

## The Modern Market of Blank Productions in Mechanical Engineering and the Problem of Standardization of New Materials and Technological Processes

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### Abstract

The widespread interest of the blank productions in mechanical engineering in mass production of shaped parts from powder materials by injection molding, based on the use of the thixotropy effect in moldable media, placed on the agenda the problem of standardization of new materials, technological processes and technological solutions. As the molding industry of metal powders and other materials with thixotropic properties of injection molding is improved, the number of national and international standards, covering all aspects of technology, is steadily increasing, too. Standardization is an important process for the creation of a database with typically attainable results, terminology, abbreviations, and the designation of the used brands and materials.

### Keywords

Metallurgy; thixotropic materials; terminology; abbreviation; alloy grades; standards; thixoforming; metal injection molding (MIM).

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Over the past quarter century, the global market for offered engineering materials, technologies and products has changed and continues to change radically. In particular, dramatic changes are observed in the blank production in the market for special casting technologies and powder metallurgy. In the studies of metallurgists, the rheology science, i.e. “a science that studies the fluidity of bodies, based on the characteristics of the viscosity of the medium and the rate of deformation” (P.A. Rebinder), unexpectedly made advances. Thus, starting from the 70s of the last century, the object of intensive research for material scientists, metallurgists and technologists that led to the birth of *thixotropic metallurgy* was a fundamentally new direction in the study of traditional aluminum alloys and features of the production of shaped castings from them. The research made by M. Flemings (MIT, USA), aimed at solving the private metallurgical problem of hot cracks in castings and turned into a study of viscosity and the effect of thixotropy in crystallizing metal alloys, opened the way to the development of a whole group of modern foundry technologies, to a paradigm that received the generalized name - “*thixoforming*”. Since 1990, this interest has been expressed in specially organized International Conferences

“Processing of Metals and Composites in Solid-Liquid State” (S2P index).

Scientific and technical development is inextricably linked with the expansion and actualization of the existing base of international and national standards, standards of enterprises. We will show on a specific example how the abbreviation added to the grade of an alloy used by the aluminum alloy seller becomes the guarantor of a new level of alloy properties and casting quality. Currently, the foreign automotive industry has accumulated and widely uses a wealth of experience in organizing the processing of foundry silumin Al–Si–Mg, Al–Si–Cu, Al–Si–Cu–Mg systems by thixoforming [1–6], which has developed rapidly at the end of the last century, when a new paradigm was adopted by the large metallurgy of Europe. The European consumer of light alloys gives the leading positions to the analogues of the popular domestic alloy AK7 (A356/357 abroad). The material of the casting prior to the formation of the part is given an additional (functional) property: the relaxation ability and fluidity under the influence of shear deformation, realized during casting. The required condition of semi-finished products ready for further processing (thix-procurements, feedstock) is provided by the features of their structure prepared for the start of part molding. The slight

formability of the prepared portion of solid-liquid material (suspension) at the stage of filling the form is achieved by the shear deformation and pre-relaxation. The main controlled factors of the blank structure are the morphological parameters of the solid  $\alpha$ -Al phase (the average grain diameter  $D_\alpha$ , the grain shape factor  $F_\alpha$ , the degree of skeletonization  $C_\alpha$ ) [6].

The characteristics of foreign material in the cast state presented in Table 1 substantially exceed the characteristics of the alloy in castings from domestic AK7 and AK7pc alloys even after heat treatment (Fig. 1). The new qualities of the final product produced by SAG (Salzburger Aluminum AG) from foreign analogues of the AK7 alloy are obtained by using primary Al and tightening control over the Mg content by creating a special structure of the material. All this is reflected in the alloy grade – Thixalloy.

Giving the material thixotropic properties and corresponding fluidity, partially characterized by the criteria mentioned above, and guarantees of obtaining the final result with a new level of properties of the product planned for production, are achieved by various alloy manufacturers with various means, which for the buyer is reflected in the standard of the metal supplier company. The standard of the Aluminum Pechiney Company in respect of all sold aluminum alloys of this type corresponds to the ALTHIX brand, the standard of the SAG Company is the TNIXALLOY brand. Thus, in the accepted designation of material grades, the main meaning is borne by the abbreviation “THIX”, which guarantees the buyer that the material has thixotropic properties and, if necessary, toughened the requirements for the composition of the alloy.

The unique qualities of amorphous materials processed by injection molding, for all alloys sold by the German company Heraeus, gave rise to a standard enshrined in the AMLOY brand.

The mechanical properties guaranteed by the standards of the new casting methods, as well as the opportunities and the preliminary solutions in the virtual space of scientific and engineering design tasks, allowed us to change the proposed casting production routes for the industrial products of the EU countries. The successive stages of the development in the preparation of the industrial technology for the production of parts by the method of casting solid-liquid metal have changed fundamentally. In SAG [7] they look as follows (Fig. 2).

