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ASSESSING CRITERIA FOR CASTING AND DEFORMATION SUITABILITY OF METALS AND ALLOYS

Purpose. Based on existing criteria for predicting the suitability of metals and their alloys for manufacturing products from them by deformation or casting analysis develop a set of dimensionless parametric criteria and their quantitative scales. Their using will allow increasing the predicting accuracy of metals and alloys for their processing by pressure or casting suitability and feasibility.

Methodology. The work uses phenomenological approach to systematic analysis results of metals and alloys mechanical and individual casting properties interpreting under uncertainty conditions, drawing on literature reference data, expert evaluation data and the authors' own research results. The authors' own data have been obtained experimentally using standard methods for mechanical properties determining and due to original authors' method for technical purity metals and alloys based on them cast samples values of their absolutely hindered linear shrinkage determination during casting.

Findings. The authors first proposed parametric dimensionless criteria and scales to them (criteria groups). Their application allows one, through such groups combinations, to assess suitability of any alloy or metal for its use possibility for products manufacturing by casting and/or pressure processing.

Originality. For the first time dimensionless parametric criteria have been developed and proposed for use at initial stages of new alloys or technologies elaboration for products from them manufacturing as well as their quantitative scales for preliminary assessment (prognosis) of alloys processing feasibility by pressure or casting, regardless of their type and method.

Practical value. Developed criteria and their quantitative scales using will allow alloys developers and specialized enterprises employees to save time and expenses both for alloy elaboration and for its implementation into production.

Keywords: *deformation, elongation, billet, plasticity, shrinkage, casting, structure, heat treatment*

Introduction. Products vast majority made of metals and their alloys has been manufactured by casting or further materials pressure processing (MPP) of their cast billets (rolling, forging, pressing, drawing, etc.). At the same time, alloys physical and structural properties, finished products geometric and/or shape features or other factors may cause particular alloy to be unsuitable for selected processing type. Therefore, by processing type, modern alloys have been divided into deformed or cast.

Any alloy suitability for particular type of processing determination is the first and key step towards achieving a positive result in any product manufacturing.

Such prediction accuracy is especially important at the stage of any alloy elaboration or introduction into manufacturing, as it allows developers in timely manner to either adjust further research direction, or, for shop technologists, to take appropriate technological regulations in production for desired result achieving.

According to their properties, metals and alloys have been characterized by varying degrees (in terms of time, deformation rate, energy consumption, etc.) of suitability for MPP. In particular, pure metals and single-phase alloys are relatively ductile and well deforming in cold state. At the same time, metals and single-phase alloys of technical purity could be hard and, in some cases, brittle. Therefore their MPP has been carried out not only in hot state, but also at extremely small values of reduction, speed, and using limited MPP types. Hot MPP methods have been also used to process billets of multiphase alloys, i.e. at the temperature at which their multiphase structure has been transformed into single-phase one (if it is possible) and the billet acquires satisfactory plasticity.

MPP and castings production conditions, alloys properties and products made from them, variety multifactorial nature have led to classifications of these processes according to many characteristics emerging.

In particular, according to MPP process's temperature level according to grain recrystallization process, there is deformation division accepted into cold and hot (complete and incomplete). According to purpose – into those that allow obtaining different profiles of constant cross-section along the length (rolling, pressing, drawing, extrusion) and those that allow obtaining parts or blanks with shape and dimensions close to finished parts (transverse and transverse-screw rolling, forging, stamping), etc. [1, 2]. Nevertheless, absolutely all technologies for manufacturing any metal products by MPP fulfill two conditions:

- primary billet in cast state using;
- plastic deformation in MPP solving problems approaches versatility.

For any metal or alloy plastic deformation implementing complexity degree depends, firstly, on its possibility to be deformed in cold state (at normal temperature), secondly, on cast billet quality, its structure, MPP selected type, final product size and shape, etc.

In modern theoretical and applied materials science deformable body's plasticity and strength issues are considered and solved from the points of view:

- dislocations theory [3, 4],
- pressure processing influence on metals and alloys structure and properties experimental data analysis results [5, 6],
- crystal lattice microscopic defects behavior under developed and limited plastic deformation [7, 8] conditions modeling results, using phenomenological and other approaches to solving problems of deformation theory, etc.

