach their upper value.

Analysis of axial stresses in metal (see pic. 2.7 б, в, г) showed a constant increase of stresses σ_x up to the extrusion area and their decrease in the area of rod outflow from extrusion area. Behaviour of stresses σ_y repeats nonmonotone distribution of normal contact stresses. Stresses σ_z change also non-monotonically and have maximum values in the area of extrusion.

As it appears from the analysis of distribution of stresses, a very favourable pattern of the stress state is formed during rolling-extrusion which is confirmed by the diagram of distribution of average normal stress σ (pic. 2.8).

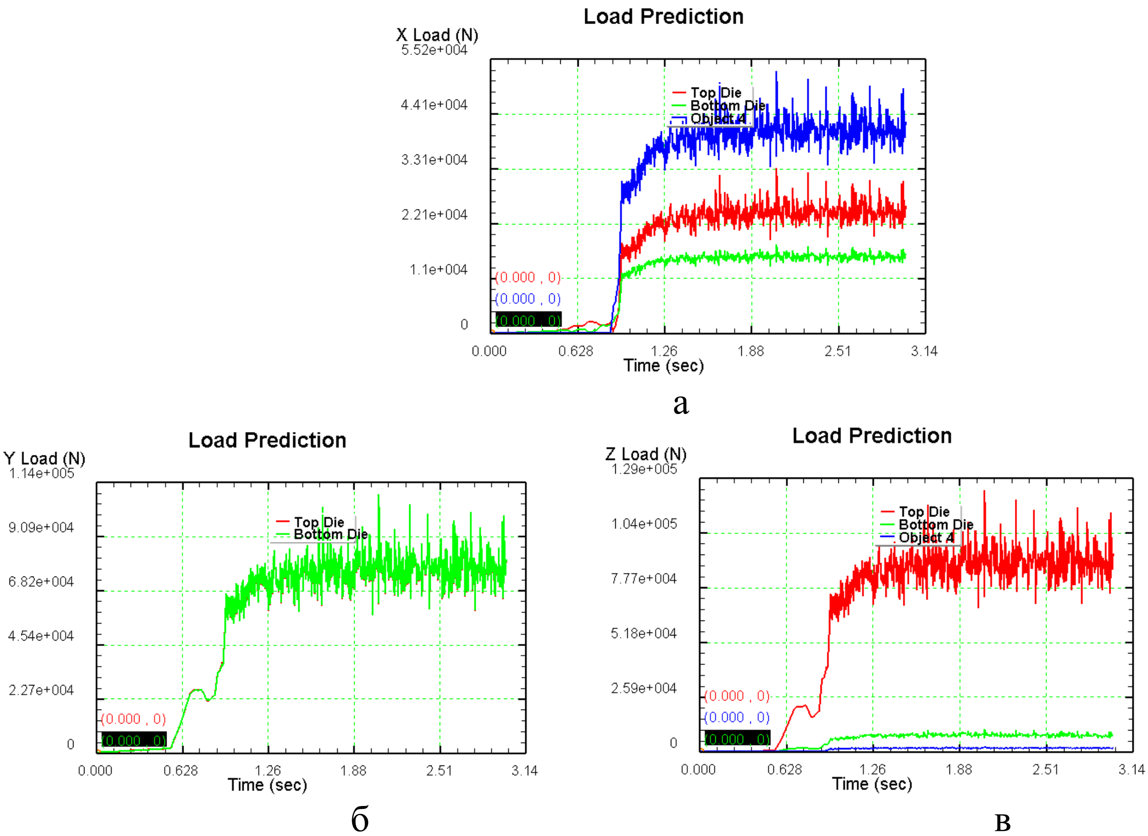


Picture 2.8 – Change of average normal stress along deformation zone

Based on this data it can be concluded that during extrusion of metal by combined method of rolling–extrusion, additional type of deformation appears – alternating deformation in which every elementary volume of metal first undergoes vertical deformation and horizontal deformation of elongation, and after passing the minimum roll gap, the deformation of opposite sign. Such deformation behavior contributes to creation of favourable pattern of stress state and higher ductility, particularly of cast metal, and also increase of the maximum allowable extrusion rate [7-9].

When simulation of force actions during combined rolling-extrusion the roll and the die were put into coordinate system so that the direction of rolling and extrusion would be opposite to the direction of axis OX (see picture 2.2). Forces affecting the rolls and die along axes X, Y, Z were calculated in Deform™-3D for such system.

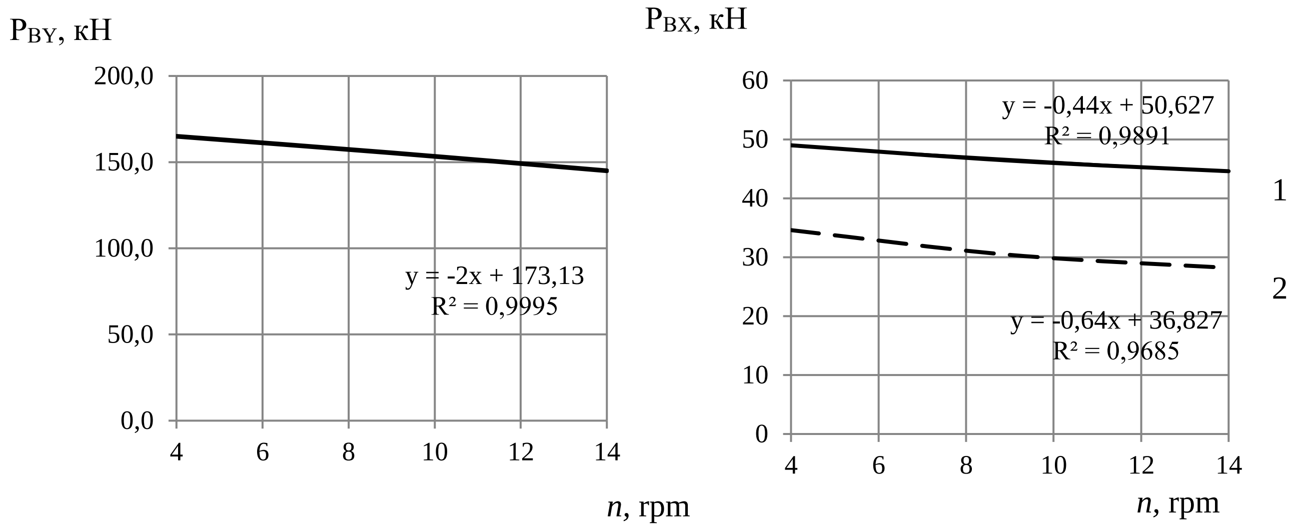
Picture 2.9 shows diagrams of change of forces on the rolls and die depending on the time of the process at the following conditions:
$T_{в} = T_{м}$ =200 °C, T_{feed} = 575 °C, rotation frequency of the rolls – 9 rpm.



Picture 2.9 - Diagrams of change of forces on rolls and die depending on time:

a – along axis X; б – along axis Y; в – along axis Z

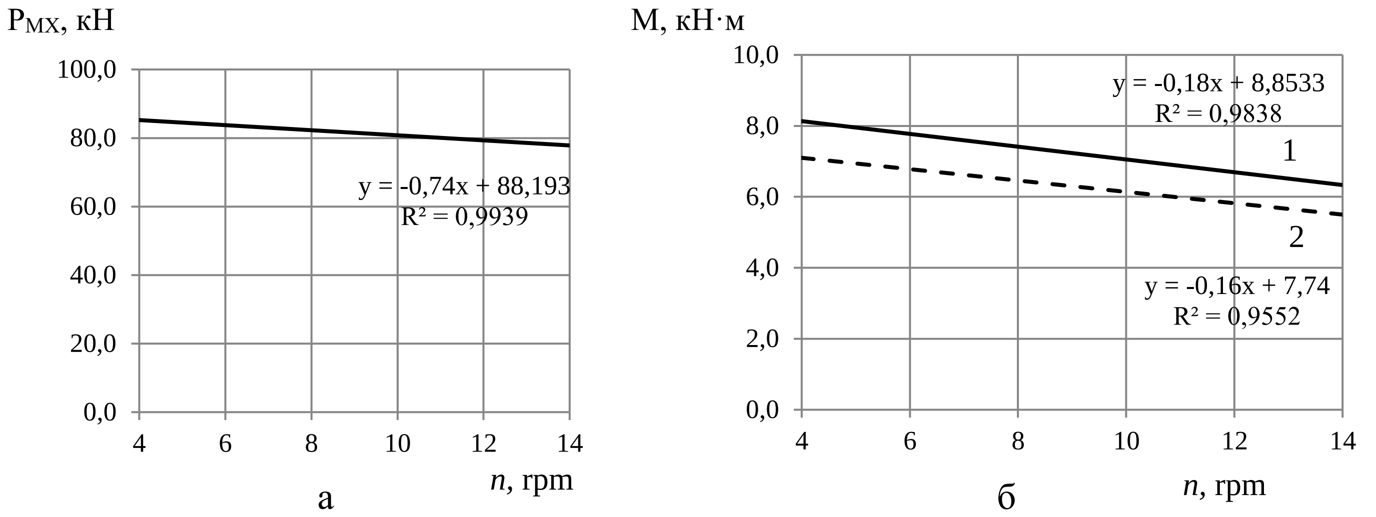
Picture 2.10 shows dependences of forces acting on roll along axis OY (P_{BY}) and OX (P_{BX}) on initial temperature of feedstock, tools and rotation frequency of the rolls. With increase of rotation speed of the rolls the temperature of feedstock in the areas of rolling and pressing-out falls. It causes decrease of forces acting on the rolls and along axis OY, at the same time force P_{BY} is practically identical for both of the rolls.



Picture 2.10 – Diagrams of forces change acting on rolls and die depending on rotation frequency of rolls: 1 – roll with groove, 2 – roll with tongue

Force P_{BX} is acting on the rolls along axis OX which leads to undesired displacement (separation) of the rolls. The value of this force for the roll with groove is 1,4-1,6 times higher than for the roll with tongue. It can cause uneven “pressing-back” of rolls from the die resulting ingress of metal into a gap between the die and the rolls.

When designing CRE plants for secure CRE process it is necessary to know the value of force P_{MX} acting on the die along axis OX and distribution of torques on the rolls. Picture 2.11 shows dependence of force and torques on the rolls with groove and the rolls with tongue upon rotation frequency of the rolls.

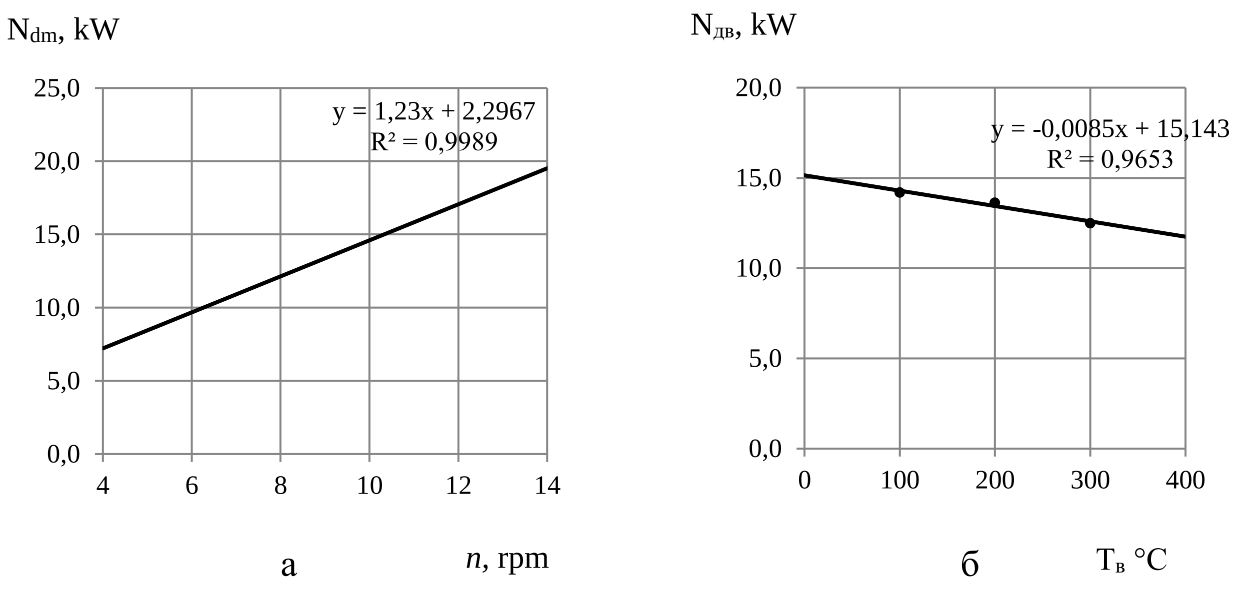


Picture 2.11 – Diagram of change of torques on rolls depending on rotation frequency of rolls:

1 – roll with groove; 2 – roll with tongue

Analysis of the dependences at T_{feed} = 575 °C and rotation frequency of the rolls 9 rpm shows that the value of torque for the roll with groove is different from the value of torque for the roll with tongue which is explained by different effective diameter of rolls. Maximum values of torques should be taken into account during design of a pinion stand and selection of gearboxes and motors.

Based on the obtained results the required power N_{dm} of a drive motor was calculated considering the efficiency coefficient of the gearbox (0,96) and a pinion stand (0,95). The obtained dependences on rotation frequency of the rolls and temperature of the tools are shown in picture 2.12.



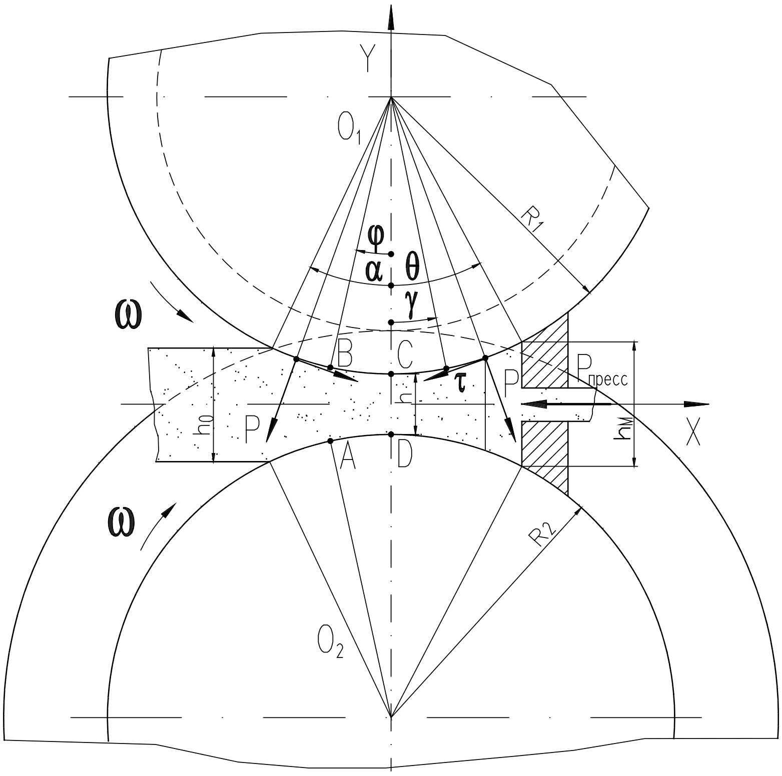
Picture 2.12 – Diagram of change of required power of drive motor depending on rotation frequency of rolls (a) and temperature of roll and die.

Thus, for the accepted conditions of processing a simulation was conducted with the software package Deform™ 3D resulting in establishing of dependences of temperature of extruded products on the rotation speed of rolls and the temperature of the tool; on forces and stresses acting the tools; on torques on the rolls and the required power of drive motor. These results were used further in design of technology and equipment and in experimental studies.

2.1. RESEARCH OF GEOMETRICAL SHAPE OF DEFORMATION ZONE AND FEASIBILITY OF ROLLING-EXTRUSION PROCESS

In steady state of combined rolling-extrusion, normal and shear stresses act on a feeding strip along all contact surface of extruded metal with the tool. According to the basic laws of the theory of metal forming, deformation of feedstock occurs in the direction of the least resistance, and the contact friction forces on the contact surface of the tool with extruded metal in the direction metal flow at the start and at the end of deformation zone will have opposite directions. According to a classic definition of the theory of rolling given in the paper of Tselikov A.I. [81], vertical section in which contact friction forces change their direction is called neutral, and the corresponding central angle γ divide the amount of extruded metal into two zones. In the first zone the speed of metal flow is lower than the speed of the rolls, that is why contact friction forces will be active and will contribute to the process of metal deformation. In the second zone contact friction forces will be reactive and will impede the process. For the case of rolling-extrusion when metal deformation at the exit of the pass is limited by the die these forces are kind of reserve. And as the angle γ decreases, the value of active friction forces will get lower and the process will become unstable and impossible. So at the first stage of research it is necessary to identify the value of angle γ that determines the geometry of deformation zone.

In order to find this angle according with recommendations of the author of this paper [81] we set up a balance equation of projections of all forces acting on metal along longitudinal axis x located in the direction of its movement (pic. 2.13). And we accept the following assumptions: the rolls rotate at the same speed and their effective diameters are equal; pressure on the arcs of contact and on lateral surfaces of the pass is constant and equal to *p*; contact friction forces are calculated according with the friction law of Siebel written as $\tau = \psi p$; edges of zones by neutral plane for arcs of rolls and lateral surfaces of the pass are located in one vertical plane; we ignore external broadening in the initial rolling area and consider it restricted during reduction in the pass.