*The most important factor in this casting technology is the rheological properties of the blank; the main scientific task of the casting theory is the construction of a complete flow curve for the material of the blank for different cooling conditions; establishing these dependencies for industrially important casting systems (alloys) and testing the suitability of flow models for specific conditions of a mold becomes the main engineering problem of the casting theory.*

Alloys with a similar prefix (abbreviation) should also appear in the Russian manufacturer of engineering materials, apparently, using the possibilities of large metallurgy. Domestic patented thixoforming technologies already exist [8–12] which fundamentally alter the properties of aluminum alloy (Table 2), but unfortunately they have not yet been assigned to the interested consumer by an appropriate abbreviation, manufacturer's standards and are not represented on the market.

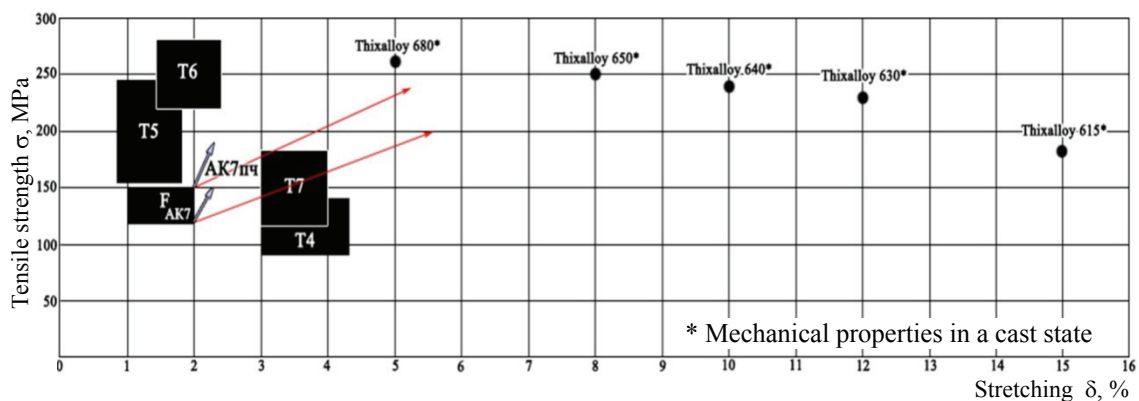


Fig. 1. Analogue variants of the alloy AK7 by the SAG Company and their guaranteed minimum mechanical characteristics in the cast state [7]

Analogue variants of the domestic alloy AK7 by the SAG Company and their guaranteed minimum mechanical characteristics in a cast state [7]

Alloy grade	Alloy composition	Mechanical properties of the alloy in a cast state, $F$	
		$\sigma_{0.2}$ , MPa	$\sigma_B$ , MPa
Thixalloy 615	Al + 7Si + 0.15Mg	100	180
Thixalloy 630	Al + 7Si + 0.30Mg	120	230
Thixalloy 640	Al + 7Si + 0.40Mg	130	240
Thixalloy 650	Al + 7Si + 0.65Mg	140	250
Thixalloy 680	Al + 7Si + 0.80Mg	150	260

Table 1

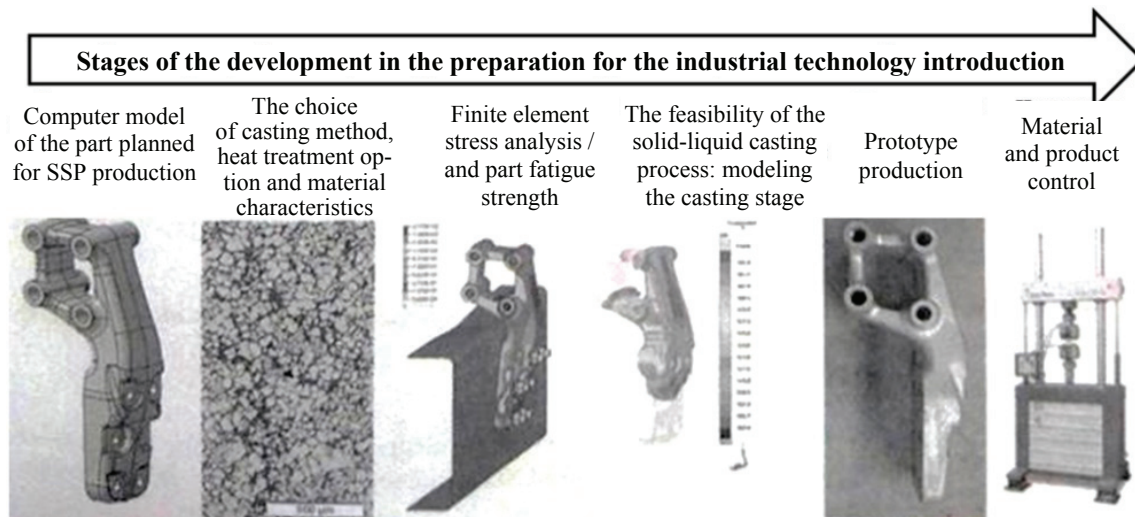


Fig. 2. The organization of the production of castings from Thixalloy brand materials [7]