All this today allows finding rational solutions to significant number of applied problems occurring in body's deformation center due to modeling by experimental, mathematical or computer processes [9, 10]: on preventing defects in workpieces during their MPP [11, 12], on issues of material stresses and displacements [13], on MPP technologies parameters specifying and optimizing for metals and their alloys [14, 15], etc.

Nevertheless, despite significant achievements in the field of fundamental and applied research into plastic deformation problems, there is currently no unambiguous answer to the purely practical question:

- is particular metal (alloy) suitable or to what extent is it suitable for MPP or for cast manufacturing products from it?

Answer to this challenge will allow alloys' developers significantly save time and costs on future alloy elaboration, and foundries and MPP shops employees will save time and costs on its implementation into production. On authors' opinion, the answer to this question at the first stage of any alloy development should be sought in the area of the initial comprehensive criteria-based assessment of casting material properties, its characteristics in cast state and final product mechanical performance, which is currently absent. Therefore, work aimed at parametric criteria developing for preliminary assessment of possibility alloys for processing by deformation or casting is relevant.

Problem establishing. According to expert evaluation results, when deciding on any metal or alloy workpiece deformation processing possibility, specialists have been primarily concentrated on requirements for final product quality and cost and process productivity. That is, for example, in the case of workpiece processing by rolling, data on final product thickness, rolled product geometric dimensions accuracy, surface quality; requirements for workpiece material corrosion resistance and its mechanical properties, process cost and productivity have been taken into account. Based on this, preliminary decision regarding workpiece by rolling processing possibility and feasibility has been made, its type (cold or hot rolling), workpiece for MPP preliminary and intermediate preparation type, its reduction degree, etc.

To predict any alloy for MPP suitability, maximum possible body deformation indicators (cast workpiece with certain sizes and shapes) under pressure influence has also been taken into account – deformation amount (linear, angular, surface, volumetric). That is, the indicator of alloy for deformation processing suitability, at this stage of evaluation, is plastic deformation maximum value at which deformed body still retains its external integrity (there are no cracks on the body surface that can be detected with naked eye). To do this, as a rule, in MPP workshops, to assign safe deformation degrees, metal (alloy) plasticity values at different temperatures, reduction values and its deformation rates have been experimentally determined in one or another way. However, for technological process developing, such data on plasticity are not always sufficient, since any material plasticity depends on many factors, including: body stressed state scheme (deformation method), chemical and, as a result, material phases composition (phases genesis and quantity in structure), cast workpiece grain size, deforming body material crystal lattice type, temperature and deformation rate, workpiece single (per pass) reduction value, body's material resistance to plastic deformation, etc. Thus, since plasticity value depends on number of mentioned above load parameters, it is currently not possible to determine a single accurate plasticity indicator for specific metal (alloy) and its MPP all types.

In this regard, according to expert assessment, at enterprises for technological process developing, any metal or alloy plasticity has been determined using indicators called the unit plasticity index. Among such indicators:

- relative deformation during cast metal (alloy) sample reducing before the first crack appears on its surface during pressure treatment under all-round friction conditions;
- workpiece's cast metal (alloy) impact toughness value at normal temperature;
- cast metal (alloy) sample relative elongation or cross-sectional area relative reduction when stretched at normal temperature with deformation rates not exceeding 10 mm/s;
- metal (alloy) hardness at normal (room) temperature in cast state, etc.

Additionally, following factors have been taken into account:

- non-brittle pure metals and alloys with single-phase structure are more suitable for MPP, in contrast to multiphase alloys, in which structure there are chemical compounds that are poorly soluble at elevated temperatures or completely insoluble substances, for example, graphite, exogenous non-metallic impurities, etc.;
- it is desirable that metals and alloys relative elongation at normal temperature be at least 20 %, and yield strength to ultimate tensile strength ratio ($\sigma_{0.2}/\sigma_B$) be at least 0.95;
- at MPP materials' deformation rate and value can be the greater, the higher its temperature and cast workpiece grain size finer. At the same time, material deformation rate and value cannot be infinitely large, since in deformation rate increasing also leads to stress (yield limit) growing and in material being deformed plasticity dropping down, which, for example, is inherent for deformation process of workpieces made of high-alloyed steel and some copper alloys;
- the higher alloy's processability, the more effective temperature interval for its pressure treatment;
- for MPP it is desirable to have workpieces with fine-grained equiaxle structure. If workpiece's grains are excessively large, they must be grinded, for example, by workpiece recrystallization tempering after its preliminary deformation;
- to reduce cast billet's strength and increase its plasticity, ingot's in mold crystallization and cooling rate should be optimized.