Picture 2.13 – Scheme for calculation of angle γ

We shall solve a problem for identification of angle γ for the case when the die is located at a certain distance from the general axis of rolls. We accept that the angle γ will increase in the direction to the right of line O_1O_2. Let us find projections of all forces acting on extruded metal, on axis x, and we shall make a balance equation of projection of forces in the following form

$$\sum F_{ix} = -2b\int_0^{\alpha} Rp\sin\varphi d\varphi + 2b\int_0^{\alpha} R\tau\cos\varphi d\varphi + 2b\int_0^{\theta} Rp\sin\varphi d\varphi + 2b\int_0^{\gamma} R\tau\cos\varphi d\varphi -$$
$$- 2b\int_{\gamma}^{\theta} R\tau\cos\varphi d\varphi + 2\int_0^{\alpha} \tau S_1(\varphi)d\varphi + 2\int_0^{\gamma} \tau S_2(\varphi)d\varphi - 2\int_{\gamma}^{\theta} \tau S_3(\varphi)d\varphi - P_{пресс} = 0. \quad (2.1)$$

For identification of extrusion force we shall use a simplified formula of Stepansky L.G. [82] which can be written as

$$P_{пресс} = 1{,}15\sigma_s F_м (1 + 1{,}4\ln\mu,). \quad (2.2)$$

Lateral surfaces of the passes $S_1(\varphi)$, $S_2(\varphi)$, $S_3(\varphi)$ contacting extruded metal shall be found the following way. Lateral surface of the pass contact and extruded metal depends on the current angle and is equal to

$$S(\varphi) = R^2\left[(2 + \frac{h}{R})\sin\varphi - \sin\varphi\cos\varphi - \varphi\right]. \quad (2.3)$$

Than

$$\int_{\varphi_1}^{\varphi_2} S(\varphi)d\varphi = -R^2\left[(2 + \frac{h}{R})\cos\varphi + 0{,}5\sin^2\varphi + \frac{\varphi^2}{2}\right]\Bigg|_{\varphi_1}^{\varphi_2}. \quad (2.4)$$

Taking into consideration that the values of gripping angle $\alpha < 20^0$, due to smallness of angles φ, we shall accept the following simplification:

$$\sin\varphi \approx \varphi;\ 1 - \cos\varphi \approx 2\sin^2(\varphi/2) \approx \varphi^2/2. \quad (2.5)$$

Than the expression (2.4) will have the following form

$$\int_{\varphi_1}^{\varphi_2} S(\varphi)d\varphi = -R^2\left[(2 + \frac{h_1}{R})\cos\varphi + \varphi^2\right]\Bigg|_{\varphi_1}^{\varphi_2}. \quad (2.6)$$

Upon integrating of equality (3.15) and after transformations we obtain equation for angle detection γ.

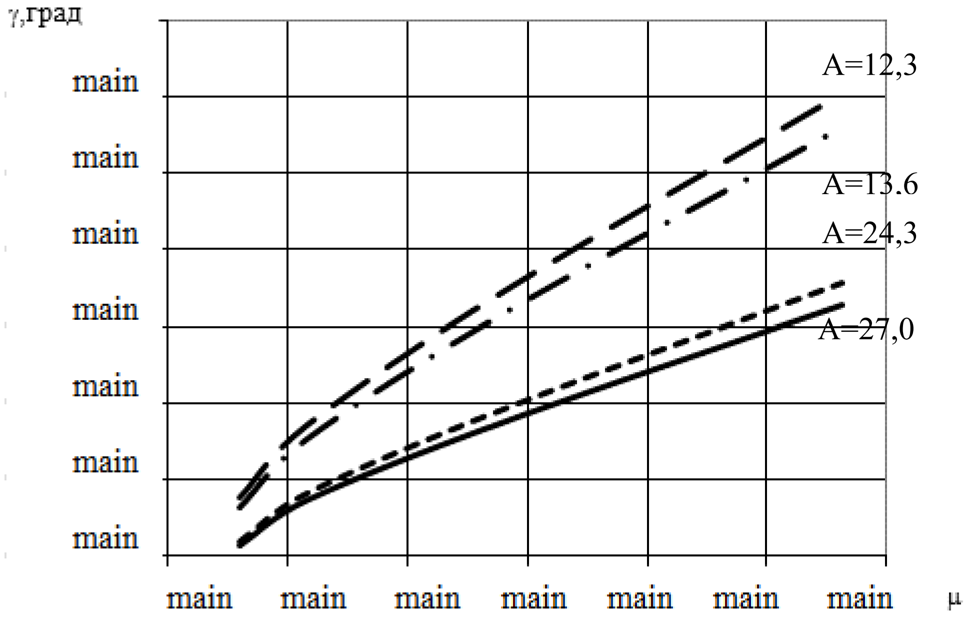
$$\gamma^2 + \frac{2b}{h}\gamma + (\cos\alpha - \cos\theta)(\frac{b}{\psi h} - 1) + \frac{b}{h}(\sin\alpha - \sin\theta) - \frac{P_{пресс}}{2\tau Rh} = 0. \quad (2.7)$$

After substitution we obtain equation for angle detection γ in the following form

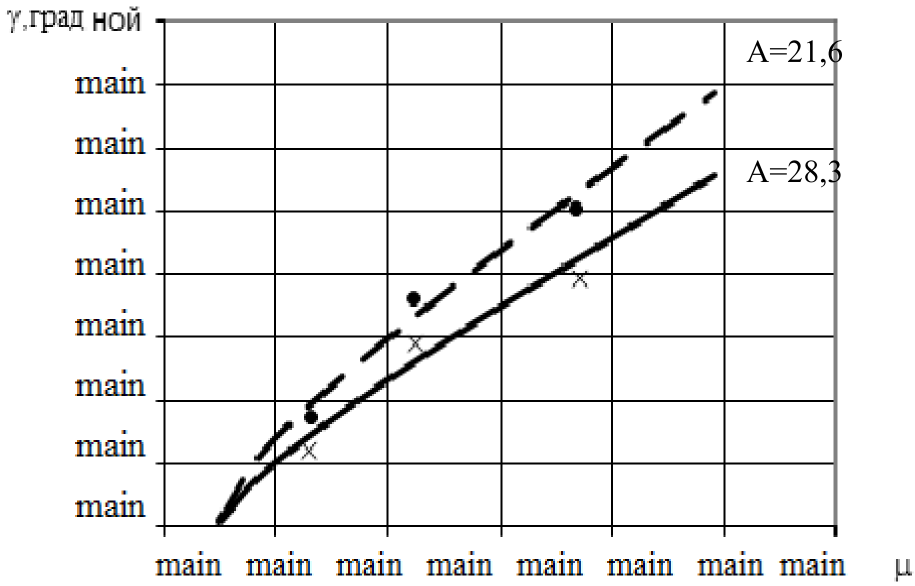
$$\gamma^2+\frac{2b}{h}\gamma+(\cos\alpha-\cos\theta)(\frac{b}{\psi h}-1)+\frac{b}{h}(\sin\alpha-\sin\theta)-\frac{1{,}15b\left[1+\frac{2R}{h}(1-\cos\theta)\right](1+1{,}4\ln\mu)}{2R\psi}=0. \quad (2.8)$$

In the general case pressure p and friction stress τ are different in the forward slip zone and backward slip zone, that is why solution of the last equations gives approximate values γ.

For calculation of the angle γ, a program in Excel and certain calculations were made, the results of the calculations are presented in graphic form in pictures 2.14, 2.15. Analysing the data one can note that with increase of reduction ratio, the angle γ grows in the whole range of deformation conditions. At the same time the area of active friction forces becomes larger because high pressures for extrusion are required.



Picture 2.14 – Dependence of angle γ on extrusion reduction μ at the following dimensionless parameters of deformation zone: $\tilde{b}=2$; $\tilde{h}_M=2$; $\tilde{h}_0=2$; $\tilde{d}_1=0{,}8$



Picture 2.15 - Dependence of angle γ on extrusion reduction μ for aluminium grade 1230 in the following dimensionless parameters:

$\tilde{b} = 2$; $\tilde{h}_M = 2{,}5$; $\tilde{h}_0 = 2$; $\tilde{d}_1 = 0{,}8$;

• ,×- experimental data respectively for A=21,6 and A=28,3

Inverse dependence is seen during analysis of the impact of specified roll diameter on angle γ. And with bigger diameter rolls having the same extrusion values it is possible to make higher pressures and reduce the area of action of active friction forces which is limited by angle γ. The calculations data were compared to the data of experiments at different distances of the die from the common axis of the rolls, for aluminium grade 1230. It is notable that during experiments it was revealed that under the experiment's conditions, optimal maximum values of angle θ (a, consequently and γ) are not higher than gripping angle α. Analysis of the graphic dependences shows good repeatability of experimental and calculation data.

For quantitative estimation of feasibility of combined rolling-extrusion, a theoretical analysis of combined rolling-extrusion was conducted by the methods given in the paper [49]. It is accepted that implementation of the process requires fulfillment of the condition of power balance, i.e. total power of active friction forces N_a should be equal (or higher) to the power of reactive forces N_p, that are used for deformation and overcoming of friction in deformation area and on the surface of the tool.

$$N_a - N_p = 0. \qquad (2.9)$$

If this condition is not fulfilled it is possible that rolls will have slipping against feedstock, so the process of extrusion will not be possible. As feasibility assessment criterion of the process, a conditional coefficient of power reserve K_N, calculated as relation of power N_a to power N_p, and if its value is higher than 1 then metal extrusion through the die is possible, and its probability grows with the growth of this coefficient.

Picture 2.16 shows calculation data obtained in accordance with these methods for production of rod of aluminium alloy 6063 depending on various conditions of contact friction of metal with rolls and die ($\psi_{м}$ - index of friction on die face, ψ_n - index of friction on the parallel land of the die $\psi_в$ и ψ_{cm} - indexes of friction respectively on the surface of the roll and the walls of the roll with a groove) by combined rolling-extrusion method on various plants (see table 2.1).

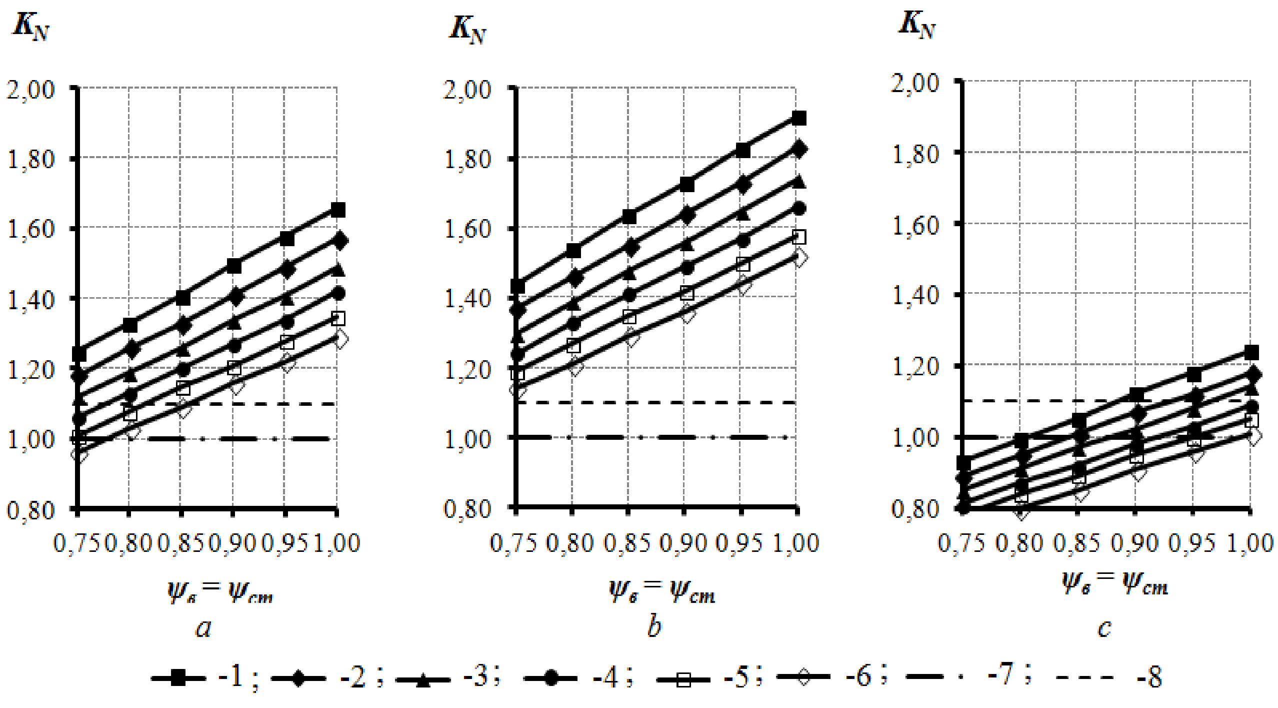


Fig. 2.16. Coefficient of power reserve K_N changing depending on the conditions of friction:
a – for unit CRE-200 (A=26), b – for unit CCRE-2,5 (A=38,4); c – for unit CCRE-4 (a=21,5);
1 – $\psi_м = \psi_n = 0{,}50$; 2 – $\psi_м = \psi_n = 0{,}55$; 3 – $\psi_м = \psi_n = 0{,}60$; 4 – $\psi_м = \psi_n = 0{,}65$;
5 – $\psi_м = \psi_n = 0{,}70$; 6 – $\psi_м = \psi_n = 0{,}75$; 7 – theoretical limit of process feasibility;
8 – boundary process feasibility

Analysis of the data given in picture 2.16 shows that the diameter of rolls (pic. 2 *а*, *б*) has a significant influence on increase of feasibility of the process, however with the increase of the pass size and with one and the same diameter of rolls (pic. 2 *б*, *в*), the coefficient of power reserve K_N decreases. This should be taken into account when designing plants for combined processing.

2.3. CHARACTERIZATION OF RHEOLOGICAL PROPERTIES OF EXPERIMENTAL ALUMINIUM ALLOYS

The most important indicator required for calculation of power conditions in metal forming processes is resistance to deformation [83].

For well-known metals and alloys such as 1230, 6063 etc. rheological properties can be found in reference literature.

We shall demonstrate identification of resistance to deformation in a wide range of deformational and temperature-speed conditions of processing for these alloys by the example of ATB1 (system Al-Ti-B). Scientific literature does not contain data on the curves of strain hardening for this alloy. To obtain this data, an updated testing method of hot torsion of samples with various diameters was used. It is shown in the paper [68]. With the use of this method you can identify rheological properties of metals and alloys at deformation degrees of up to 99% which is compared to real values of rolling—extrusion.

Samples for torsion testing were made of bars, diameter 163 mm. The bars were cut into templates of 50 mm high, then they were cut into feedstocks 30x30x110 mm which were used further to make samples with a turning machine, the diameter of the samples in the test section – 8 and 10 mm, length – 50 mm. Torsion testing of the samples was performed with a machine [64] equipped with a DC motor, torsion converter, a thyristor converter and an instant star-and-stop clutch. The machine allows to identify resistance to deformation and ductility of metal not only at any fixed deformation rate in the range 0,1 – 2800 rpm but also to simulate production processes with continuous change of speed and having stops as well.

Two standard samples with different diameters in test section were subject to torsion testing in order to minimize errors related to uneven distribution of speed and degree of deformation in cross section of a solid sample. The heating temperature of the sample was identified by the temperature of the molten salts in which it was placed for torsion. After achieving the temperature of the molten salts preset by potentiometer one end of the sample was placed with special clamps into “active” grip, and turned counterclockwise up to the stop. By manual rotating clockwise and by lowering a spindle the other end of the sample was put into the lower “passive” grip which was fixed at the bottom of a glass with nitrate melt. After heating the sample and checking correctness of adjustment of all measuring channels for all registered parameters of the process, the spindle rotation mechanism, oscillograph and then coupling clutch were activated. After the torsion of the sample the coupling clutch and oscillograph were switched off, the spindle rotational mechanism – stopped. The spindle was lifted, both ends of the sample were removed with special clamps. Next sample was put the same way, the whole sequence of actions was repeated.

Duration time of sample in the molten salts for heating up to required temperature was calculated by formula [63].

$$t = 0{,}1 \mathrm{d}\, \mathrm{k}_1 \mathrm{k}_2 \mathrm{k}_3 + \mathrm{t}_{\text{в}}, \qquad (2.10)$$

Where d – diameter of sample, mm; k_1 – environment coefficient (for nitrate melt k_1=1); k_2 - form ratio (for cylindric sample k_2=2); k_3 - uniformity ratio of heating (heating is uniform k_3=1); $t_{в}$ – hold time of a sample in the salts, seconds.

Calculation showed that the time required for the sample to remain in the melt should not exceed 7 min., so it was heated up to the required temperature during 2 min., and soaked during 5 minutes. And in the period if heating and torsion of a sample the molten salts were as stirred by gas purging (argon).

The melt temperature was measured with a chromel-alumel thermocouple XA. Hot junction of the thermocouple always remains in a fix position in a glass with the molten salts. Testing of a working thermocouple was done with a mercury thermometer which was put together with the thermocouple in the salt melt. The processed results of fifty tests of the working thermocouple (at different temperatures of the salts) are shown in table 2.2.

Table 2.2 – Testing results of the working thermocouple

Reading of mercury thermometer, °C	Arithmetic mean value of readings from working thermocouple, °C	Mean square deviation of readings of working thermocouple	
		°C	%
200	196	±1,5	±0,8
250	247	±1,5	±0,6
300	298	±1,2	+0,4
350	351	±1,0	±0,3
400	402	±1,2	+0,3
450	453	±1,5	±0,3
500	504	+1,8	±0,4

Data of this table shows that deviations of temperature measurement on average are ± 0,4%.

In order to obtain reliable data on the value of torsional moment a strain-gauge shaft was systematically calibrated using a set of balance weights. The processed results of numerous calibrations were at different levels of torsional moment are shown in table 2.3.

Table 2.3 – Results of verification of strain-gauge shaft

Values $M_{кр}$, $H \times mm$	Arithmetic mean value of beam deflection, mm	Mean square deviation of readings of strain-gauge shaft	
		mm	%
125	5,1	±0,27	±5,2
250	10,2	±0,52	±5,1
500	20,4	+0,65	+3,2
750	30,6	±0,9	±2.94
1000	40,8	±0,7	±1,72
1250	51,0	+0,9	±1,76
1500	61,2	±1.0	±0,61

Data in this table shows that accuracy of torsional moment on average is ± 3,0%.

When conducting the experiment it is necessary to meet the basic requirement concerning registration of parameters of all processes, that is the frequency characteristics of the equipment must be at least 3-4 times higher than frequency characteristic of the recorder process. So for instance at deformation rate of ξ=15 s^{-1} , the value of deformation γ=tgφ=9, the process time amounts

$$t = \frac{\gamma}{\xi} = \frac{9}{15} = 0{,}6\,\text{c}\,, \tag{2.11}$$

and the frequency of the process is

$$f = \frac{1}{t} = 1{,}66\ \text{герц} \tag{2.12}$$

However the first calculation point on the curve will be registered at γ=0,05, i.e. at frequency of the process f=300 Hz. Consequently, the vibrator (galvanometer) of an oscillograph should have in this case natural vibration frequency in the air not lower than 900 Hz.

Light beam deflection of the oscillograph vibrator H071.6M was recorded on photo paper UV, 120 mm wide, coiled around cassette reel. To get a compact and easy-to-calculate oscillogram the rotation speed of the reel is selected depending on deformation rate.