Table 2

**Mechanical characteristics of the domestic alloy AL25 with thixotropic properties in the piston part [9 – 11]**

No.	Method of casting piston parts, AL25 T6	Characteristics			
		$\sigma_B$ , MPa	$\sigma_{0.2}$ , MPa	$\delta$ , %	HB
1	Chill casting	220	220	0.50	107
2	Liquid stamping ( $P = 150$ MPa)	250	240	0.85	120
3	Liquid stamping ( $P = 150$ MPa) + HIP ( $T = 460$ °C, $P = 180$ MPa, $t = 3$ hours)	310	290	1.20	121
4	Thixostamping	309	274	6.83	150

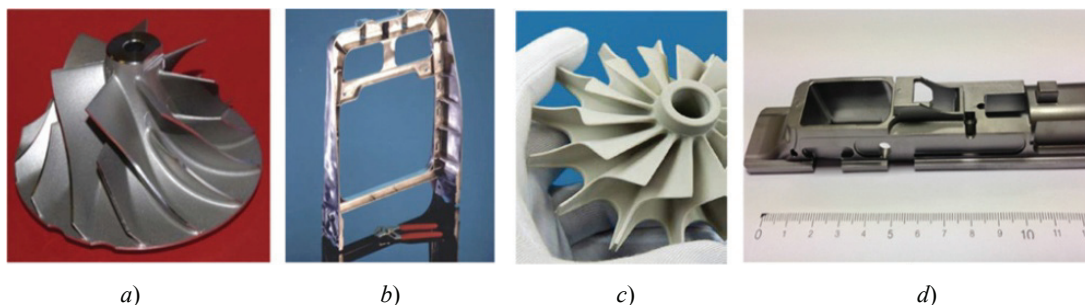


Fig. 3. Powder materials examples:

*a* – an aluminum part made by thixolite; *b* – a magnesium alloy part made by tixomolding; *c* – a ceramic part (CIM); *d* – a steel part (MIM)

On the background of the achievements of modern productions of precise parts from thixblends, the creation of similar products by casting powder materials (Fig. 3 and 4) not only led to the emergence of the abbreviations PIM (MIM, CIM) behind the ruler, but due to the general physical nature, new abbreviations, together with the abbreviation THIX, became symbols of metallurgy of thixotropic materials [6, 9 – 18]. In the case of PIM technologies, the possibility of forming powder-polymer blends is also provided by their thixotropic properties.

However, in Russia, in the conditions of the emerging industry and relevant scientific schools, without the organizing role of institutions like, for example, the American National Federation of Powder Metallurgy

(MPIF), the organization of production and the emergence of scientific and technical information through private initiatives creates quite a lot of uncertainties and absurdities in matters that require an unambiguous resolution.

Here are some excerpts from the review “Standards for casting metal powders under pressure: current state and challenges for the future” prepared by M. Mulser and prof. F. Petzoldt, employees of the Fraunhofer IFAM, for the PIMI journal [19]. A wide range of materials is available for MIM production, and MIM specifications have already been offered for a large number of special steels, titanium and titanium alloys, nickel super-alloys, a large number of special materials such as copper, cobalt-chrome or tungsten. The need for new materials is primarily due to promising