From above analysis, it follows that, in essence, any metal or its alloy workpiece's MPP possibility, conditions, degree and type has been determined, for the most part, by plasticity level and structural state of its cast billet. Based on this, it is advisable to establish correspondence between metals (alloys) casting properties and their pressure processing possibility and feasibility.

Purpose. Based on existing criteria for predicting the suitability of metals and their alloys for manufacturing products from them by deformation or casting analysis develop a set of dimensionless parametric criteria and their quantitative scales. Their using will allow increasing the predicting accuracy of metals and alloys for their processing by pressure or casting suitability and feasibility.

Methodology. In this work for interpreting studied objects, systematic analysis under uncertainty results phenomenological approach has been used. It has been performed by borrowing reference literature data from other authors and own research results, obtained using standard methods for determining mechanical properties at normal temperature and original method for cast samples manufacturing to determine their absolutely hindered linear shrinkage value.

Non-ferrous metallic alloys melting have been carried out in graphite crucible in induction furnace using charcoal as protective melt coating. Bronze melts deoxidation has been carried out with phosphorous copper before they were released from crucible. Cast iron and steel melting has been carried out in induction furnace in crucible with quartz and magnesite lining, respectively.

Studied alloys mechanical properties have been calculated based on results of samples testing with working part dimensions of ∅8 × 40 mm during their static uniaxial tension on universal machine FP-100/1 at temperature of 20 ± 1 °C. Samples have been manufactured by mechanical processing from club-shaped samples, which melts have been poured into mold made of sand-sodium-silicate mixture. Elongation at rupture (δ_5) has been calculated based on results of samples' working part lengths measuring with caliper of 0.01 mm accuracy before and after their testing.

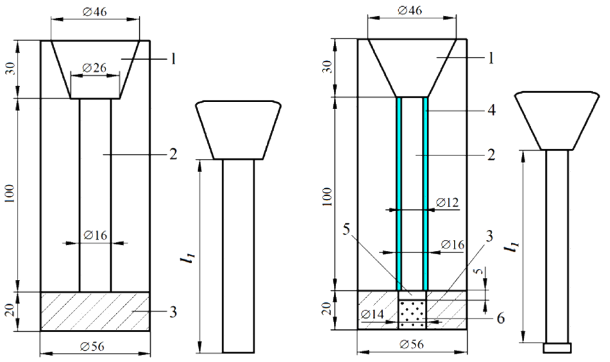
Cast cylindrical samples' free and absolutely hindered linear shrinkage determination has been carried out based on cast non-thermally treated samples lengths measurements results. Unlike method [16], measured samples have been manufactured in casting molds with improved design, which allowed increasing metals and alloys linear shrinkage values accuracy determination. That is, in order to increase accuracy of absolutely hindered linear shrinkage coefficient determining, steel chill and sand-sodium-silicate casting molds have been used in this work, which schemes are presented in Figs. 1 and 2.

Principal difference between adopted original method and technique in work [16] is constructive change in sample force resistance to linear shrinkage scheme due to quartz tube using, which thermal linear expansion coefficient is in two orders smaller than similar coefficient for steel chill-mold material.

Cast samples control length has been measured 24 hours after they have been poured into casting molds at temperature of 19 ± 1 °C.

Results. According to expert evaluation by specialist's results, in MPP processes, regardless of deformation method, it has been established that, if metal or alloy:

- has multiphase structure;
- characterized by small (up to ~20 %) relative elongation at normal temperature;
- has significant quantity of undesired impurities or nonmetallic particles;
- has narrow range of reliable deformation temperatures;



a *b* *c* *d*

Fig. 1. Schemes of chill molds (a, c) and length measurements of samples that solidified and cooled under free (b) and absolutely hindered linear shrinkage (d) conditions:

1 – pouring basin riser; 2 – mold working cavity; 3 – steel washer; 4 – quartz tube; 5 – sample's shrinkage-inhibiting element; 6 – solidified sand-sodium-silicate mixture