During torsional testing for the purpose of studying ductility, resistance to deformation at fixed deformation rates and for process simulation characterized by increasing deformation rate, the coupling clutch was activated manually.

In hot torsion tests according with the common practice of testing, for each point at least three samples of each diameter were taken. If the results of two samples of one diameter coincide, than the third sample was not tested. If the results of testing of the three samples did not coincide then torsion test was repeated on a larger number of samples. Based on numerous observations it was found that the matching of results for two samples occurs in 90% of tests.

Resistance to shear deformation τ is defined as an average value of the cross section of conditionally tubular sample and is characterized by the value of tangential stress [63]:

$$\tau = \frac{3(M_1 - M_2)}{2\pi(\rho_1^3 - \rho_2^3)}\,, \tag{2.13}$$

where M_1, M_2 – moments during torsion of samples with diameter 10 and 8 mm respectively,

$H \times mm$; ρ_1, ρ_2 – radii of samples with diameter 10 and 8 mm.

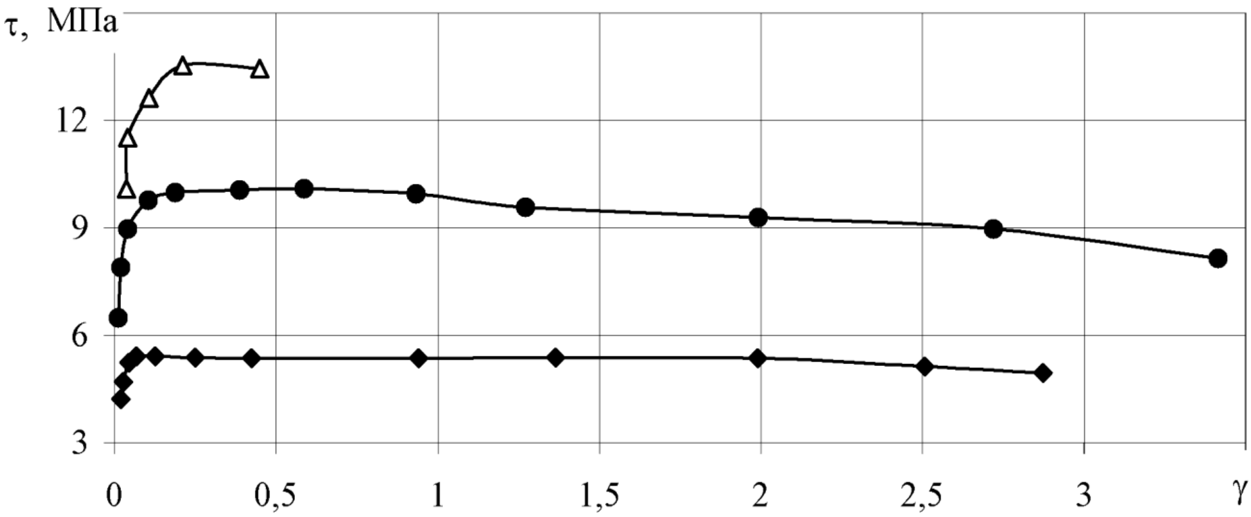
For conversion of the number of torsions by the torsion diagram into shear deformation and deformation rate, the following relations were respectively used [63]:

$$tg\varphi = \gamma = \frac{\rho_1 + \rho_2}{2l}\varphi \; ; \tag{2.14}$$

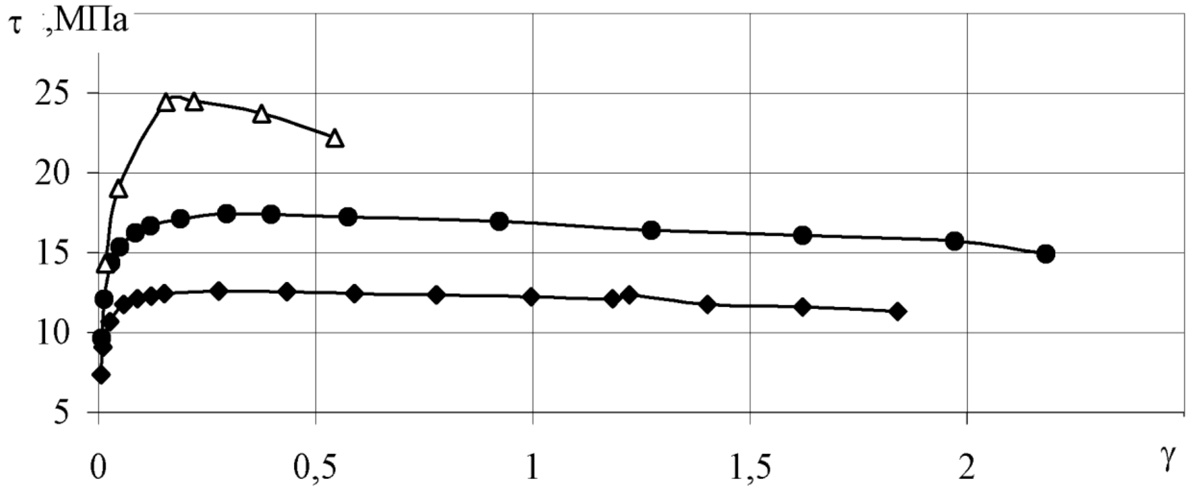
$$\xi = \frac{\rho_1 + \rho_2}{2l}\omega \; , \tag{2.15}$$

where ω - angular speed of spindle, rad; l – length of test section of sample, mm; $\varphi=2\pi n$ - angle of rotation of spindle, rad; n – number of rotations in torsion.

Using the above method shear resistances and ductility of foundry alloys ATB1 and ATB2 were studied at temperatures 350, 450 and 550°C in the range of deformation rates 0,034, 0,340 и 3,403 c^{-1}. The results are presented as dependences of shear resistance τ on the value of deformation $tg\varphi$ at above fixed temperatures θ and deformation rates ξ (picture 2.17, 2.18). The results of the research showed that dependence $\tau=\tau$ (T,ξ,γ) is in agreement with c physical theory of hot plastic deformation. It should be noted that owing to the high modulus of elasticity of aluminum the envelope of the curves of resistance to deformation at the desired scale almost merges with the vertical axis. The initial sections of the curves until the moment of detachment from the envelope correspond to the stage of plastic deformation due to the motions of dislocation in the slip planes where there are generators of dislocation.



а



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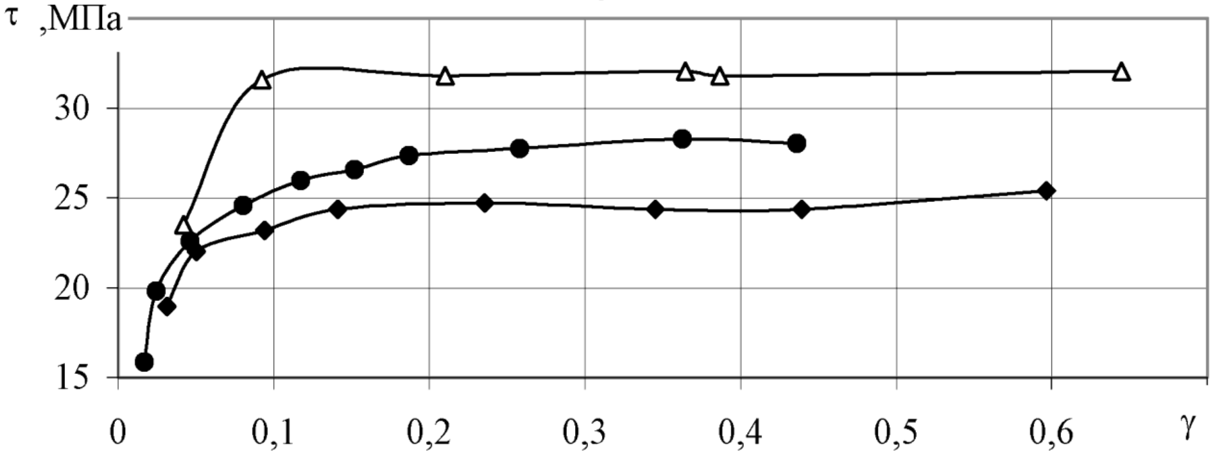
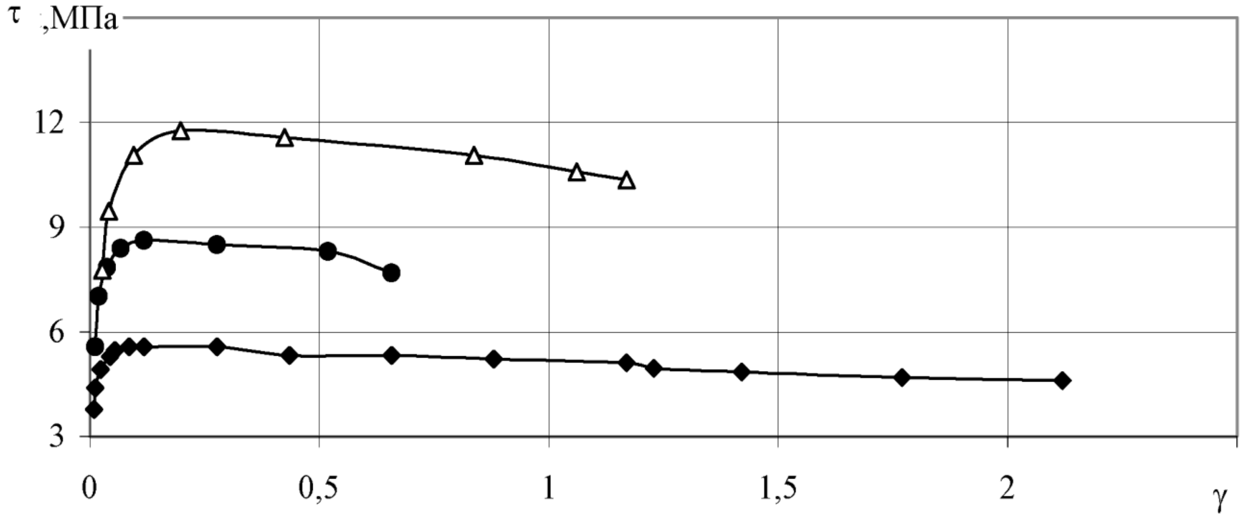
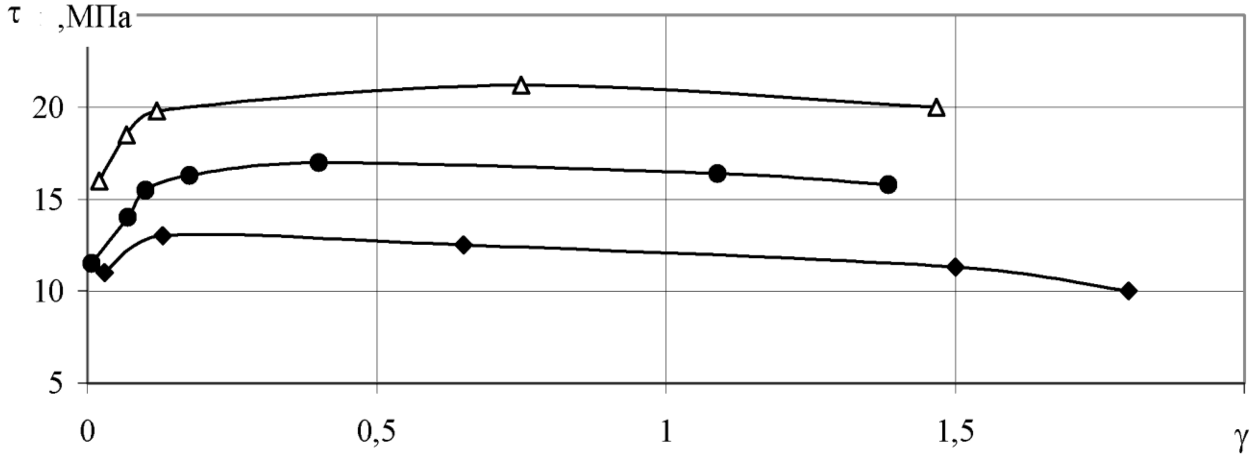


в

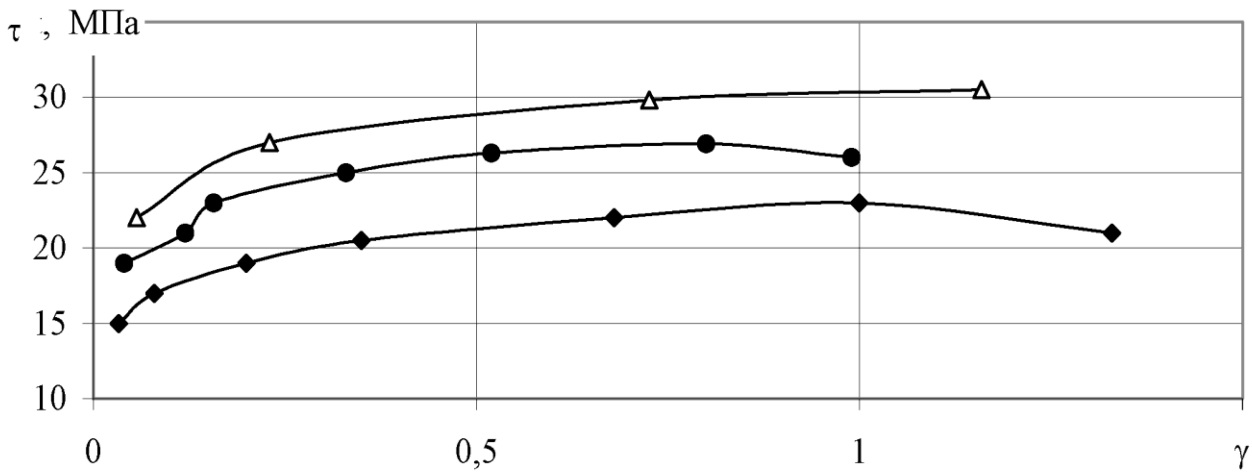
Picture 2.17 - Shear resistance of alloy АТВ 1 in relation to temperature, rate and value of deformation: а, б, в –550, 450, 350 ^{0}C respectively;
Δ - ξ=3,403 c^{-1}; • - ξ=0,304 c^{-1}; ♦ - ξ=0,034 c^{-1}



а



б



в

Picture 2.18 - Shear resistance of alloy ATB 2 in relation to on temperature, rate and value of deformation: а, б, в –550, 450, 350 ^{0}C respectively;
Δ - ξ=3,403 c^{-1}; ● - ξ=0,304 c^{-1}; ♦ - ξ=0,034 c^{-1}

After occurrence of obstacles in these planes the plastic deformation continues at the expense of dislocation motion in parallel planes where dislocations occur by cross sliding. This stage of plastic deformation is corresponded by detachment of the curves of resistance from the envelope. It is seen from the shape of the diagrams that the higher the deformation rate, the higher the stress is, wherein the resistance curve detach from the envelope. The envelope itself can be considered as a curve of the curve of hardening at infinitely large rate of deformation.

The relation $\tau=\tau$ (T,ξ,γ) of the studied alloys is mostly characterized by strain hardening, apparent softening is not observed because as soon as softening occurs, the samples break down. This is especially visible in the curves of hardening at 350°C. Moreover, highest resistance is shifted to the areas of larger degrees of deformation with increasing temperature and deformation rate. After reaching the maximum resistance sudden softening is observed only in one sample that was twisted at 550°C and strain rate 0,034 c^{-1}

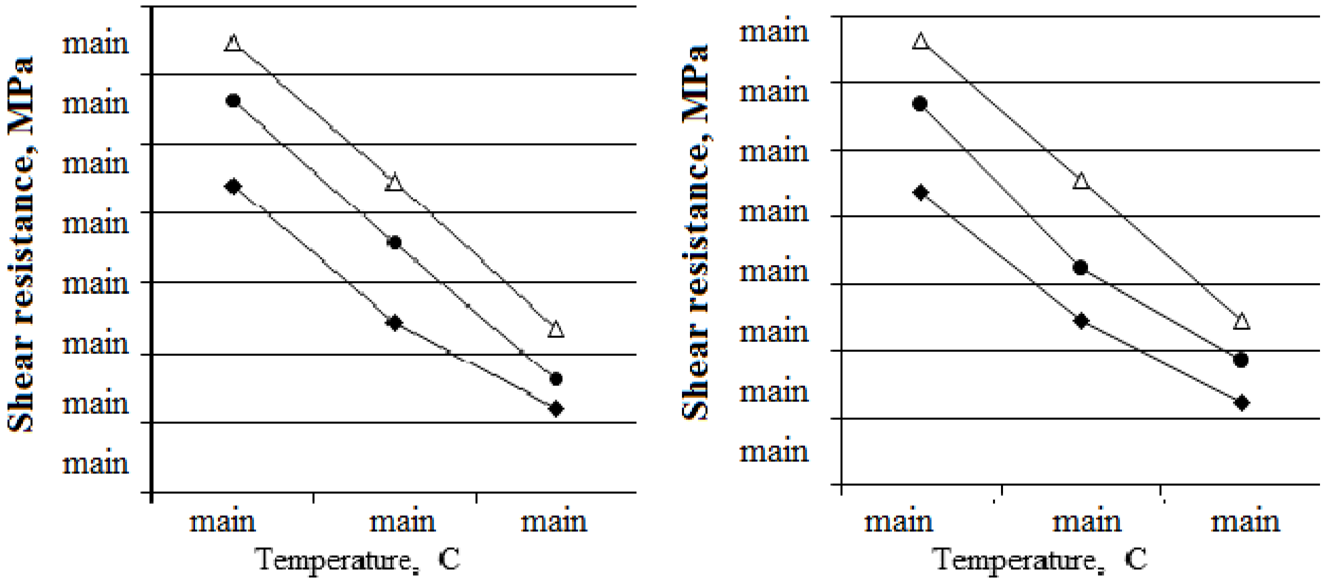
The average value of deformation at which rapid hardening is characteristic for all the curves of shear resistance, can be specific for each alloy. So, for ATB1 γ=0,25. With increase of testing temperature there is a slight increase of rapid hardening. So, for instance at the temparature of 350°C and average γ for the alloy, the increase of rapid hardening from 0,034 c^{-1} to 0,340 c^{-1} leads to increase of resistance to a greater degree than at a temperatures of 450 and 550°C (table 2.4).

Analysis of the resistance curves of shear deformation allows to note that the intensity of softening of the studied alloys Al-Ti-B of different chemical composition grows with the increase of deformaation rate and falls with the increase of the test temperature at very limited plasticity.