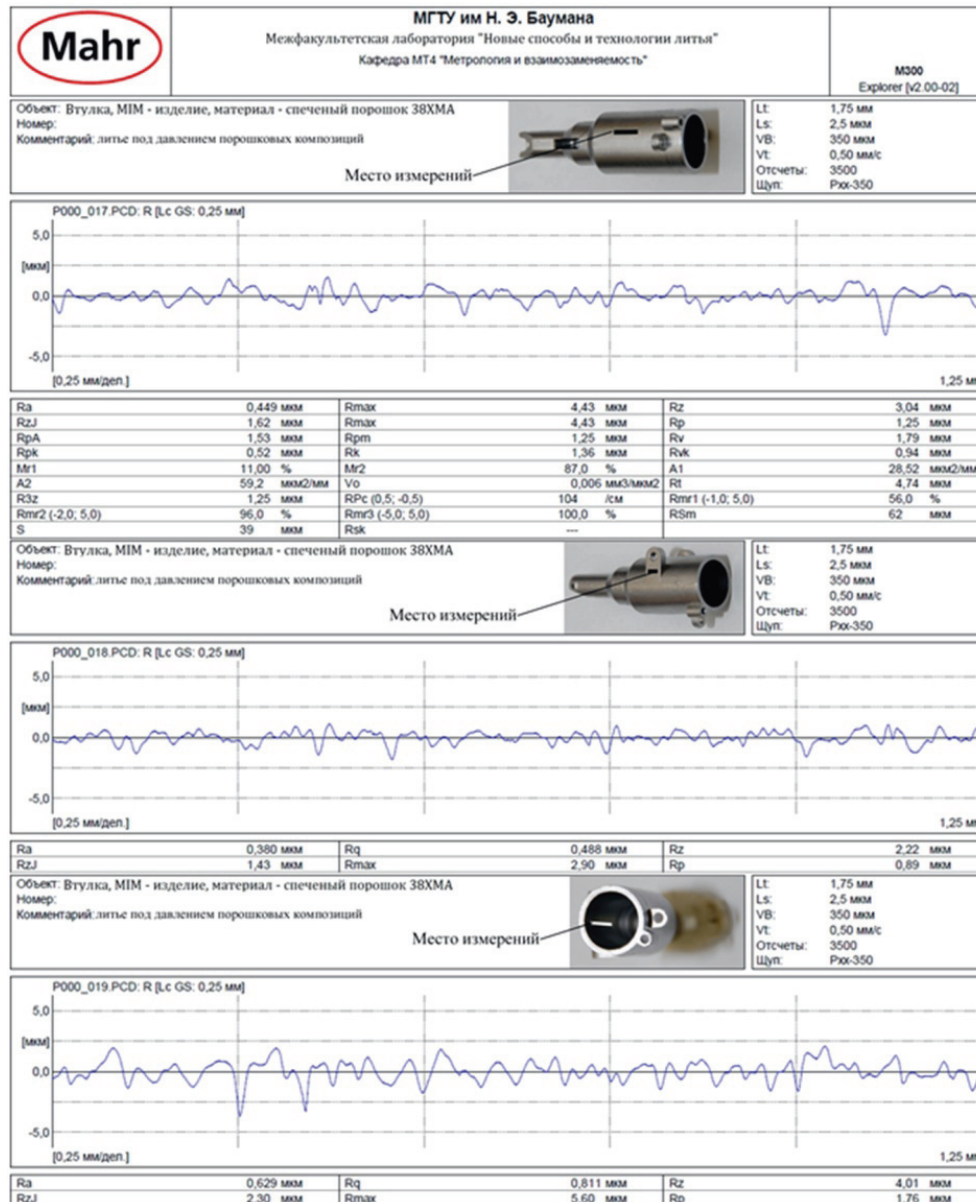


Fig. 4. Protocol for measuring the surface roughness of the MIM part "Sleeve"

applications in the automotive, aerospace and medical fields. To help designers, engineers, technologists and customers evaluate the merits of one production process over another and make choices for new design and technological solutions, it is very useful to have an available reliable basis for comparison. Standardization is an important process for ensuring such a database of typical results achieved. As the die-cast metal powder industry improves, the number of national and international standards covering all aspects of technology is steadily increasing. Standards and precise terminology are an important factor for a successful relationship between the manufacturer of the MIM part and the customer. This simplifies communication and avoids misunderstandings between both parties. The need to develop a special terminological standard for the MIM arose from the fact that there are several terms and expressions that differ from those used in production technologies such as

machining, forging and casting. This terminology also differs from the already used standard terms related to powder metallurgy (in the English-language literature, these are MPIF 9 and ASTM B243) or plastics processing (ASTM D883). One such standard is MPIF Std. 64 "Definition of terms used in injection molding (MIM)". The purpose of the standard 64 is to ensure consistent use, correct understanding and accurate interpretation of the terminology associated with MIM. These are the terms necessary for descriptions of powder particles (for example, spherical powder, chop powder, surface area value, particle size distribution, ultimate bulk density), terms for each stage of the process along the processing chain (mixing, molds terms, preliminary sintering, etc.) and terms for key process parameters (for example, volume fraction of solids, melt temperature, compaction pressure, shrinkage factor). The standard defines the names for MIM parts at different stages of the process



(green detail, brown detail, sintered detail, etc.), typical defects in MIM parts that arise due to violations of technology (jetting, burr, weld line, shell, shrinkage, pore, swelling, cracking, etc.) are identified, terms characterizing the MIM material (density, open and closed porosity, etc.) are presented.

Most startup organizers in Russia forget that the commercialization of technologies for the manufacture of products from metal powders, ceramics and composites in a solid-liquid state must also be built using appropriate standards. It is important to emphasize that the meaning of the problem solved by a foreign supplier of the material and represented in the abbreviation in Latin letters should be preserved either by the previously used symbols or by a consistent Cyrillic abbreviation when switching to the Russian version. Some examples: in the Russian version, AFC (Automatic Frequency Control) is either AFA (Automatic Frequency Adjustment) or AFR (Automatic Frequency Regulation); AU (Arithmetic Unit) in the Russian version is AD (Arithmetic Device); MTR (Metal Testing Reactor) in the Russian version is MNR (Metallurgical Nuclear Reactor), i.e. upper-case Russian letters must be decrypted. If the term is Russified, for example, composite, the thixotropy effect, *thixbland*, *thixoforming*, *feedstock*, *debinding*, the word is written in lower case. These requirements are the same for thix and powder technologies, in which the casting processes are based on the use of a single theoretical model of the flow of non-Newtonian media.