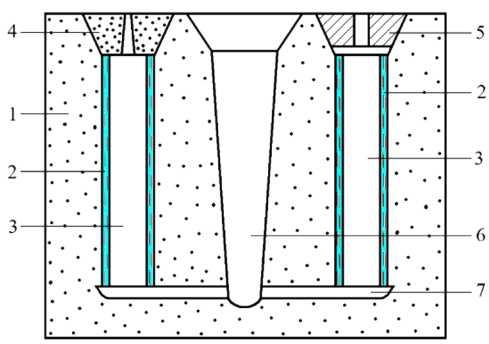


Fig. 2. Scheme of casting mold for cast iron samples making that solidified and cooled under free and absolutely hindered linear shrinkage conditions:

1 – sand-sodium-silicate casting mold; 2 – quartz tube; 3 – mold working cavity; 4 – sand-sodium-silicate cork; 5 – steel cork; 6 – sprue; 7 – runner

- contains in its structure phase or phases that retain their stability when alloy is heated up to its solidus temperature (for example, graphite in cast iron), then, to deform workpiece made of such metal (alloy), it is necessary:
- increase workpiece pressure treatment temperature;
- lower one-pass deformation value (reduction, passage);
- restrict total deformation amount;
- decrease deformation rate;
- perform tempering before and/or between deformation cycles, or preliminary normalization or workpiece quenching (depending on material's phase equilibrium diagram type);
- establish product's size and shape limitation;
- use on MPP realization special conditions.

That is, with undesirable factors number in metal (alloy) characteristics increasing, additional technological operations number in MPP process increases [17, 18], its productivity decreases, final products limitation in assortment occurs [19, 20] and, accordingly, its cost and quality instability grow [21, 22].

In some cases, MPP using becomes impractical because result achieved is not proportional to MPP expenses. For example, two-component bronzes with tin content up to 5 % (by weight) can be cold forged, but with less reducing than for pure copper. With tin content of 5 to 15 %, bronze can only be forged at temperature 550–600 °C. With tin content of 15 to 24 %, bronze almost completely loses its plasticity and its MMP must be carried out in special mode (with small reducing) in hot state. With tin content of 24–25 %, bronze becomes multiphase and, consequently, extremely brittle. After all, it is possible to forge only small and simple-shaped products from it at elevated temperatures with extremely low reducing. Similar nature in conducting MPP conditions changing observed in other bronzes.

In particular, aluminum bronzes with aluminum content 6–8 % are so ductile that they can be pressure-treated in both cold and hot states, while bronzes with aluminum content 8–10 % are deformable only at high temperatures.

As a result of this regularity, all bronzes, like other alloys, are divided into deformed and foundry alloys according to current national and European standards.

This, in particular, is discussed in works of Greshta V. L. (2014), Merkulov G. A. (2008), Arzamasov B. N. (2008), in publications [23, 24], etc., and is given in Table 1.

At the same time, depending on factors number, including final product quality, cost-effectiveness, demand and industrial productivity, bronzes are suitable for deformation by not all MPP types and not for all products types, as evidenced, for example, data of V. L. Greshta (2014) work and our own expert assessments, which are given in Table 2.

Data values in Tables 1 and 2 comparative analysis results: yield strength to ultimate tensile strength ratio; cast bronzes samples, during their stretching, elongation at rupture or reduction of area; impact strength and hardness at normal temperature, indicates the weak correlation between them. Therefore, using impact toughness, hardness, elongation or reduction of area, or yield strength to strength limit ratio (brittleness index) for any metal (alloy) as the only suitability indicator of this metal (alloy) for MPP is not appropriate. That is, for metal (alloy) MPP suitability assessing, in addition to economic and commercial component, criteria are needed, which using would increase predicting accuracy of any metal or alloy for above processing types suitability.

In order to increase suitability (technological suitability) accuracy assessing of any metal or alloy for MPP, dimensionless parametric criterion "*A*" has been adopted. For this criterion metal or alloy with absolutely hindered linear shrinkage during casting solidification has been determined using original methodology elaborated in this work

$$A = \frac{\alpha_{ah}}{\alpha_f},$$

where α_{ah}, α_f – correspondently, cast metal (alloy) absolutely hindered and free linear shrinkage, %.