Table 2.4 – Rapid hardening of foundry alloy Al-Ti-B

Alloy	T, °C	Shear resistance τ, MPa at deformation rates ξ, c^{-1}			$K_{ck} = \frac{\tau_{0.34}}{\tau_{0.034}}$	$K_{ck} = \frac{\tau_{3.403}}{\tau_{0.034}}$
		0,034	0,340	3,403		
ATB1 at tgφ=0,25	350	22	28,1	32,3	1,277	1,468
	450	12,3	17,9	22,4	1,455	1,821
	550	6,2	9,3	12,3	1,50	1,984
ATB2 at tgφ=0,3	350	21,9	28,4	33,2	1,297	1,516
	450	12,3	16,2	22,7	1,317	1,845
	550	6	8,1	11,8	1,35	1,967

Analyzing the results of the tests one can notice that shear resistance of the experimental alloy at three different rates and test temperature 350 ^{0}C was within the range of approximately 22-34 MPa, at 450 ^{0}C – 11-22 MPa and at 550 ^{0}C – 3-11 MPa (picture 2.18).



a б

Picture 2.18 – Relations of shear resistance of metal to temperature and deformation rate: a – ATB1; б – ATB2; Δ - ξ=3,403 c^{-1}; ● - ξ=0,304 c^{-1}; ♦ - ξ=0,034 c^{-1}

The obtained data on resistance to deformation was used for simulation and calculations of power parameters of CRE process.

2.3. CALCULATION OF POWER PARAMETERS FOR ROLLING-EXTRUSION

For calculation of the forces acting on the die P_{die} and the rolls P_{roll}, formulas and their dependences on dimensionless parameters of rolling-extrusion process obtained by authors of the paper [1] (see part 1) were used. Which helped to determine power parameters for processing of the examined aluminium alloys for three different roll passes on laboratory units CRE-200 and CCRE-2,5, and also on a semi-production experimental unit CCRE-4 at Irkutsk aluminium smelter (see table 2.1).

The calculation was done for two experimental alloys 5082 and 6063 that have different level of resistance to deformation and processability, for two temperatures of a feedstock 400 and 550 °C, various values of deformation rate, and for three reductions that characterize the deformation degree during extrusion of a product.

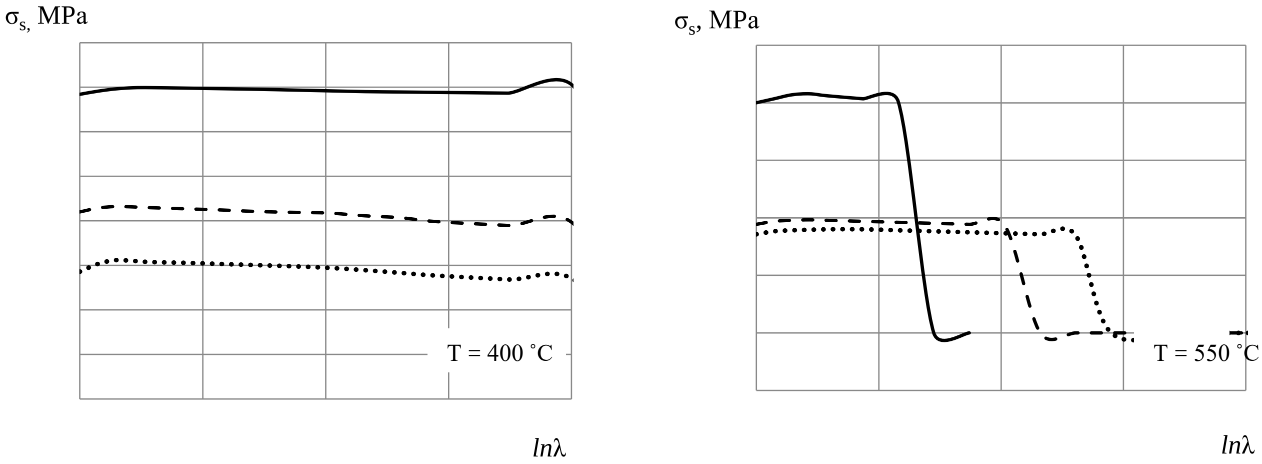
Values of pawer parameters for CRE-200 unit are shown in table 2.5.

Table 2.5 – Power parameters of alloys processing on CRE-200

Alloy 5082		$T_з$=400 °C			$T_з$=550 °C		
		4,4	7,3	14,3	4,4	7,3	14,3
	P_{roll}, кН	215,47	238,37	251,38	61,05	68,68	-
	P_{die}, кН	143,25	187,85	239,85	40,59	54,13	-
	P_{roll}, кН	298,07	331,29	359,12	68,23	72,72	-
	P_{die}, кН	198,16	261,08	342,64	45,36	57,31	-
		$T_з$=400 °C			$T_з$=550 °C		
		4,4	7,3	14,3	4,4	7,3	14,3
	P_{roll}, кН	104,14	113,12	121,20	57,46	60,60	62,85
	P_{die}, кН	69,24	89,15	115,64	38,20	47,76	59,96
	P_{roll}, кН	129,28	141,40	152,63	64,64	68,68	71,82
	P_{die}, кН	85,95	111,44	145,62	42,97	54,13	68,53
	P_{roll}, кН	158,01	169,68	179,56	89,78	96,96	103,25
	P_{die}, кН	105,05	133,72	171,32	59,69	76,41	98,51

It is obvious that for a pass with dimensions in the minimal section 7x15 mm even at a temperature 400 °C the force on the rolls is nor higher than 360 кН, but the force on the die – 350 кН. Moreover with increase of reduction the values of the forces grow. Increasing the temperature to 550 °C makes the force lower almost by 2-3 times. Increasing the deformation rate (rotation speed of the rolls) leads to rapid hardening of metal and higher power parameters of CRE process. Maximum values of power parameters are obtained for alloy 5082 which has the highest resistance to deformation. It is notable that calculation at high rates and degrees of deformation for alloy 5082 was not performed because under such temperature-rate conditions of the process no data on rheological properties was obtained (picture 2.19) due to samples rapture.

Table 2.6 shows calculated values of power parameters for CCRE-2,5 unit which has the roll pass in the smallest section 10x20 mm. Obviously the forces on the rolls and the die with increased size of the pass, grow and reach 740 кН and 480 кН, respectively, at deformation rate ξ = 1,5 s^{-1} , temperature of feedstock $T_з$=400 ^oC and reduction μ=14,3.



Picture 2.19 – Relation of resistance to deformation σ_s of alloy 5082 on logarithmic degrees of deformation lnλ at various deformation rates ξ:
········ ξ = 0,5 c^{-1} ; ------- ξ = 1,5 c^{-1} ;—— ξ = 10,0 c^{-1}

Table 2.6 – Power parameters of processing on CCRE - 2,5

Alloy 5082		$T_з$=400 ^oC			$T_з$=550 ^oC		
		4,4	7,3	14,3	4,4	7,3	14,3
	P_{roll}, кН	444,09	491,27	518,10	125,82	141,55	-
	P_{die}, кН	201,33	264,48	337,93	57,04	76,21	-
	P_{roll}, кН	614,32	682,78	740,15	140,63	149,88	-
	P_{die}, кН	278,50	367,58	482,76	63,75	80,69	-
		$T_з$=400 ^oC			$T_з$=550 ^oC		
		4,4	7,3	14,3	4,4	7,3	14,3
	P_{roll}, кН	214,64	233,15	249,80	118,42	124,90	129,53
	P_{die}, кН	97,31	125,52	162,93	53,69	67,24	84,48
	P_{roll}, кН	266,45	291,43	314,56	133,23	141,55	148,03
	P_{die}, кН	120,80	156,90	205,17	60,40	76,21	96,55
	P_{roll}, кН	325,66	349,72	370,07	185,04	199,84	212,79
	P_{die}, кН	147,64	188,27	241,38	83,89	107,59	138,79

Deformation rate at $\xi = 10\ s^{-1}$ was not calculated because thermal cracks appear on extruded products at such deformation rates and set temperatures of processing. It was confirmed also by experimental research [1]. Other trends of power parameters remain the same as when processing on the CRE-200 plant.

Similar calculations were performed for a pass with maximum dimensions 19x42 mm for semi-experimental unit CCRE-4 (table 2.7).

Table 2.7 – Power parameters of processing on CCRE -4

Alloy 5082		$T_з$=400 ºC			$T_з$=550 ºC		
		4,4	7,3	14,3	4,4	7,3	14,3
	P_{roll}, кН	1109,31	1227,17	1294,19	314,30	353,59	-
	P_{die}, кН	629,18	826,14	1054,39	178,27	238,04	-
	P_{roll}, кН	1534,54	1705,56	1848,84	351,28	374,39	-
	P_{die}, кН	870,37	1148,19	1506,27	199,24	252,04	-
		$T_з$=400 ºC			$T_з$=550 ºC		
		4,4	7,3	14,3	4,4	7,3	14,3
	P_{roll}, кН	536,16	582,39	623,98	295,81	311,99	323,55
	P_{die}, кН	304,11	392,06	508,37	167,78	210,03	263,60
	P_{roll}, кН	665,58	727,98	785,76	332,79	353,59	369,77
	P_{die}, кН	377,51	490,08	640,17	188,76	238,04	301,25
	P_{roll}, кН	813,49	873,58	924,42	462,21	499,19	531,54
	P_{die}, кН	461,40	588,10	753,14	262,16	336,06	433,05

At the same time the forces at a temperature 400 ºC on the rolls and on the die significantly grew which may cause failure of the tools when running CRE process. That is why processing of the studied alloys is recommended at low degrees of deformation and temperatures 500-550 ºC.

Analyzing the experimental date one can conclude that processing of alloy 5082 at temperature $T_з$=550 ºC and deformation rate higher than $\xi = 0,5\ s^{-1}$ is not recommended due to its low ductility in this temperature-and-rate range. Alloy 6063 is characterized by high processability, has relatively low values of power parameters and it can be processed well with different sizes of roll passes (specified diameter of rolls A) in the specified range of deformation and temperature-and-rate parameters.

3. EXPERIMENTAL RESEARCH OF COMBINED ROLLING-EXTRUSION PROCESS

When studying metal deformation and power parameters of combined rolling-extrusion (CRE), and for analysis of the results of theoretical studies it is necessary to have a set of experimental data in a wide variation range of conditions of the process. Data of experimental research available in scientific literature is devoted mainly to the study of the regularities of metal flow and partly to the power characteristics in a relatively narrow variation range of the parameters of rolling-extrusion process. (see part 1). Meanwhile experiments are conducted at various conditions of deformation for some non-ferrous metals, such as lead, aluminium and copper. And the results of the experiments have a scatter which complicates their comparison and use. In addition, it does not allow to make a change of some characteristics of the process in the complex because deformation is usually considered in isolation from the study of power costs. This part shows comprehensive experimental research of the conditions of deformation and power costs when changing each of the parameters that characterize the geometrical conditions of a rolling-extrusion process.

3.1 DESCRIPTION OF EQUIPMENT AND METHODS OF EXPERIMENTAL RESEARCH

Specifications of CRE-200 and CCRE-2,5 used for experimental studies available in laboratory of Chair for Metal Forming of Institute of Non-Ferrous Metals and Material Science, Siberian Federal University are shown in table 3.1.

Table 1 – Specifications of combined rolling-extrusion plants

Parameter	CRE-200	CCRE-2,5
Inlet diameter of roll, mm	200	480
Length of roll body, mm	240	250
Diameter of roll neck, mm	100	150
Number of rotation of roll, rpm	4, 8, 14	1-15
Gear box ratio, unit.	40	40
Power of motor, kW	20	45
Output torque, kNm	10	20
Working pressure of hydraulic station, MPa	10	20
Maximum clamping force, kN	300	300

The data of the plant provided a number of experiments to study the influence of cross-sectional size of the pass on power conditions of the process when varying the set parameters.

Extrusion and roller components, as well as a heating device for heating the rolls and the die block were designed for experimental studies, and also a strain gauge instrument – for measurement of basic power parameters.

Rolling and extrusion tools for deformation of aluminium alloys were designed based on the developed software, including software modules and graphical package AUTOCAD [1]. Rolling tools consist of the following prefabricated elements:

- a shaft with a key groove and a collar that serves for fastening of working couplings;
- removable roll necks made in the form of cylindrical bushings and located in the sliding bearings of the rolling mill;

- couplings with a groove and couplings with a protruding ridge that form a box-type closed pass when matching;
- nuts serving as retaining elements and fixing the working couplings in a determined position.

All prefabricated elements on the shafts were fastened using a key joint that prevented rotation of the deformation tool and facilitated the transmission of torque.

The main principals of the construction were:

1. Unit components under compression axial stress were calculated for maximum force - 300 кN.
2. Rolls were designed in assembly to address the possibility of quick change of working couplings, replacement of one type of pass for another etc.
3. To ensure removal of extruded discards from the working pass the coupling were design detachable in the plane perpendicular to the roll.
4. The couplings were fixed on the roll with the use of a key joint which on the one hand allowed to transfer a large torque to the deforming component, and on the other hand facilitated the assembling of the roller component.

The extrusion component consists of a V-shape device, a die ring and a die. The main element of the component is the die. Since the basic requirement in the design of the die was a to secure a thrust of the die to the rolls, its shape was chosen to be conical. Along with that the size of the larger base of the truncated cone should be as high as possible, and the size of the smaller one – as low as possible in order to secure cover of the closed roll pass. An orifice area should be located on the die face in the form of a profile so that equidistance of the die opening from the external contour of the die should be secured. Special flanges in the base of the die should keep it fixed in the die ring. Moreover the requirement of matching the center of exit opening in the parallel land and the corresponding opening in the die ring should be met. The edges of the die face should be filleted and fully adjoin to the surface of rolls preventing metal from getting into a gap between the rolls and the die. The material for manufacturing the die should correspond to requirements to extrusion tools. In this case steel grade 3Х2В8Ф widely used for production of extrusion tools was chosen. Thermal treatment of dies was performed up to hardness level HRC=

45...48. When designing the parallel land, temperature shrinkage allowance of the rod dimensions was taken into account, and the width of the working parallel land was 3 mm. Preliminary design studies showed that extrusion block should consist of the following main elements:

– a die;
– die ring;
– an instrumental board with a cover joined to a platen;
– a guide for fixing and moving the die along the extrusion axis for removal and replacement of the tool.

Power parameters of deformation process on a laboratory plant were recorded with a strain gauge instrument. Three measuring cells were also made for measurement of forces. To identify power parameters of combined rolling-extrusion process the measuring cells were installed under the pressure screws for recording the forces acting on the rolls, and under the die for recording the extrusion force.

Thus, design and engineering works are performed, and an experimental plant for the study of CRE process is made.

In order to fulfill the experiment plan the following methods were developed on the existing laboratory mill DUO 200:

– choose a variation range of dimensionless parameters for experimental research (see table 2.1);
– calculate dimensions of feedstocks and prepare them, and determine dimensions of the tools;
– design and manufacture the main components of CRE plant;
– develop methodology for experiments;
– determine the set of strain gauge instruments and make measuring cells for recording deformation forces;
– conduct experiments in accordance with the planning matrices and process the acquired data;
– identify stability of CRE process.

Levels of dimensionless parameters chosen for the experiment are shown in table 3.2.

Table 3.2 – Variation levels of deformation zone parameters

Dimensionless parameters	Minimum value, mm	Maximum value, mm	Size of tool and feedstock	Minimum value, mm	Maximum value, mm
A	19,0	32,3	h	6	10
$\tilde{b}$	2,2	2,5	b	15	22
$\tilde{h}_м$	2,0	2,5	$h_м$	15	20
$\tilde{h}_0$	2,0	2,3	h_0	12	20
$\tilde{d}_1$	0,5	1,5	d_1	5	9

For production of a rod 5,0, 7,0 and 9,0 mm feedstocks of rectangular section 12x15 and 20x22 mm of alloys 1230, 6063 and ATB1 (see table 1.5) were used.

Alloy 6063 was prepared in crucible furnaces with a capacity of 5 tons. Pouring was a semi-continuous casting in the form of cylinder bars with a diameter of 215 mm from temperature 710 ^{o}C (for 1230) and 740 ^{o}C (for 6063) at a speed 85 mm/min. Then by mechanical treatment these bars were transformed into rectangular feedstocks 12x14 and 20x21 mm.

Alloy ATB1 was prepared in a combustion furnace with a capacity of 1 ton. The metal pouring was performed into a steel mold in the form of cylinder bar with a diameter of 170 mm from temperature 1050 ^{o}C. Then by mechanical treatment these bars were transformed into rectangular feedstocks 12x14 mm and 20x21 mm.

For identification of feasibility of CRE process with the accepted values of deformation zone the above methods were used (see part 2.2), and distance of the die from the common axis of the rolls was 30 mm and 25 mm respectively, for two passes with dimensions in the minimal section 10x22 mm and 6x15 mm.

For the experiments, the following methodology was created. In an electric resistance furnace at the same time several feedstocks (bars) were heated to preset range of temperatures 480 ^{o}C – 580 ^{o}C and soaked for 10-15 minutes. The heating temperature of the bars was controlled with a chromel-alumel thermocouple and a potentiometer. At the same time the rolls were heated to the maximum temperature 200 ^{0}C using a special furnace made in the form of a casing corresponding to the shape of the rolls and equipped with nichrome heaters. After heating the bars and the rolls to required temperature the rolls were put into rotation and the heated bars were driven into the extrusion area.

Experiments were conducted in the following sequence. As soon as the feedstock is gripped by the roll with a tongue and the roll with a groove the strain gauge instrument with the use of measuring cells records the force acting on the rolls. Then the metal goes to the die pass and reaches the die itself which is installed in the ring. Using a wedge and a wedge-type device the die was tightly thrusted to the rolls from bottom. The metal was pressed-out filling the die pass in the area of pressing-out. Then, due to continuous supply of metal into the pass, the metal is extruded through the die channel in the form of a rod (picture 3.1). The force on the die is recorded with a strain gauge instrument using a special measuring cell. After the process of rolling-extrusion of a feedstock had finished it was repeated changing the rolling rate.

For measurement of power parameters the ring measuring cells were connected to recording equipment for which a strain-gauge station Zet017-T8 made by ZetLAB (Russia) was used. For measuring the force on the die and the pressure screws, force sensors were used CWW-50tf and CWW-100tf by Dacell Co. LTD (South Korea) with the maximum permissible compressive force 0,5 and 1 MH.

Picture 3.1 – General view of extrusion block of combined processing plant with an extruded rod.