Unfortunately, the work of Rosstandard in the period under review did not contribute to the strengthening of this ideology, as a result of which, first of all, we are faced with gross violations of the rules for using terms. Of course, it is important to foster the emergence of scientific publications and a wide exchange of information in solving scientific and technical problems related to import substitution, but it should not be allowed that early proposals that are not supported by sufficiently complete analytical literature reviews and requirements for translations of foreign texts and abbreviations used by the developer of the material or process appear on the pages of domestic scientific and technical journals in the pursuit of advanced technologies. A barrier to this, according to the authors, should be a deeper editorial check of published materials for the compliance with international and national standards. An example of information about the MIM process, when the purpose of a publication is to represent a fundamentally different surface quality, the roughness of which in the sintered state corresponds to pure turning, can be the surface roughness measurement protocol of the MIM part "Sleeve" in Fig. 4.

In the last decade, more than 50 publications related to the metallurgy of thixotropic materials, and more specifically, the casting of powder materials, have appeared in the domestic technical literature. A number of authors of publications about PIM (Powder Injection Molding), – injection molding of powders and its varieties MIM (Metal Injection Molding) and CIM (Ceramic Injection Molding), – often offer readers to consider these foreign methods as fundamentally new special casting technologies for us today, at the same time neglecting both the rules for using

abbreviations and the requirements of the international standards for marking brands of sintered materials in Russia and in particular for the requirements of the specialized IS standard O 22068: 2012 "Sintered-metal injection-molded materials - Specifications" [20, 21], and for earlier domestic publications.

In the middle of the last century, domestic and foreign scientists proved the high efficiency of the technology patented in the USSR and received in our country the name "hot casting under pressure of ceramic products". "The essence of hot casting technology is to create thermoplastic casting systems from powders of solid materials in a mixture with organic substances (bundles), followed by pouring these systems in a liquid state at elevated temperature into metal forms" [22 – 24]. This technology, which has quickly gained a solid place in the chemical industry, is still used as an independent direction in ceramic technology. Creative scientific idea by P.O. Gribovsky: "*Hot casting technology provides the ability to manufacture products from any solid materials, ranging from natural minerals, pure oxides, carbides, metals, etc. and ending with multicomponent complex synthetic materials and their combinations*", commercialized more than 60 years ago in the USSR, China and several European countries and fixed today throughout the world with the abbreviation LP PIM (Low Pressure Powder Injection Molding [25]), unfortunately, in a timely manner was not evaluated by domestic metallurgists.

According to Gribovsky, the principal technological scheme for the manufacture of shaped articles using the advanced method of powders of any composition suitable for sintering consists of four main stages (we pay attention to the content of operations and terminology):

- *the first stage* (the formation of a dispersed system powder - a functional binder), it is necessary to ensure the technological possibility of obtaining a product of a given configuration;

- *the second stage* (production of a semi-finished product) aims to use the capabilities of intermediate disperse systems to form a semi-finished product of a given configuration and size (taking into account the subsequent volumetric changes that occur during the consolidation of powder particles);

- *the third stage* (removal of the binder from the semi-finished product), it is necessary to prepare the semi-finished product for sintering, resulting in a porous powder semi-finished product, from which the final product is obtained during sintering;

- *the fourth stage* (sintering of the powder particles that are in the semi-finished product into a monolithic product) is achieved by appropriate heating and is the main, final stage of the technology, which determines the characteristics of the molded products.

It is difficult to find, apart from the specification of descriptions, in the modern PIM-casting of powder mixtures (Fig. 5), proposed to Russian readers in publications [13 – 18, 26 – 28], at least one principle difference from the above description. The niche of MIM-technologies in the modern blank production is based on the achievements of powder metallurgy technologies and on the modern understanding of the technology of casting filled polymers.