Table 1

Grades of some deformed and foundry bronzes

TIN					
БрО5*	БрОФ4-0.25	БрОЦ4-3	БрОС8-12*	БрОЦС4-4-2,5	БрО3А3*
БрО10*	БрОФ6.5-0.15	БрОЦ8-4*	БрОС5-25*	БрОЦС4-4-17*	БрО3К5*
БрО19*	БрОФ7-0.2	БрОЦ10-2*	БрОС10-10*	БрОЦС5-5-5*	–
–	БрОФ10-1*	–	БрОС6-15*	БрОЦС6-6-3*	–
ALUMINUM					
БрА5	БрАМц9-2	БрАЖ9-4	БрАЖМц10-3-1.5	БрАЖН10-4-4	
БрА7	БрАМц10-2*	–	БрАЖНМц10-4-4-1	БрАЖН11-6-6*	
SILICON		BERYLIUM	CHROMIUM	MAGNESIUM	
БрКМц3-1		БрБ2	БрХ0.8	БрМг0.3	
БрКН1-3		БрБ2.5	БрХ1	БрМг0.5	
БрКН0,5-2		БрБНТ-1.9	БрХ1Цр	БрМг0.8	
CADMIUM		ZIRCONIUM	MANGANESE	LEAD	
БрКд1		БрЦр0.2	БрМц5	БрС30*	
БрКдХ0.5-0.15		–	–	–	

Note: Bronze grades used exclusively or predominantly as foundry alloys are marked with an "asterisk" in the table

According to industrial experience results generalizing for castings in foundries and MPP workshops, it has been established that according to criterion *A* metals (alloys) with $1.0 \geq A \geq 0.7$ are more suitable for MPP, but are not very suitable for manufacturing products by casting methods.

The reason for this limitation is these metals (alloys) tendency in cast state to form hot cracks, gouging and their dimensional accuracy instability. That is, it is advisable to produce small castings with simple shape from such metals (alloys).

Table 2

Recommended MPP types for copper and bronzes semi-finished products

Bronzes grades	Semi-finished products									Number of MPP types
	sheets	strips	slabs	tapes	bars	profiles	tubes	wire	forgings	
Cu	+	+	+	+	+	+	+	+	+	8
БрА5	+	+	+	+	+		+	+	–	7
БрХ0.4Ко0.4Кр0.2Мг0.04	+	+	+	+	–	+	–	–	–	5
БрАМц9-2	–	+	–	+	+	–	–	+	+	5
БрБ2	–	+	–	+	+	–	+	+	–	5
БрБНТ1,9	–	+	–	+	+	–	+	+	–	5
БрОЦ4-3	–	+	–	+	+	–	–	+	–	4
БрКМц 3-1	+	+	–	–	+	–	–	+	–	4
БрАЖМц10-3-1.5	–	–	–	–	+	–	+	+	+	4
БрН2.5Х0.7К0.6	–	+	–	+	+	–	–	+	–	4
БрАЖ9-4	–	+	–	–	+	–	+	–	+	4
БрА7	+	+	–	+	+	–	–	–	–	4
БрАЖН10-4-4	–	–	–	–	+	–	+	–	+	3
БрКН1-3	–	–	–	–	+	–	–	–	+	2
БрАЖНМц9-4-4-1	–	–	–	–	+	–	–	–	+	2
БрТ5Х0.5	–	+	–	+	–	–	–	–	–	2
БрСр0.1	–	–	–	–	–	–	+	+	–	2
БрНЦР	–	–	–	–	+	–	–	+	–	2
БрОЦС4-4-4	–	+	–	+	–	–	–	–	–	2
БрАМц10-2	–	–	–	–	–	–	–	–	+	1
БрМц5	–	–	–	–	–	–	–	–	+	1
БрКд1	–	–	–	–	–	+	–	–	–	1
БрМг0.3	–	–	–	–	–	+	–	–	–	1
БрН10.5А0.5	–	–	–	–	–	–	–	+	–	1
БрОФ2-0.25	–	–	–	+	–	–	–	–	–	1

Table 3

Criterion “*A*” values for castings made of copper, bronze, steel 45Л and gray cast iron СЧ350 with absolutely hindered and free linear shrinkage