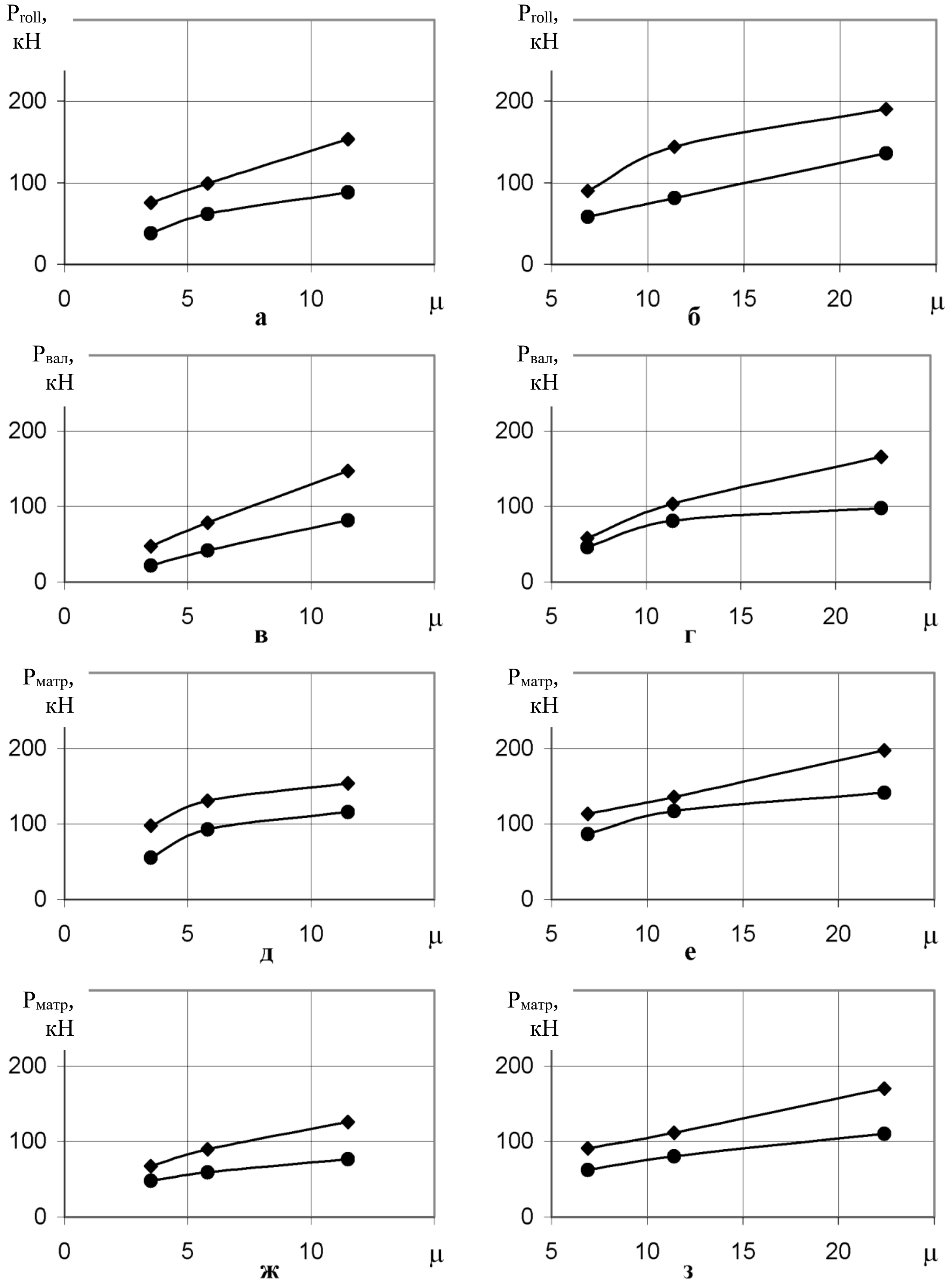
As a result of the works, experimental plants equipped with strain gauge instruments were prepared for research, feedstocks of various aluminium alloys were made, methodology of experiment was developed and sample of extruded products from experimental alloys were taken.

3.2. RESULTS OF EXPERIMENTAL RESEARCH AND THEIR ANALYSIS

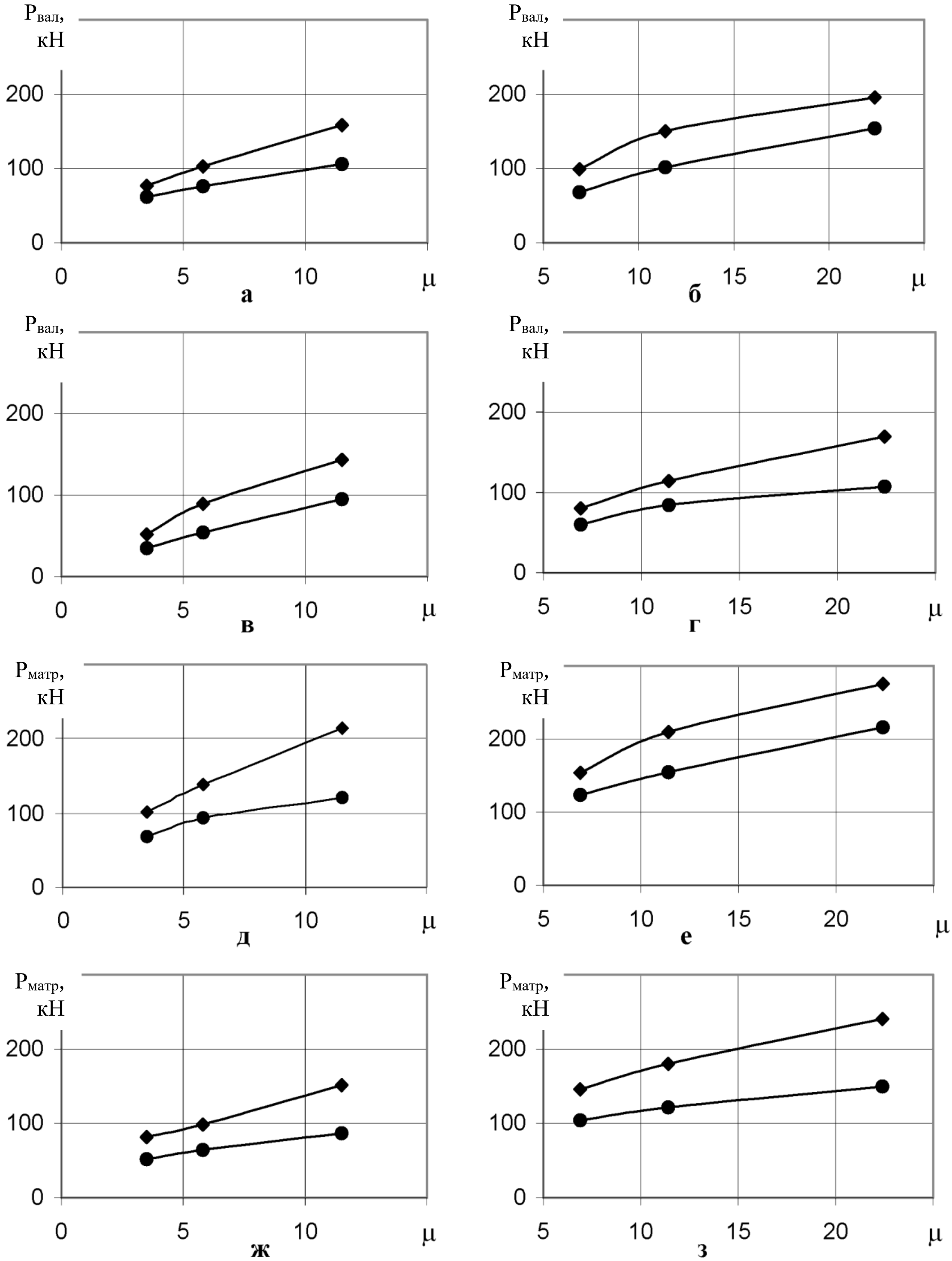
Research of power parameters of CRE process for experimental alloys 1230, 6063, ATB1 and ATB2 was performed according with the developed methodology.

Results of the experiments are presented in graphical form in picture 3.2 - 3.4.

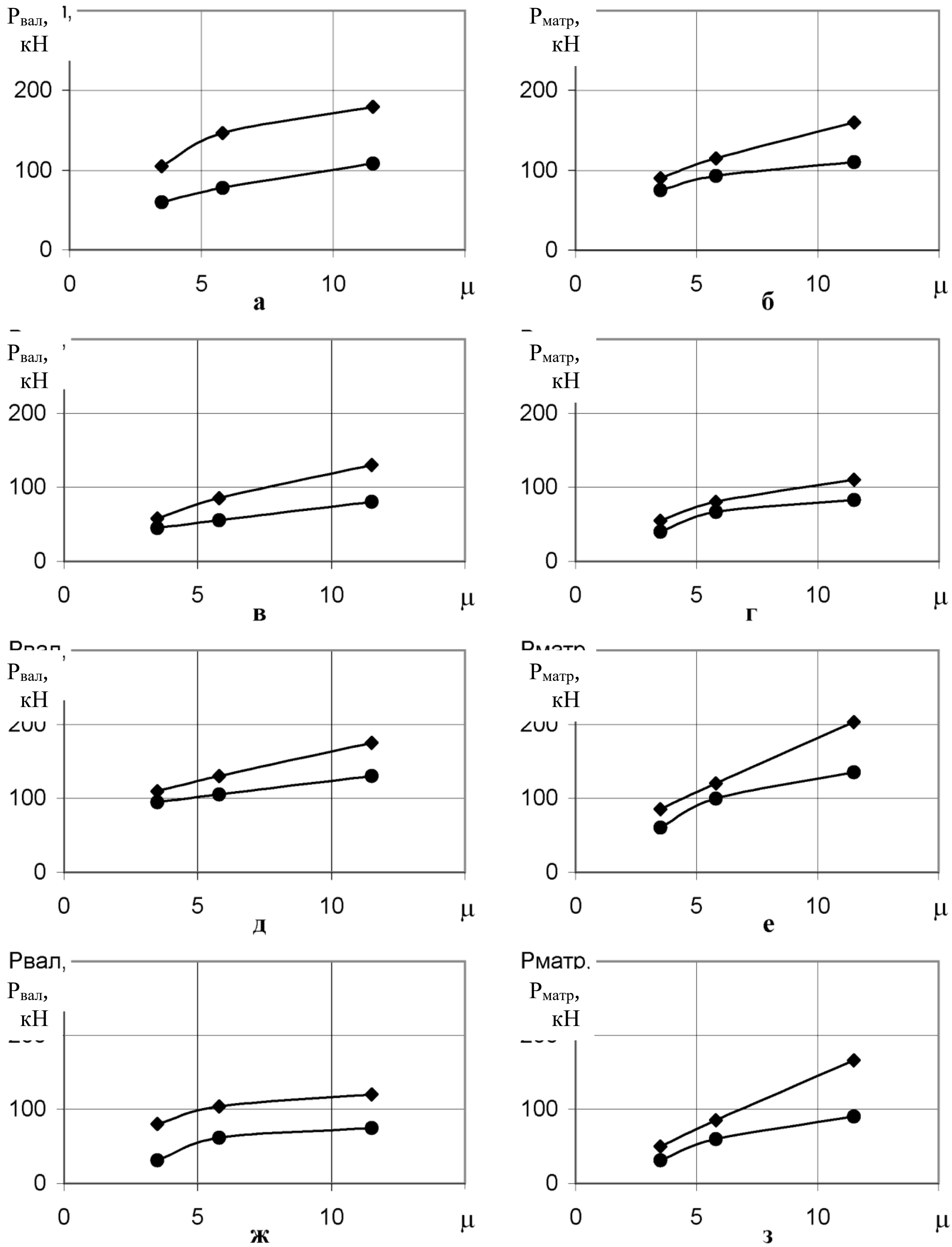
Analysis and comparison of the obtained experimental data showed that the character of dependences of studied parameters and their quantitative evaluations for aluminum alloys are confirmed by the data given in the paper [1]. The obtained data of power parameters indicate a feasibility of production of rods of these alloys by method of combined rolling-extrusion at the maximum measured forces not higher than 170 kN (clamping force of 300 kN) and 180 kN on the rolls.



Picture 3.2 – Dependences of force on rolls (P_{roll}) and die (P_{die}) for aluminium grade 1230 on extrusion μ and heating temperature of feedstock T at parameters values: A=32,3 (а,в,д,ж); A=19 (б,г,е,з); ξ=0,54 $с^{-1}$ (а, б, д, е); ξ=2,32 $с^{-1}$ (в, г, ж, з); ♦ - T=480 ^{0}C; • - T=580 ^{0}C



Picture 3.3 - Dependences of force on rolls (P_{roll}) and on die (P_{die}) for alloy 6063 on extrusion μ and heating temperature of feedstock T at parameters values: A=32,3 (а,в,д,ж); A=19 (б,г,е,з); ξ=0,54 c^{-1} (а, б, д, е); ξ=2,32 c^{-1} (в, г, ж, з); ♦ - T=480 ^{0}C; • - T=580 ^{0}C



Picture 3.4 - Dependences of force on rolls (P_{roll}) and on die (P_{die}) for alloy АТВ1 (а-г) and АТВ2 (д-з) on extrusion μ and heating temperature of feedstock T at deformation rates:
ξ=0,54 c^{-1} (а, б, д, е); ξ=2,32 c^{-1} (в, г, ж, з) ; ♦- T=480 ^{0}C; • - T=580 ^{0}C

As shown by the analysis of experimental data one can outline the following patterns of change of dependences of the researched parameters among the general. The forces of deformation on the rolls and the die naturally increase with the growth of reduction ratio. This can be explained by the fact that with increase of the degree of deformation during extrusion with all other equal parameters the volume of extruded metal increases which requires additional energy consumption. Moreover with the increase of reduction ratio the pressure in the area of pressing-out grows, and the required force supplied by the rolls increases as well.

Analysis of dependences of power parameters for all alloys showed the following. With the increase of heating temperature of a feedstock the forces on the die and rolls decrease which corresponds to the generally accepted theory of metal forming, and is related to decrease of deformation resistance of metal. With the increase of deformation rate according with the basic provisions of the theory of metal forming, the deformation resistance increases due to strain hardening which is confirmed by theoretical dependences for calculation of power parameters. On the other hand, at the same time, the temperature of the processed metal increases due to deformation heating, and heat transfer to the tool decreases because of shorter time of contact with the feedstock. During the experiments it was found that the forces acting on the die and rolls decrease with the increase of deformation rate. That is the processes of softening due to increasing temperature of heating for the studied alloys are predominant compared to the high-speed strain hardening.

Curves of testing of power parameters for the studied of foundry alloys Al-Ti-B are also characterized by the fact that with the increase of temperature under the same reduction value the deformation force decreases both on the rolls and on the die. Increase of the reduction ration leads to increase of forces on the die and on the rolls, however the incrise of the force on the rolls is different for different chemical compositions of foundry alloy. Alloy ATB2 is characterized by sharp rise of forces of CRE. Apparently it is explained by physicometallurgical aspects of the behavior of alloys of Al-Ti-B system, in particular by relaxation of internal stresses on the boundaries of deformation lines along the grain boundaries and at interphase boundaries. A characteristic feature of these dependences is that at small values of reduction ratio a difference in the forces of deformation is small, and with increase of the reduction this difference in forces increases. It is apparently also related to the special behavior of the alloy system Al-Ti-B at high deformations and to the presence of intermetallic compounds in the alloy.

Comparative analysis of the quantitative dependences of the forces on the rolls and the die for alloy 6063 and aluminum grade 1230 showed that the forces of deformation for 1230 are lower than for 6063. This is due to lower deformation resistance of aluminum grade 1230 compared to 6063 ceteris paribus.

Thus, new experimental data on power parameters for combined rolling-extrusion are obtained for different aluminium alloys, and patterns of their change in the range of parameters variations of the research are found. The results of the experiments will be used to calculate power loading of the equipment, to calculate the tool strength and for validation of the relations derived theoretically.

3.3. RESEARCH OF STRUCTURE AND PROPERTIES OF PRODUCTS MADE BY CRE (COMBINED ROLLING-EXTRUSION) METHOD OF EXPERIMENTAL ALLOYS

Mechanical, technological and operational properties of semi-finished products and full products are substantially dependent on macrostructure, therefore, metallographic studies allow to reveal defects of processing, to establish the causes of their formation and to determine the optimal parameters which in combination provide the best characteristics of structure.

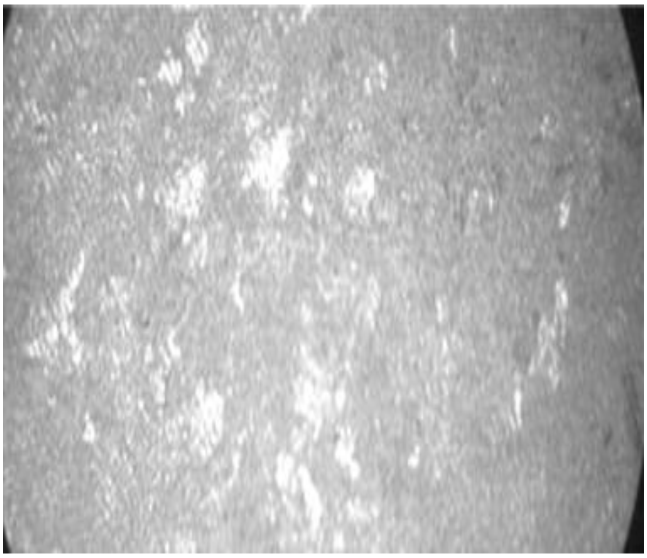
Macro-slices in cross-section of the rod (templates) were made for investigation of the macrostructure of the rod produced of alloy 6063 and aluminium grade 1230 through combined rolling-extrusion. The surface of the template for macro slice was ground on a milling machine because the surface finish R_z=6-7 is usually sufficient so that after etching to reveal the structure. Macro-slices were pre-treated by a surface etching reagent for identification of the nature of segregation, metal flow pattern, grain structure. Template contaminated with dust and grease were wiped with alcohol. For etching the slices were immersed in an alkali solution at room temperature and kept in it for 30-40 minutes. NaOH solution 10-20% was used as an alkaline etching agent. After etching in alkali the macro-slices were washed for a few seconds in running water and immersed in a 50% water solution of nitric acid to remove black stain from the surface of the slice that is formed by etching in alkali.