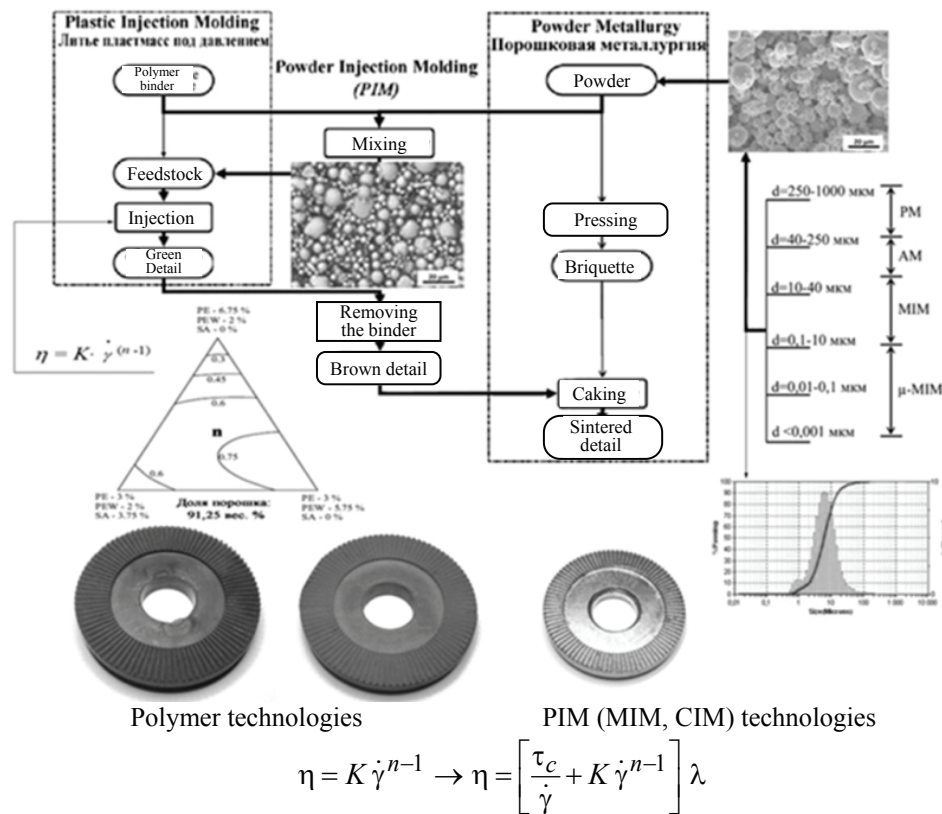


Fig. 5. Niche of the PIM-technology in modern blank industries [18]

Today, when Russia entered the WTO, the designer of a new product, if it wishes to use MIM technology, should be aware of the designations of types of materials that meet the ISO 22068:2012 standard. In accordance with the requirements of the standard, the decision to use MIM technology to obtain a product from a specific material must be spelled out by the product developer in the title of the part drawing: this way not only the requirements for the chemical composition of the part material but also the requirements for its production method are fixed in the title. Therefore, the principal mistake of the designer, due to the violation of the requirements of ISO 22068:2012, will be the use of designations of sintered MIM material brands in the following form: the brand “4140” instead of “MIM-4140” or the brand “40XMA” instead of “MIM-40XMA”. It is also unacceptable to use the terms “MIM-technology”, “MIM-feedstock”, “MIM-product”, as it is done in a number of domestic publications, since the introduced transliterated abbreviation “MIM” is not fixed by the national standard and must be decoded as any abbreviation. However, at present such a decoding does not exist or, at least, is not proposed, and therefore the equating of the terms MIM feedstock and MIM feedstocks is unacceptable. Moreover, in our opinion, it is desirable that the MIM abbreviation, until the well-established Russian version is formed, be present in published studies, since the terminology of publications should be based on the current standards, in this case – international ISO standards. In case the Russian version is obligatory, the following replacement is possible: the phrase

“Metal Injection Molding” (MIM) is replaced by “Injection Molding of Metal Powders”, as a result of which we have “IMMP-technology”, “IMMP-feedstock”, “IMMP-product”; the phrase “Ceramic Injection Molding” (CIM) is replaced by “Injection Molding of Ceramic Powders”, as a result of which we have “IMCP-technology”, “IMCP-feedstock”, “IMCP-product”. There is a variant “Powder Casting Forming (PLF)” proposed by the authors of the publication [29]. The best options are possible: “Casting Technology of Powder Materials (CTPM)”, close to the name introduced by P.O. Gribovsky and used as an abbreviation in the publication [30]; or – “Injection Casting of Powder Materials (ICPM)”, which is preferable, because it corresponds to the modern name, fixed in the textbook [31]. Therefore, based on the fact that in most cases the powder designation is used, given by the manufacturer (supplier), then the material type designations in MIM products also take the appropriate form: for example, the “MIM-4140” brand, if the manufacturer uses foreign raw materials, or “ICPM-38XMA” when using domestic materials.