Alloy	α_{Ay}, %	α_B, %	*A*	Alloy, metal	α_{Ay}, %	α_B, %	*A*
БрА7	0.88	1.17	0.75	БрА9Ж3Л	1.15	2.44	0.47
БрА5	0.80	1.10	0.72	БрА10Ж3Мц1.5	1.12	2.44	0.46
БрА6К1	0.74	1.05	0.70	БрА11Ж6Н6	0.79	1.82	0.43
БрМц5	1.07	1.58	0.68	БрО5Ц5С5	0.56	1.51	0.37
БрА6Мц1	0.87	1.29	0.67	БрО3А3	0.44	1.34	0.33
БрА3К1Мц1	1.03	1.57	0.66	БрО6А3	0.33	1.16	0.28
БрА9	0.69	1.37	0.50	Cu	0.48	2.31	0.21
БрА10Ж4Н4	0.87	1.82	0.48	Steel 45Л	1.04	2.20	0.47
БрА9Мц2Л	0.94	2.01	0.47	Cast Iron СЧ350	0.42	1.07	0.39

If $0.7 > A > 0.5$, then such metal (alloy) is suitable for MPP, but with certain its processing conditions in technological process, with restrictions on future product size and shape, etc. It is quite suitable for castings manufacturing with certain restrictions on castings design and size.

Alloys with $A \leq 0.5$ are unlimitedly suitable for castings manufacturing by any casting method, but require certain conditions for products manufacturing using MPP types. As an example, Table 3 shows criterion *A* values for some bronzes grades.

Table 3 data analysis shows that double bronzes БрА7 and БрА5 having $A > 0.7$ are known to be mainly used for products using MPP manufacturing methods. For castings these bronzes are used limitedly, in particular, for small size marine propellers or for large size marine propellers’ individual elements. At the same time, bronzes БрА9Мц2Л, БрА9Ж3Л, БрА11Ж6Н6, БрО5Ц5С, cast iron and other alloys with $A \leq 0.5$ are mainly used for any mass, size and shape castings manufacturing, by any type of casting. Pure metals (Cu, Al, Pb, etc.) with $A \leq 0.5$, as is known, are used both for castings manufacturing and for products by MPP manufacturing.

Based on this, according to criterion *A* value, metals and alloys have been classified into the following subgroups:

- subgroup *A*1 – metals and alloys with values $1.0 \geq A \geq 0.7$;
- subgroup *A*2 – metals and alloys with values $0.7 > A > 0.5$;
- subgroup *A*3 – metals and alloys with values $A \leq 0.5$.

It should be noted that for some pure metals and alloys with value $A > 0.5$, it is not always possible to determine absolutely hindered shrinkage value using the method adopted in this work, due to hot cracks on samples occurrence. Therefore, for qualitative assessment of any metal or alloy with BCC and FCC crystal lattice, without insoluble in α-phase at any temperature another phase (phases), suitability (technological suitability) and possibility of its deformation processing by MPP, dimensionless parametric criterion *B* has been adopted

$$B = \frac{\delta_5}{100} \cdot \frac{\sigma_B}{\sigma_{0.2}},$$

where δ_5 – elongation at rupture, %; σ_B, $\sigma_{0.2}$ – correspondently, strength limit and yield stress of metal (alloy) cast samples at testing temperature 20 ± 1 °C, MPa; 100 – balance constant, %.

Adopted for calculation mechanical properties parameters values and criterion B calculating results values according to own data and data [25] for some metals and alloys in cast state, as well as conditional subgroups of their manufacturability according to criterion *B*, are given in Table 4.

From Table 4 data analysis, it follows that all the studied metals and alloys can be divided into the following 7 manufacturability subgroups (subgroups of their deformation and/or casting complexity) according to criterion *B* value:

- subgroup *B*0 – metals and alloys with values $B \geq 1.8$;
- subgroup *B*1 – metals and alloys with values $1.8 > B \geq 0.9$;
- subgroup *B*2 – metals and alloys with values $0.9 > B \geq 0.5$;
- subgroup *B*3 – metals and alloys with values $0.5 > B \geq 0.2$;
- subgroup *B*4 – metals and alloys with values $0.2 > B \geq 0.1$;
- subgroup *B*5 – metals and alloys with values $0.1 > B > 0$;
- subgroup *B*6 – metals and alloys with value $B = 0$.

Subgroup *B*0 includes metals and alloys, products from which are manufacturing mainly in cold state from their blanks by any MPP types with relatively large single deformation degree and at high speed.

Subgroup *B*1 contains metals and alloys, products from which are manufacturing both in cold and hot state from their blanks by any MPP types with relatively large single deformation degree and at high speed.