Microanalysis was performed at high magnification under a microscope (up to 2000 units of magnification). The microstructure research was carried out on specially prepared samples – micro-slices. The micro-slices were prepared by mechanical method and by method of electropolishing.

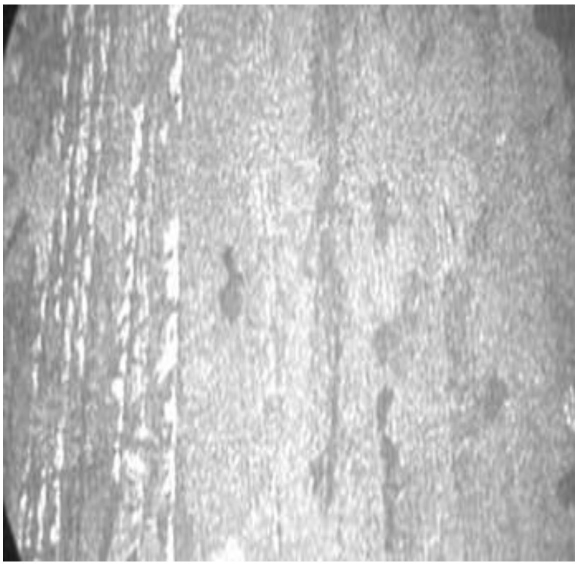
Keller's reagent was used for etching of micro-slices used Keller's reagent. The micro-slices were etched in a fume hood. After etching, the slices were quickly washed under running water. Washed with water and alcohol the samples were dried with filter paper. A sign of adequate etching was a weak fogging of the slices surface. Identification of the structure during etching was controlled with a microscope.

For each alloy, 5 macro- and micro-slices were selected that showed characteristic changes of macro- and micro-structure depending on the parameters of metal forming: temperature, extrusion reduction (degree of deformation) and deformation rate.

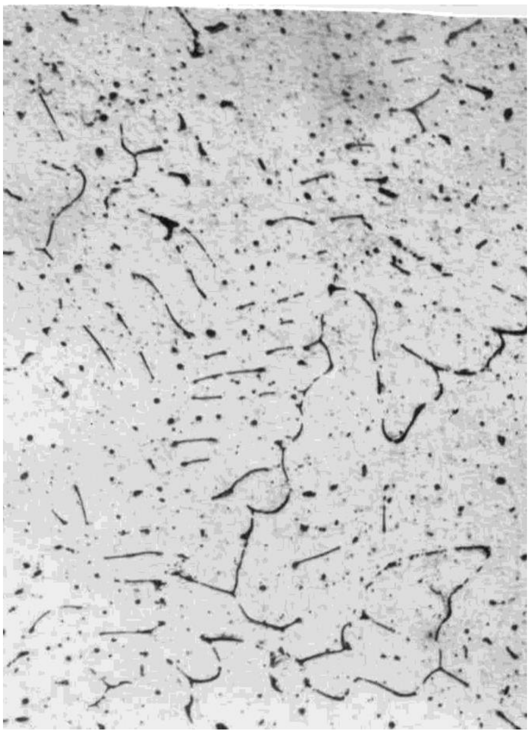
Aluminium alloy 6063 is characterized by fir-tree structure and has a characteristic texture that changes under deformation. The microstructure of a cast bar (picture 3.5) has a dendritic structure of solid solution with the release of excess phase Mg_2Si along the boundaries of dendrite cells.



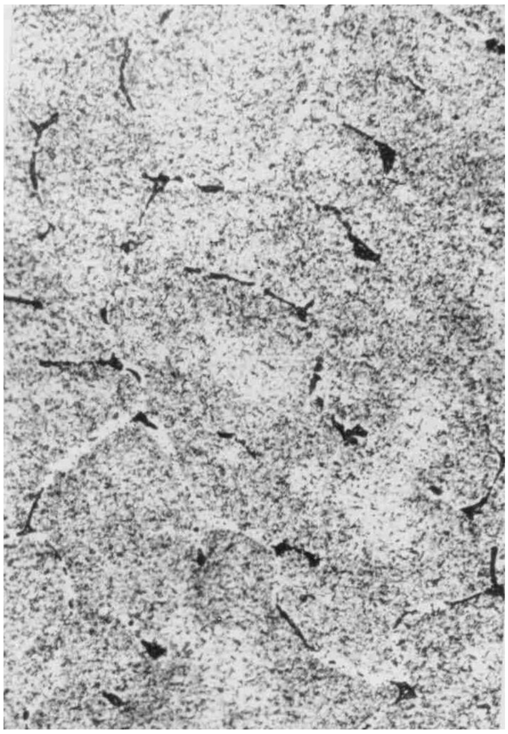
а x10



б x10



в x200



г x200

Picture 3.5 – Macro- and microstructure of a cast bar of alloys 1230 and 6063:

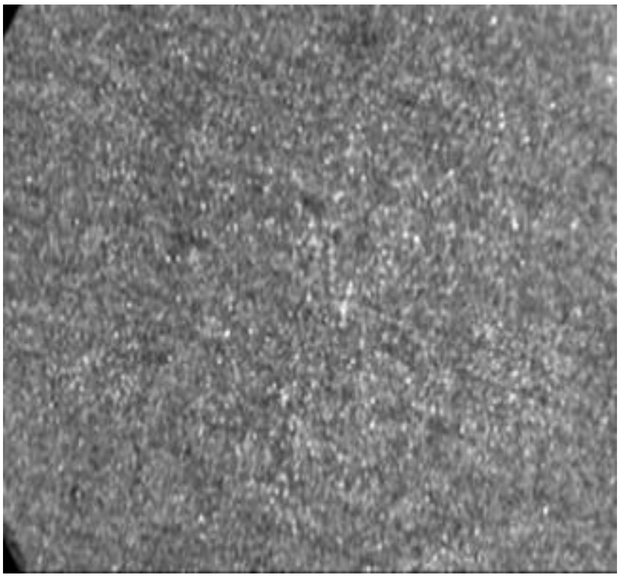
а - macrostructure 1230 (as cast); б - macrostructure 6063 (homogenized condition);

в - microstructure 1230 (as cast); г - microstructure 6063 (homogenized condition)

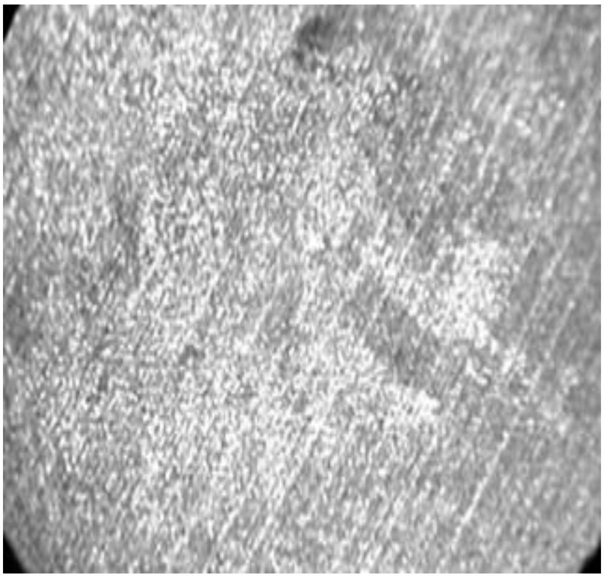
Also there is different density of precipitates in the solid solution along the section of dendrite cells. That indicates the presence of residual chemical inhomogeneity in the cross section of a solid solution. A significant change of macro- and micro-structure occurs in plastic deformation. With the increase of deformation degree and temperature, and decrease of deformation rate the effects of structure conversion consisting in the increase of homogeneity degree of the solid solution and distribution of precipitations of the excess phase in it – these effects enhance.

At the highest deformation rates (picture 3.6) the elements of the original structure with coarse precipitates of excess phases on the boundaries of dendrite cells retain. At the lowest deformation degree, the coarse precipitates on the boundaries of dendrite cells are eliminated even at low temperatures of deformation but with the use of maximum degree of deformation (picture 3.7). The simultaneous increase in speed and deformation temperature enhances coagulation of secondary precipitates of the phase Mg_2Si, as a result they become more coarse than at small degrees of deformation but at the same temperature and strain rate.

Thus, increase of temperature, degree of deformation, and decrease of the deformation rate contribute to development of diffusion processes that ensure transformation of the structure of a deformed feedstock. There is a combination of parameters that ensures the best characteristics of the structure from the point of view of homogeneity and particle dispersion of precipitate phase. That combination is: temperature – 580 ^{0}C, reduction – 3,5 and deformation rate – 0,54 s^{-1}. Deviation from these parameters in deformation degree to 11,5 cause excessive development of diffusion processes that leads to coagulation of particles of the excess phase (coarsening, spheroidization and increase of the distance between large particles) with simultaneous clarification of the background. Decrease of deformation temperature down to 480 ^{0}C (picture 3.8) causes increased heterogeneity of distribution of inclusions due to persistence of the residual segregational phenomena of solidified metal (incomplete degree of homogenization).



а x 33



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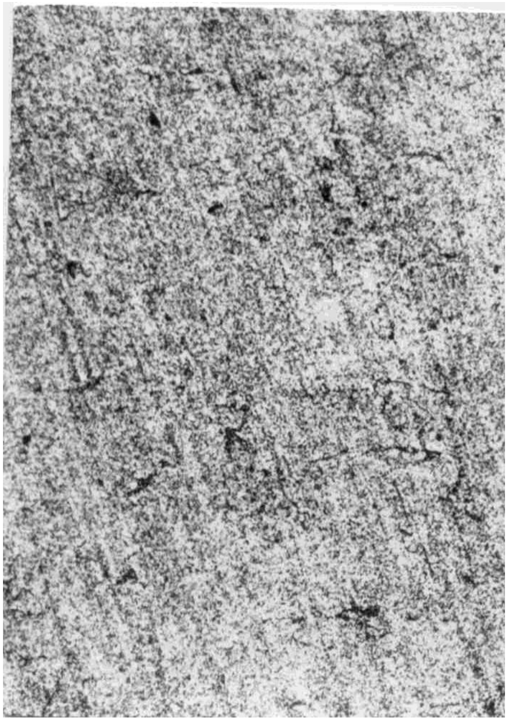
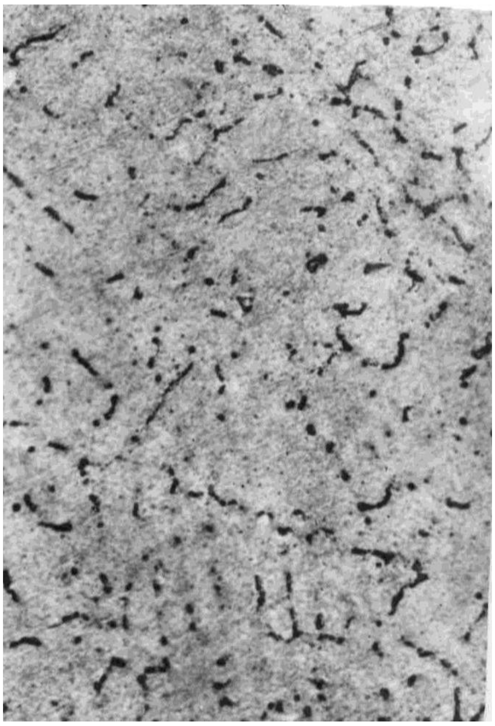
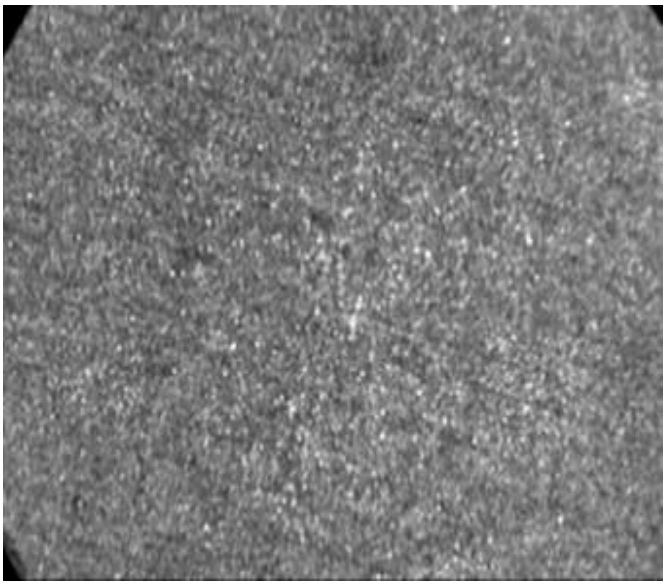


в x 200

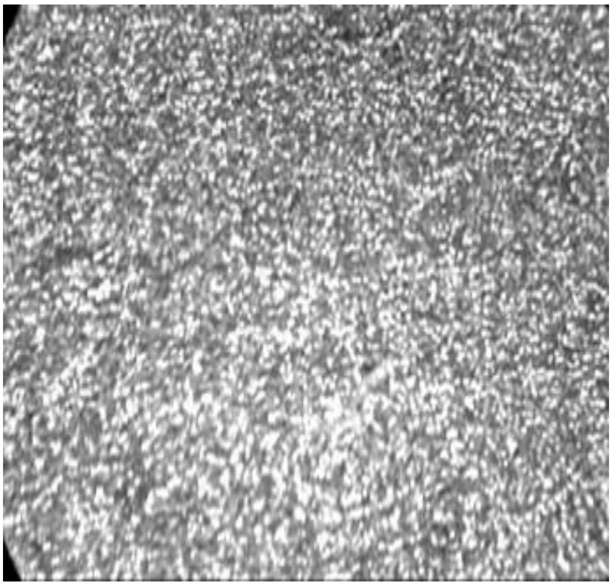


г x 200

Picture 3.6 – Change of macro- (а, б) and micro-structure (в, г) of alloy 6063 at T=580 ^{0}C, μ=3,5 and deformation rate ξ: 0,54 s^{-1} (а, в); б) 2,32 s^{-1} (б, г)



а x 33



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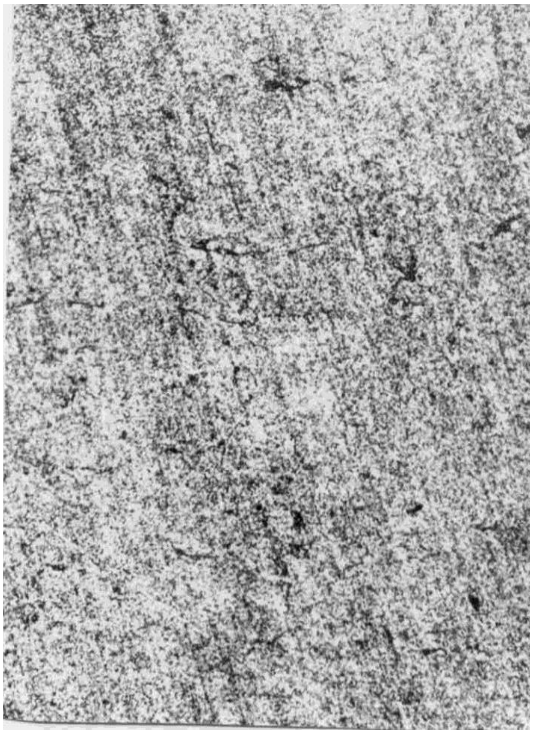
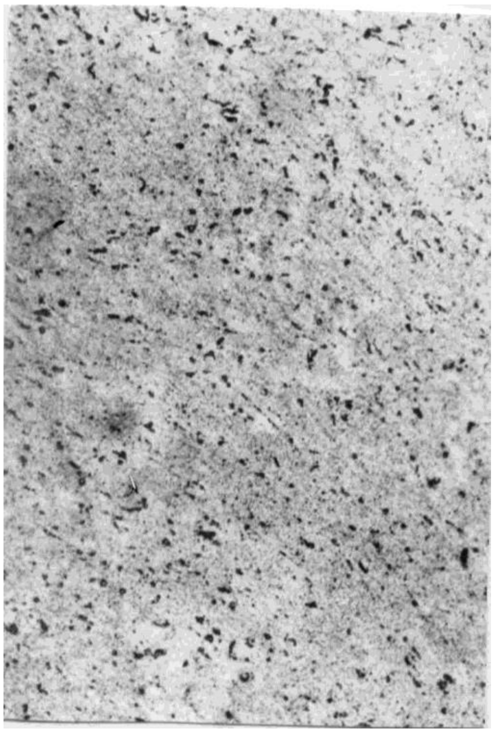
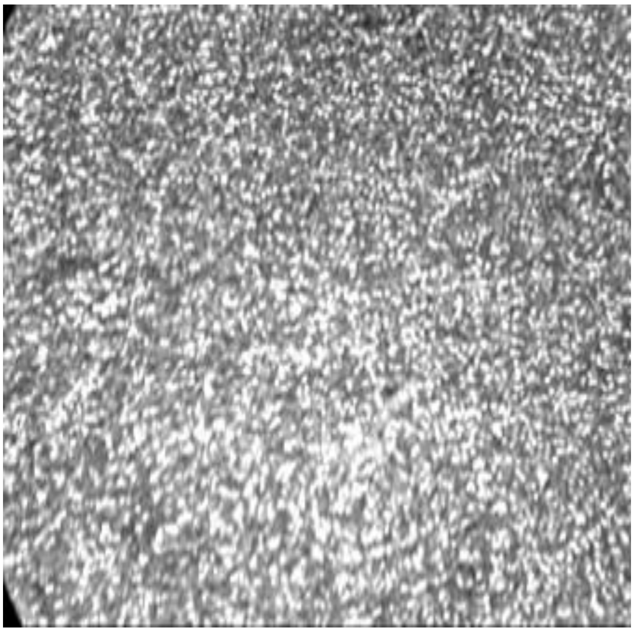


в x 200

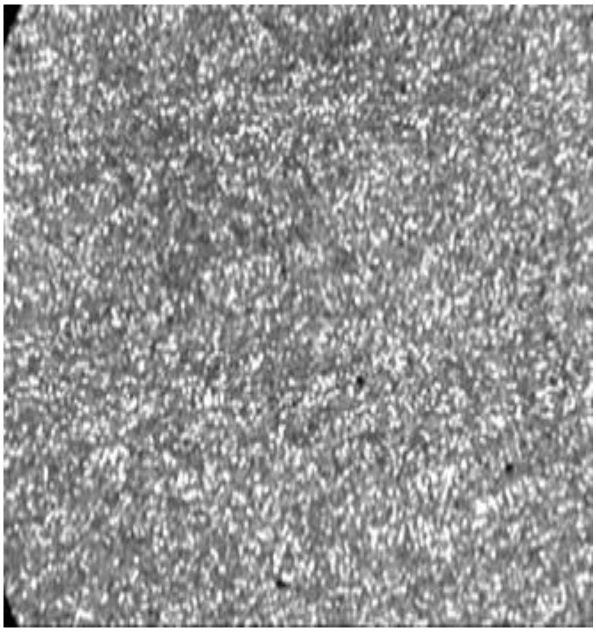


г x 200

Picture 3.7 - Change of macro- (а, б) and micro-structure (в, г) of alloy 6063 at T=580 ^{0}C, ξ=0,54 s^{-1} and extrusion μ: 3,5 (а, в); 11,5 (б, г)