The use of the phrase “metal mixture” in relation to the raw material for the MIM technology, which is referred to as “feedstock” in the English-language literature, is completely unacceptable in some domestic publications. In accordance with the purpose, composition and structure, “feedstock” is an artificially created functional polymer dispersion-filled composite material that has little in common with the definition of “metallic mixture”. The dispersed phase in such a composite is a mixture of powders of the required

composition (metallic or ceramic), the dispersion medium is a thermoplastic polymer binder; but the principal feature of “feedstock” is precisely the totality of a number of functional properties that provide the possibility of molding a semi-finished product and defect-free removal of the technological binder from it, the possibility of sintering to obtain a finished part with the required chemical composition and complex physical and mechanical properties. Due to the lack of updated national standards, to designate such special powder-polymer mixtures in the Russian-language scientific and technical literature, in our opinion, it is advisable to use a specialized term, which, for example, can be the transliterated foreign word “feedstock”, which, like the word “composite”, may possibly become the language norm. Similarly, the phrases “raw part” instead of “green”, “calcined part” instead of “brown” are not permissible.

We also turn to the domestic standards of powder metallurgy (PM). The terms available in GOST 17359–82 (there is no later edition of the standard), such definitions as powder casting, slip casting and extruding do not correspond to the molding method called Metal Injection Molding (MIM). The terms and definitions of GOST 17359–82, containing only 83 positions, have not yet been clarified, while in the international standard ISO 3252: 1999, which was issued later, 192 positions were already defined, in which the types of powders were reflected, the shape of the powder particles, powder properties and research methods, powder pretreatment, powder additives, molding, compaction processes and conditions, equipment, pressing properties, pre-sintering, sintering, sintering conditions and furnaces, phenomena observed during sintering, sintering properties products and processing after sintering, classification by materials. More information about this information can be found in the monograph “Powder Metallurgy. Encyclopedia of International Standards” by O.N. Fomina [20]. In the above mentioned work it is, without details, mentioned the existence of the standard Std. 64, prepared by the American National Federation of Powder Metallurgy, which published a database on the properties of powder materials processed by the MIM method in 1997.

Since January 2001, there is the European Powder Metallurgy Association (EPMA), which has prepared guidelines for technologists and designers: “Metal Injection Molding – a Manufacturing Process for Precision Engineering Components”. The European MIM industry has long recognized the need to develop international standards. An important result of the work of the EuroMIM group of the European EPMA Association, joint discussions with the North American and Japanese trade associations, as well as with the relevant ISO subcommittee, was the publication of the ISO 22068 standard published in 2012. The materials in products produced by injection molding of powders are today in world practice represented by the notation used in the international standard ISO 22068: 2012 (E) “Sintered metal materials obtained by injection molding. Technical requirements”. The European Committee for Standardization adopted with the same name and published a document under the index EN ISO 22068: 2014 “Sintered-metal injection-molded materials – Specifications”. These standards are

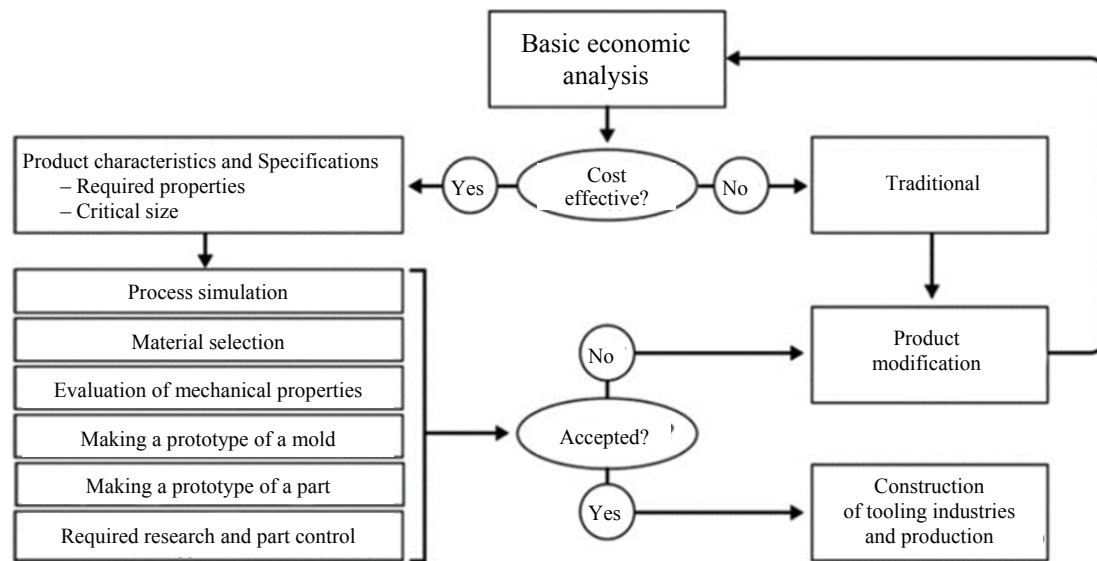
made to provide designers and process engineers with the necessary information to specify materials in products made only by the high-pressure casting process (MIM), and the information part of the alloy designation before the material code must contain the Latin letters MIM. These standards do not apply to structural parts made by other methods of powder metallurgy, such as “classic” slip casting, electrophoretic molding, pressing and sintering technologies, pulse shaping, or rolling metal powder.