а x 33



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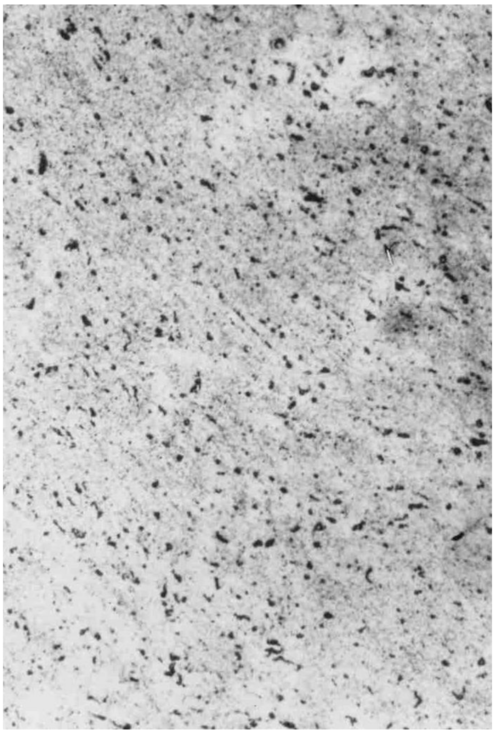


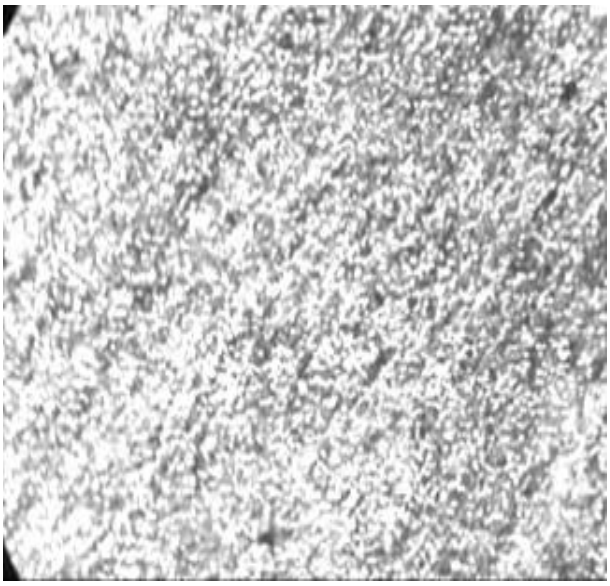
в   x 200

г   x 200

Picture 3.8 - Change of macro- (а, б) and micro-structure (в, г) of alloy 6063 at μ=11,5 and ξ=0,54 s^{-1} and temperature T: 580 ^{0}C (а, в); 480 ^{0}C (б, г)

In the macrostructure as technological parameters changes it is possible to observe similar structural changes that indicate that at high deformation rates, traces of fir-tree structure remain, and with increase of deformation degree and decrease of deformation rate, the volume fir-tree becomes lower in the micro-slices.

The macrostructure of a cast bar of aluminum grade 1230 is fine-grained, equiaxed. It also undergoes a change during subsequent extrusion processing. The formation of such macro-grain in a cast bar was influenced by the technology of melt preparation and casting parameters: overheating temperature of metal, cooling rate during solidification, material of the mold, grain refinements. The macrostructure of a cast alloy is significantly influenced by alloying elements and impurities. In aluminium 1230 impurities are Fe and Si dissolved in solid solution. Plastic deformation causes formation of recrystallized structure, that is a significant change of the macro- and micro-structure occurs. Recrystallization processes lead to formation of a new structure and dissolution of the excess phase through the body of grain. With the increase of temperature and degree of deformation, and with the decrease of deformation rate, the recrystallization is higher, and more uniform and dispersed structure is formed. At the highest deformation rates the elements of the original structure with precipitates of intermetallic compounds based on Fe and Si along the grain boundaries retain. But at the minimum deformation rate the recrystallization process enhances and more intensive grain refinement occurs (picture 3.9). The simultaneous increase of the degree and temperature of deformation result in maximum dissolution of the excess phase through the body of grain and refinement of it (picture 3.10 and 3.11). So from the point of view of homogeneity and dispersion of the structure the technological modes in which the temperature of a feedstock is 580 ^{0}C, reduction – 3.5 and deformation rate – 0,54 s^{-1} , can be recommended.



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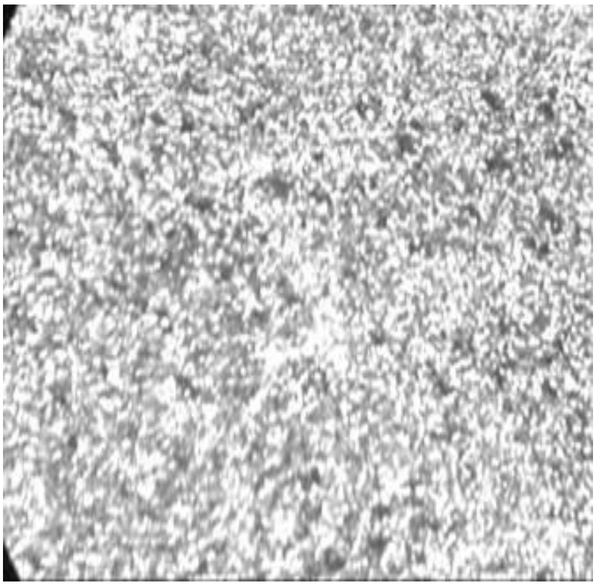

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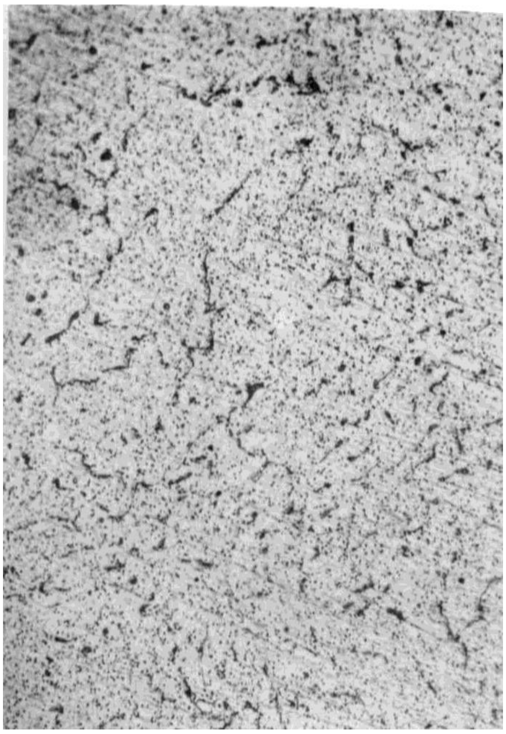
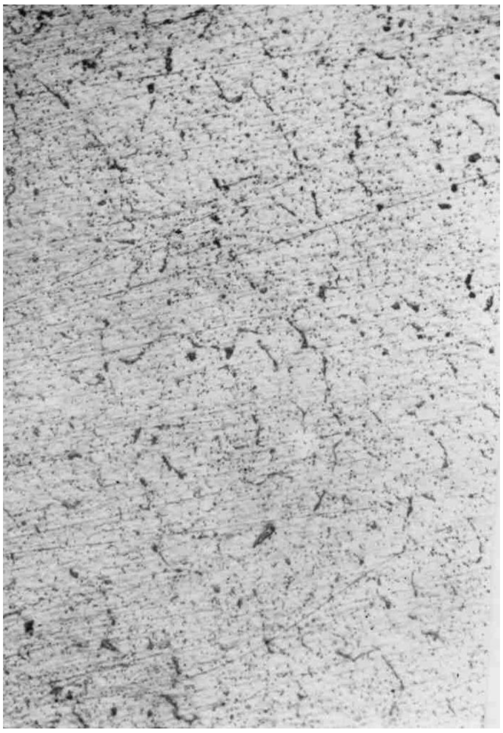
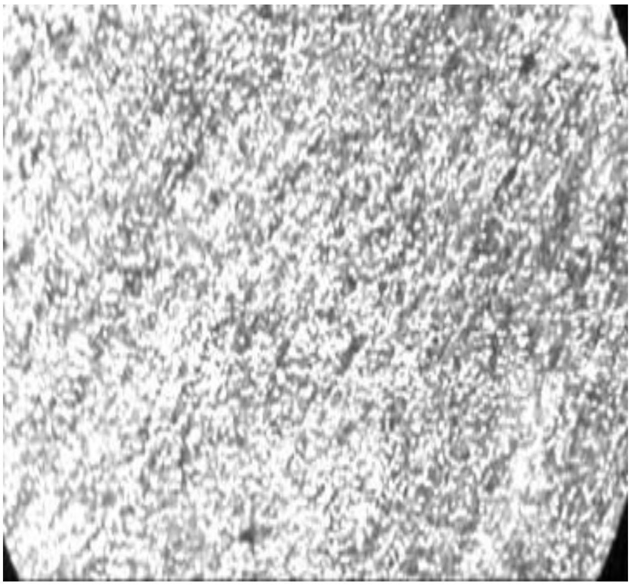


в x 200



г x 200

Picture 3.9 - Change of macro- (а, б) and micro-structure (в, г) of aluminium grade 1230 at T=580 ^{0}C, μ=3,5 and deformation rate ξ: 0,54 s^1 (а, в); 2,32 s^{-1} (б, г)



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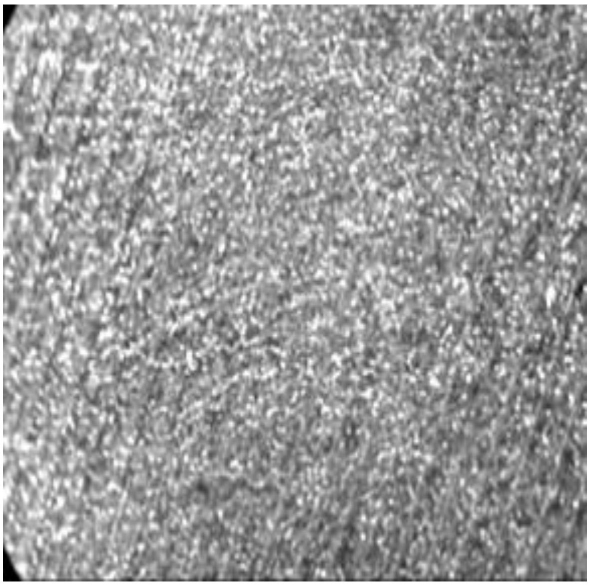

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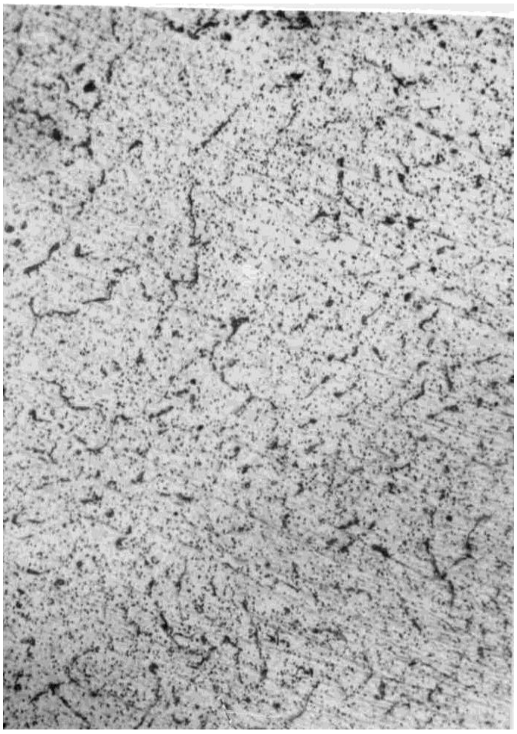

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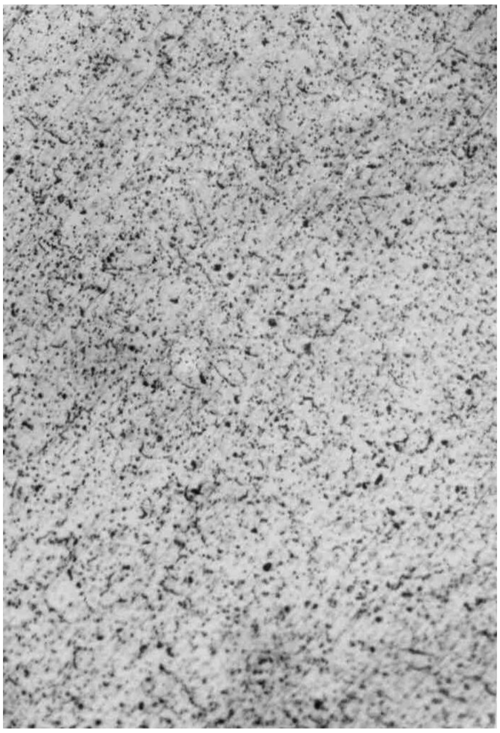

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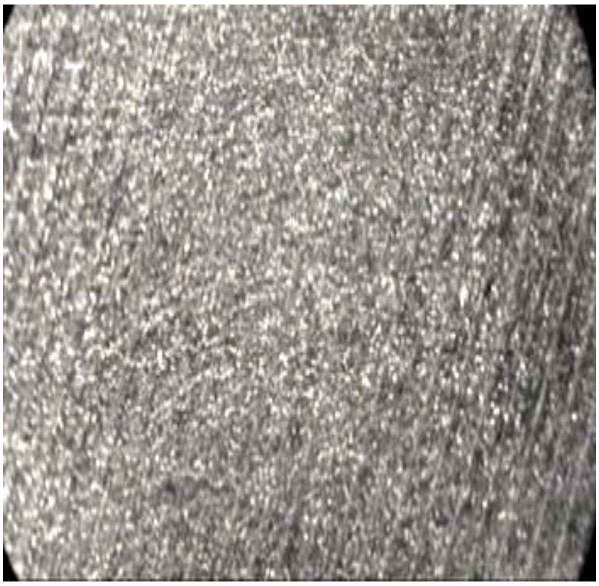
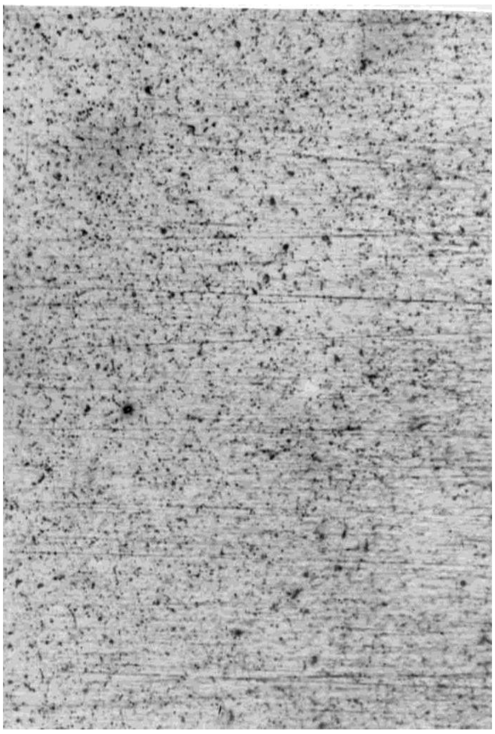
Picture 3.10 - Change of macro- (а, б) and micro-structure (в, г) of aluminium grade 1230 at $T=580\ ^0C$, $\xi=0,54\ c^{-1}$ and extrusion μ: 3,5 (а, в); 11,5 (б, г)



а х 33

б х 33

в x 200



г x 200

Picture 3.11 - Change of macro- (а, б) and micro-structure (в, г) of aluminium grade 1230 at μ=11,5 и ξ=0,54 s^{-1} and temperature T: 580 ^{0}C (а, в); 480 ^{0}C (б, г)

Mechanical properties of extruded rods were identified by tensile testing, and the obtained data on conventional yield strength ($\sigma_{0,2}$), tensile strength ($\sigma_в$) of the alloy and relative elongation (δ) are shown in table 3.3. The submitted data shows that on average mechanical properties of extruded rods for example of aluminium grade 1230 correspond to requirements of international standards.

Table 3.3 (at end)

3.4. PRACTICAL APPLICATION OF RESEARCH RESULTS

Based on the research a semi-production plant CRE-400 was designed and made (picture 3.12).

Picture 3.12 – General view of combined processing plant CRE-400

Technical parameters of the plant are shown in table 3.4.

Table 3.4 – Parameters of plant CRE-400

Parameter	CRE-400
Inlet diameter of roll, mm ne	400
Length of roll body, mm	240
Diameter of roll neck, mm	140
Number of rotation of roll, rpm	
Gear box ratio, unit.	
Power of motor, kW	
Output torque, kNm	
Working pressure of hydraulic station, MPa	
Maximum clamping force, kN	

This plant processed bars of aluminium grade 1230 and alloy 5082 with an area of cross section up to 900 mm^2 and length up to 1,5 м. According with the developed technology the feedstocks were heated till required temperature in an electric furnace and then driven into heated rolls one after another provided possibility to weld them butt. The first stage of the field research was tracking the performance of the plant with the aim of bringing it to operating condition and practicing the technology of production of rods of aluminum grade 1230. And with the use of a hydraulic cylinder the die block was thrusted to rolls at different efforts, at the same time the thickness of metal between the die and the roll, temperature of the rolls, die and the bar were recorded. The calibration force of the thrust at which metal did not penetrate into the gap between the rolls and the die, was 260 kN. Then the metal was deformed (extruded), and a experimental lot of rods was produced. Some of the produced rod were further drawn. It was carried out on a drawing machine ВСГ-1/550А designed for cold drawing of coiled wire 9-12,5 mm of different aluminum alloys coil in single feeding. In this regard, starting with the 6th experiment, 50 samples of length 600 mm were extruded, weld coils of aluminium grade 1230 with the weight of 75 kg were produced. Table 3.5 shows the results of experimental research on a pilot plant CRE-400.

Table 3.5 - Experimental results of CRE process

№ experiment	Section of feed-stock, mm^2	Length of feed-stock, mm	Length of 1 rod, mm	Temper. of rolls, °C	Temper. of die, °C	Temper. of feedstock, °C	Rotation frequency of rolls, rpm	Flow rate of rod, m/min
1230								
1	30x30	600	500	190	170	585	2	14,8
2	30x30	600	5000	200	230	580	2	15,2
3	30x30	600	8400	200	230	480	2	16,0
4	30x30	600	8400	200	230	425	2	18,0
5	30x30	600	8400	100	280	480	2,25	16,5
6	30x30	600	8400	190	300	490	2	16,0
7	30x30	600	8400	190	300	490	2,25	16,8
5082								
8	30x30	600	2000	350	200	480	2,25	16,0
9	30x30	600	5000	380	200	480	2,25	15,2
10	30x30	600	8400	370	260	430	2,25	17,0
11	30x30	600	8400	380	260	430	2,25	16,8

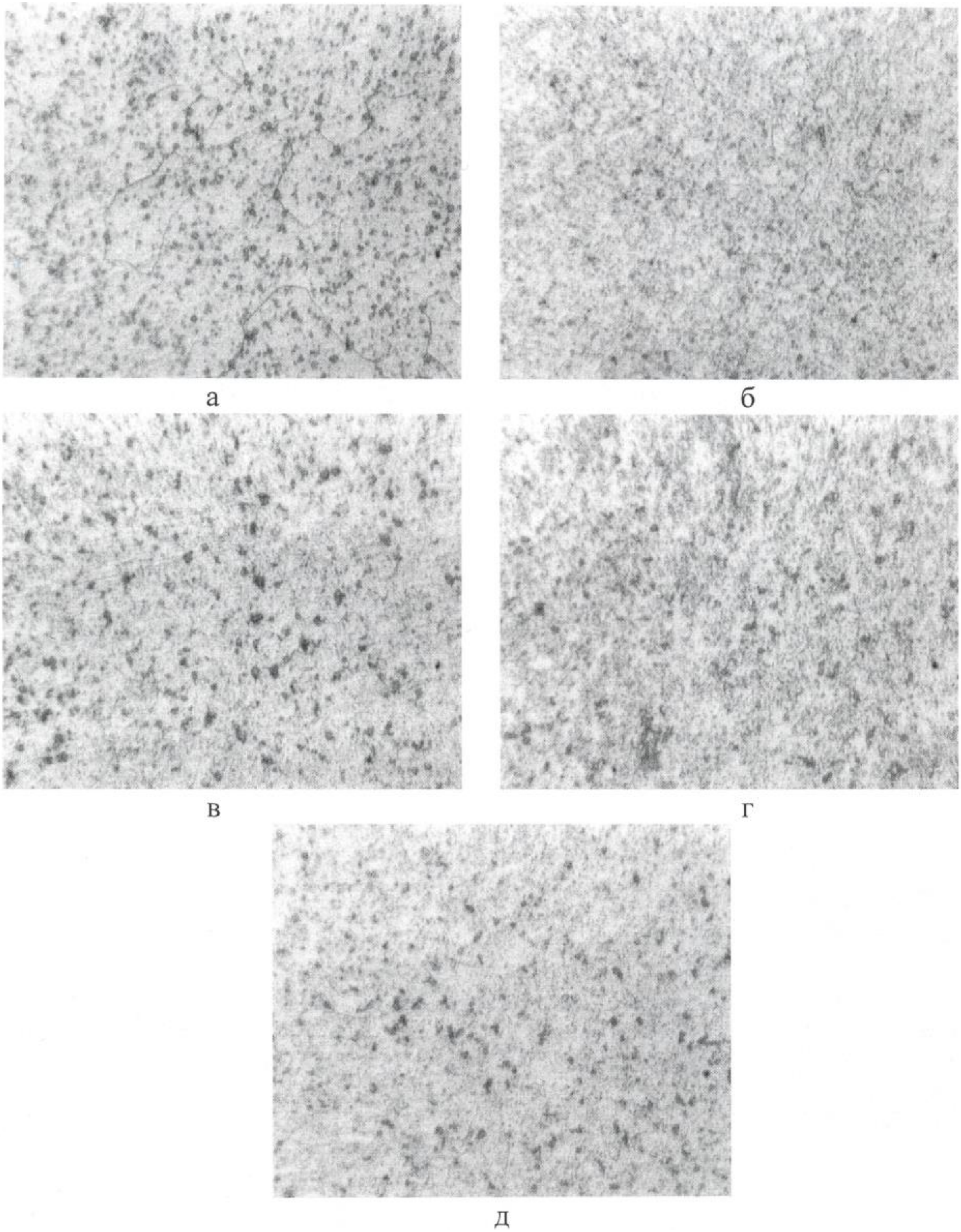
It was found that the optimal practice for production of coiled aluminium, grade 1230 consists if the following: heating temperature of the bar – 490°C, temperature of rolls - 190 °C, temperature of die – 300 °C, with the dimensions of the bar 30x30 mm. These data are in good agreement with those obtained in field research at Verkhnyaya Salda Metallurgical Production Association [1]. A slight difference in the heating parameters of the tool can be explained by smaller pass of the rolls and the bar, and a longer duration of processing of one bar (26 seconds) at the expense of decrease of the circumferential speed of rotation of the rolls.

Mechanical properties of the rod made during the research are shown in table 3.6. To estimate the formability of the rod the coil was drawn into wire with diameter of 3 mm. Thus, after each passage the rod was tested for rupture strength (tensile strength) and elongation. The mechanical properties are given in table 3.7. Analyzing the given data you can notice that the process of production of wire 3 mm was conducted without annealing and breaks. Moreover it should be reminded that the long-length rod was produced by welding of discrete bars in the deformation zone of rolling-extrusion.

Table 3.6 - Mechanical properties of rod made by CRE method

№ of experiment	Metal or Alloy	Tensile strength, MPa	Elongation, %
1	1230	107,5 110,5	21,7 21,7
2	1230	92,3 90,4	10,6 12,7
3	1230	77,8 78,7	28,0 27,9
4	1230	78,2 76,5	28,2 28,3
5	1230	95,2 92,9	24.8 25,4
6	1230	95,2 96,7	26,0 25,8
7	1230	77,7 79,6	24,9 25,9
8	5082	253,1 261,3	11,6 11,4
9	5082	265,8 288,4	11,7 11,6
10	5082	318,7 315,8	11,2 11,1
11	5082	317,0 322,5	11,0 11,1

Metallographic research of the rods showed that quite homogeneous microstructure with uniform distribution of excess phases and secondary precipitation formed (picture 3.13). The microstructure of the wire samples (see picture 3.13) given in comparison with the rod is characterized with similar structure.

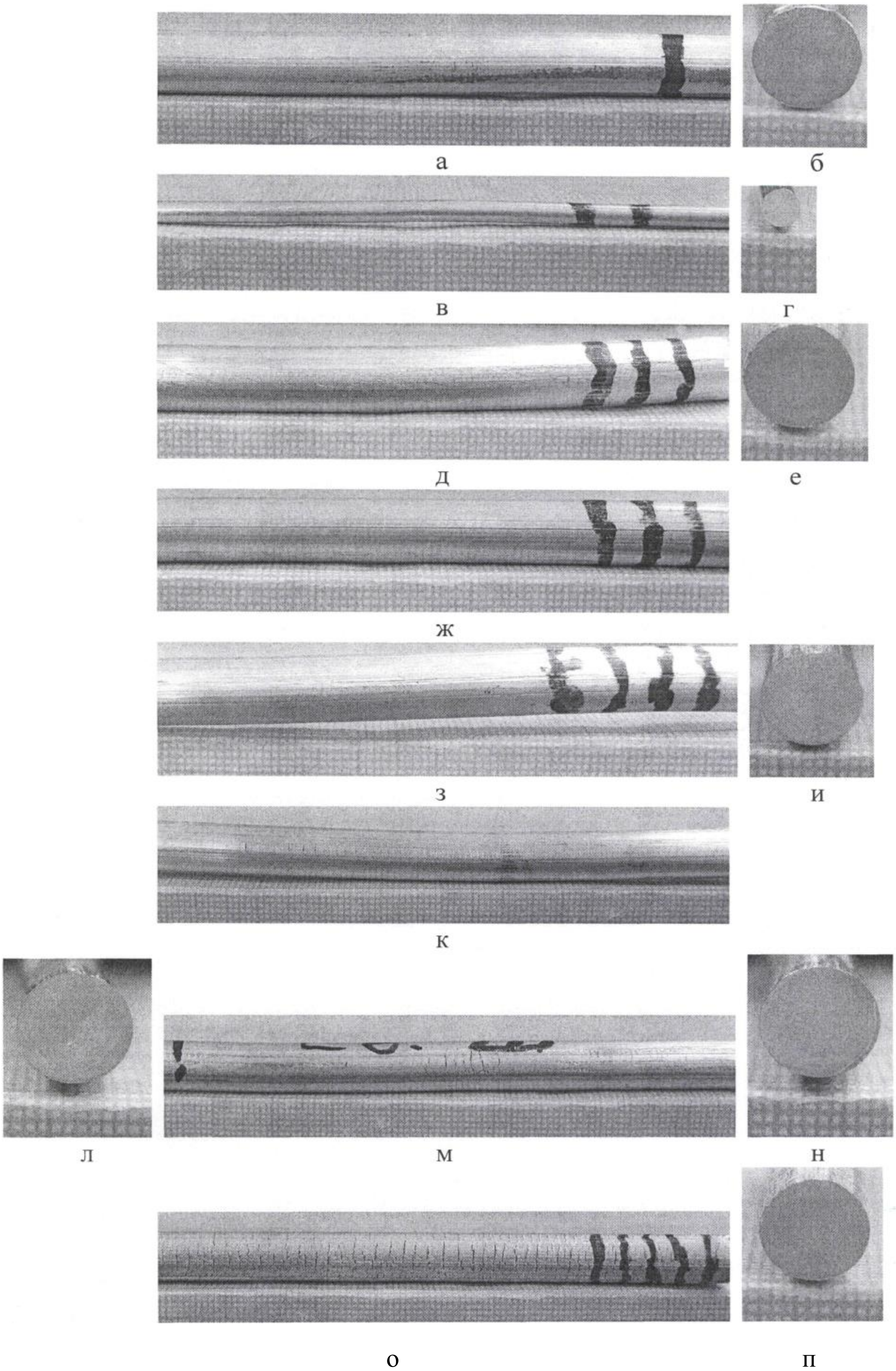


Picture 3.13 - Characteristic microstructure of the samples of deformed semi-finished products, x720: а – with diameter 9 mm of alloy 1230; б - with diameter 3 mm of alloy 1230; в - with diameter 9 mm of alloy 5082 (experiment 9); г - with diameter 9 mm of alloy 5082 (experiment 10); д - with diameter 9 mm of alloy 5082 (experiment 11)

Table 3.7 – Change of mechanical properties during drawing of wire of alloy 1230

№ of pass	Diameter of sample, mm	Tensile strength, MPa	Elongation, %
1	9,00	77,74 79,63	24,9 25,8
2	8,50	113,83 113,86	7,0 7,1
3	6,80	122,70 123,24	3,9 3,1
4	5,88	138,38 132,51	4,1 3,6
5	5,20	141,31 145,52	3,0 3,3
6	4,55	142,83 145,87	3,2 3,1
7	3,95	143,71 156,03	2,9 3,0
8	3,45	154,26 153,21	2,7 3,0
9	3,00	155,77 159,99	3,1 3,0

On the second stage of the research, rods of alloy 5082 were produced according to similar technology. However it was much more difficult to conduct the process of rolling-extrusion in stable mode of deformation as compared to deformation of aluminium grade 1230 due to formation of high stresses on the rolls. Since alloy 5082 is more difficult-to-form in comparison with 1230 and has higher resistance to deformation the temperature of the bar was selected as 480°C, and the heating temperature of the rolls was increased to 350°C. At the same time rods with diameter 9 mm (see table 3.6) were successfully produced, however the quality of the surface of the extruded products (transverse microcracks) does not meet the requirements of the standards. The presence of microcracks on the wire (picture 3.14) is due the rise of temperature in the deformation zone over critical temperature caused by additional heating of the bar during the extrusion. The heating temperature of bar was decreased as low as possible (to 430 °C), and the temperature of the tool was slightly increased in further experiments. Owing to this the extrusion of aluminium rods of alloy 5082 was successfully stabilized, and satisfactory surface quality was achieved.



Picture 3.14 - Characteristic surface (а,в,д,ж,з,к,м,о) and macrostructure (б,г,е,и,л,н,п) of rods: а,б – diameter 9 mm made, alloy 1230; в, г- diameter 3 mm, alloy 1230; д,е,ж - diameter 9 mm, alloy 5082 (experiment 9); з,и – diameter 9 mm made of alloy 5082 (experiment 10); о,п – diameter 9mm, alloy 5082 (experiment 11); к,л,м,н – area of welding for alloy 5082

Tensile strength properties of the rods (see table 3.6) correspond to international standard. Analyzing the microstructure of the rods one can notice that a relatively homogeneous structure with uniform distribution of excess phases and secondary precipitations was formed.

Thus, as a result of the research a pilot plant CRE-400 for combined processing was designed and made. Experimental tests for production of extruded products of aluminium 1230 and alloy 5082 (picture 3.15) were conducted on it. Along with it, optimal dimensions of the bar were found, operating practices of combined rolling-extrusion processing for industrial conditions established.

Picture 3.15. View of a product of alloy 5082 made by combined rolling-extrusion method on CRE-400 plant

Economic efficiency calculations for introduction of this plant showed that in comparison with conventional technologies (discrete extrusion on horizontal hydraulic press) by which similar products in Russia are currently produced, the cost of rods of various aluminum alloys can be reduced by 30-80%. At the same time productivity increases by 2-3 times, and the properties of extruded products meet the requirements of GOST 21488-97. The research data provide an opportunity to recommend the developed modular equipment and operating practices for implementation into production, especially for making low-tech products with small cross-section of aluminum alloys of different alloying systems.

CONCLUSION

Comprehensive theoretical and applied research of the CRE process allowed for the data of power parameters for aluminium alloys of various alloying systems in a wide range of temperature-speed and deformational parameters. The deformation force due to the use of active forces of friction proved to be 8-10 times lower than in comparison with conventional extrusion technology and did not exceed 300 kN. It allowed to create a new energy-saving technology and designs for original plants for combined rolling-extrusion of aluminium alloys, test them at a number of metallurgical plants and to manufacture experimental lots of extruded products of aluminium and its alloys.

Modelling of CRE process with a software package DEFORM^{TM}-3D in a preset range of deformational, temperature-speed parameters made it possible to identify the structure of plastic area of deformation zone and to identify the dependences of the temperature of extruded products on the rotation speed of the rolls and the temperature of the tool; forces and stresses acting on the tool, torques of the rolls and the required power of a drive motor which was not higher than 45 kW. The possibility of secure deformation during CRE process is provided at the highest values of Siebel friction (ψ = 0,8-1,0), at the deformation rate during rolling of at least 50% and a distance of the die from the common axis of the rolls up to 0,35 of the diameter of the rolls.

Experimental techniques were developed, comprehensive research of the deformation process by CRE at various temperature (T=480-580 ^{o}C) and speed (ξ=0,54-2,32 c-1) conditions of processing was conducted in a preset range of dimensionless parameters that unambiguously describe the deformation zone. Experimental data on shear resistance was obtained for understudied foundry alloys of Al-Ti-B for theoretical calculations, the data were within a range of 15-25 MPa. Metallographic research of the structure and properties of rods of aluminium alloys produced by CRE allowed to identify the regularities of their formation depending on the temperature-speed and deformational parameters. The level of strength and ductile properties of the produced extruded products (for example, ultimate tensile strength of alloy AMг6 was σ_B=318,7 MPA with elongation δ=11,2%) allows to conduct advanced processing during the production of wire without intermediate annealing.

As a result of the research, new designs of components of modular equipment for making long extruded products of aluminium alloys were created and protected by RF patents. A pilot plant CRE-400 was made and implemented into production which allowed to prove the technology of production of rods with a diameter 9 mm of aluminum grade 1230 and aluminum alloy 5082.

Application of new technologies and equipment for combined processing of aluminium alloys proposed in this paper have provided an opportunity to reduce the production costs of rods of various aluminium alloys by 30-80%, at the same time productivity increases by 2-3 times, and mechanical properties of extruded products meet the requirements of the Russian and international standards.

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Table 3.3 – Mechanical properties of rods

Alloy	Parameter	A=32,3											
		T=480 ^{0}C						T=580 ^{0}C					
		ξ=0,54 c^{-1}			ξ=2,32 s^{-1}			ξ=0,54 s^{-1}			ξ=2,32 s^{-1}		
		μ=3,5	μ=5,8	μ=11,5	μ=3,5	μ=5,8	μ=11,5	μ=3,5	μ=5,8	μ=11,5	μ=3,5	μ=5,8	μ=11,5
	$\sigma_{0,2}$,MPa	90	105	117	71	81	83	95	104	118	65	70	73
	$\sigma_{в}$,MPa	118	125	133	123	118	112	111	121	131	98	103	107
	δ, %	22	21	18,6	23	22	14	25	23	22	26	25	16
	$\sigma_{0,2}$,MPa	100	114	112	82	72	79	113	123	138	124	93	97
	$\sigma_{в}$,MPa	134	144	140	116	115	123	145	152	160	166	138	130
	δ, %	25	16	18	28	25	21	22	21	14	25	26	17
		A=19											
		T=480 ^{0}C						T=580 ^{0}C					
		ξ=0,54 s^{-1}			ξ=2,32 s^{-1}			ξ=0,54 s^{-1}			ξ=2,32 s^{-1}		
		μ=6,9	μ=11,4	μ=22,4	μ=6,9	μ=11,4	μ=22,4	μ=6,9	μ=11,4	μ=22,4	μ=6,9	μ=11,4	μ=22,4
	$\sigma_{0,2}$,MPa	113	110	107	97	93	88	84	105	118	80	85	88
	$\sigma_{в}$,MPa	132	128	127	123	105	123	113	114	136	111	115	122
	δ, %	23	20	16	27	24	22	24	24	22	32	27	28
	$\sigma_{0,2}$,MPa	101	95	90	84	79	87	123	108	150	98	90	119
	$\sigma_{в}$,MPa	135	130	121	114	113	114	140	140	177	134	122	154
	δ, %	12	18	18	20	20	21	18	26	14	20	28	17