A similar regulatory document of Rosstandard does not yet exist, as there is no centre of competence in the field of MIM-technologies in the country that can advise and provide services on organizing a full production cycle in the Russian Federation from materials of domestic manufacturers for import substitution of feedstock and powder-polymer products compositions molded by injection of suspensions (slips) and sintering of shaped blanks. Today in the world the number of MIM-companies has exceeded 400, and, for example, the EuroMIM group unites more than 70 companies. In Russia, at present, on the basis of publications, there is at least one company producing MIM products, starting to use the relevant regulatory documents and developing an enterprise standard, – it is “Kalashnikov” Concern and LLC “Rifmet” [32].

MIM, as a modern method of casting shaped products from metals and alloys, has replaced the traditional special types of casting and PM technologies, which often do not guarantee sufficient material density in shaped blanks. MIM’s ability to provide competitively priced high-volume production of precise blanks with very tight dimensional tolerances from a wide range of alloys, while providing excellent mechanical properties, has played an important role in the restructuring of many foreign companies, in particular, firearms manufacturers. It is considered that it is possible to save up to 40% in comparison with machining or in the production of equivalent products using the method of precision casting. Maintaining the dimensions of the sintered parts within the specified tolerances is ensured by careful control of the sintering process. Matt Bulger, Vice President of NetShape Technologies, Inc. (USA) believes that new alloys and new processing methods will also be of great importance for the opening of new orders for MIM in the weapons sector: “At present, standard MIM materials provide a high percentage of requirements made by manufacturers of firearms. Improved viscoplastic properties, especially fatigue strength, will help expand the use of MIM in new developments of MIM parts with its ability to use a variety of alloy compositions and types of heat treatments. This will be carried out through the improvement of alloys and processes such as GUIs. MIM manufacturers must move forward, relying on new standards and improving process management” [32].

In order to develop this new and very promising sector for the production of precision blanks and parts for mechanical engineering in Russia, and to choose the material that is optimal both in terms of properties and cost-effectiveness, it is important that the design principle of a MIM part be thoroughly studied at the university stages of the design engineer and process engineer preparation.





**Fig. 6. The logical diagram of the transition from the general concept of MIM-production to a specific product based on the enterprise standards**

There is a critical need for training designers – developers of general technology information about MIM technology, since it is in this group of specialists where there is often a lack of knowledge [28]. A series of regularly organized seminars in the USA, Asia and Europe testifies to the beginning of such training for engineers, when the topics under consideration usually include an introduction to the basics of the MIM process chain, processing of metal powders, design rules for MIM parts, quality control and control of properties of the resulting material.

As Fig. 5 shows, the processing of MIM feedstock is similar to plastic injection molding, but the physical properties of the slips are significantly different from polymeric materials. These differences affect the formation of the MIM feedstock. Understanding and consideration of this circumstance allows implementing MIM technology with a significantly higher level of accuracy. Modeling can be useful, especially if it can take into account the significant differences that exist in the properties of the MIM feedstock compared to unfilled plastics. The modern logic scheme for the transition from the general concept of a MIM product to its production (Fig. 6) is similar to that shown in Figure 2 for thixoforming.

Molding in both thix and MIM technologies is based on injection molding suspensions prepared according to certain rules, possessing thixotropic properties, i.e. the material of the molded product is capable of *locally* changing its technological and physical properties *during* the implementation of the technological operation of molding. Therefore, during molding, it is impossible to rely only on the postulates of the polymer casting theory with their non-Newtonian dependence of viscosity on shear rate (see Fig. 4), as well as only on the postulates of the thermal theory of casting liquid metals with Newton's viscosity. The unified scientific *model of the suspended material processed in a solid-liquid state (partially cured by any methods)*, suitable for analyzing and modeling processes occurring during the flow of a thix or MIM-slip in a casting tool, was the

*Herschel-Bulkley model*, in the publications of specialists in the field of classical methods of powder metallurgy [26, 27], present under the name Cross WLF + HB, also presented in Fig. 5. All this leads to the necessity to choose the design of the mold, the casting system, the choice of the design and location of the feeder, the casting modes. For this reason, all model parameters relating to the viscosity of the slip must be verified at the stage of MIM-production of a particular part.

### Conclusion

In order to prevent a significant lag in the Russian industry and the accompanying scientific and technical schools from the world community, to ensure the proper level of their mutual understanding, it is necessary to use common terms and definitions for a specific specialty. Standardization in the field of terminology, as in other areas of technology, greatly contributes to scientific and technical development.

The solution of the problem of standardization of special casting technologies new to Russia raised in this work is important for the development of the country's industry, for the development of its specific branch and the scientific school of thixotropic materials in metallurgy.

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