In subgroup *B*2 – metals and alloys, products from which are mainly manufacturing from their billets in hot state by limited number of MPP types with single deformation and its speed lower degree than in subgroup *B1*.

In subgroup *B*3 – metals and alloys, products from which are manufacturing exclusively from their billets in hot state with more limited number of MPP types than for subgroup *B*2, with single deformation and its speed lower degree.

In subgroup *B*4 – metals and alloys, products from which are manufacturing exclusively from their billets in hot state with more limited MPP types number than for subgroup *B*3, with relatively small single deformation and its speed degree.

In subgroup *B*5 – relatively brittle metals and alloys, products from which are manufacturing exclusively from their billets in hot state, with significantly limited MPP types number than for subgroup *B*3, with small single deformation and its speed degree.

Subgroup *B*6 includes extremely brittle metals and multiphase alloys, which MPP can be performed in one or two types, exclusively in workpiece hot state under certain conditions, at extremely low speed and single deformation degree with limited dimensions and simple product shape, or this materials group cannot be performed under any MPP conditions.

Non-heat-treated metals and alloys (Table 4) division into conditional subgroups according to their criterion *B* (suitability for MPP) value is presented in Fig. 3.

From discussed above it follows that any metal or alloy is more suitable for MPP and less suitable for casting on the greater criterion *B* (from subgroup *B*0 to *B*6) and *A* (from subgroup *A*1 to *A*3) values and vice versa.

To increase preliminary forecast objectivity for any metal or alloy based on experimental studies results, it is advisable to establish both criterion *A* and criterion *B* values. That is, for example, according to experimental data, investigated alloy belongs to groups *A*1 + *B*1. It means that this alloy is quite suitable for any MPP type in cold and hot state, but is not suitable enough for making medium and large-sized heavy castings using traditional casting methods. This means that it is advisable to make castings from such alloy only of small size, mass, sim-

Table 4

Values “*B*” calculation results for some metals and alloys [25]

Metal, alloy	σ_B, MPa	$\sigma_{0.2}$, MPa	δ, %	*B*	Subgroup	Metal, alloy	σ_B, MPa	$\sigma_{0.2}$, MPa	δ, %	*B*	Subgroup
Pure metals						БрО5Ц5С5Л*	151	72	7	0.15	*B*4
Au	120	10	50	6.00	*B*0	В4	680	320	5	0.11	B4
Ag	140	20	50	3.50	*B*0	В4	220	175	8	0.10	B4
Pb	11	2.7	69	2.81	*B*0	В4	74.5	39	5	0.10	B4
Al	50	5	25	2.50	*B*0	БрО8С12	160	100	5	0.08	*B*5
Pd	180	50	35	1.26	*B*1	БрО10	215	175	6	0.07	*B*5
Pt	141	60	50	1.18	*B*1	БрО5С25	125	90	5	0.07	*B*5
Cu	160	35	25	1.14	*B*1	БрО10Ф1	195	135	3	0.04	*B*5
Sn	19	12	60	0.95	*B*1	Brass					
Rh	400	69	15	0.87	*B*2	ЛО64-2	310	78	55	2.19	*B*0
Fe	245	137	45	0.80	*B*2	ЛМш68-0.05	310	98	50	1.58	*B*1
Nb	334	248	48	0.65	*B*2	Л96	216	62	45	1.57	*B*1
Cr	380	353	44	0.47	*B*3	Л68	290	98	50	1.48	*B*1
Ti	300	250	30	0.36	*B*3	ЛК80-3	275	105	53	1.39	*B*1
Mg	117	25	7	0.33	*B*3	Л70	290	130	60	1.34	*B*1
Ir	491	89	6	0.33	*B*3	Л80	290	120	55	1.33	*B*1
Ru	490	373	10	0.13	*B*4	Л85	235	98	55	1.32	*B*1
Zn	150	20	0.5	0.04	*B*5	Л63	350	108	40	1.30	*B*1
Cast Iron						ЛАМш77-2-0.04	320	120	45	1.20	B1
ВЧ 350-22	350	230	22	0.33	*B*3	Л90	235	125	52	0.98	*B*1
ВЧ 400-15	400	260	15	0.23	*B*3	Л60	360	147	40	0.98	*B*1
ВЧ 450-10	450	320	10	0.14	*B*4	ЛОМш70-1-0.05	310	160	50	0.97	*B*1
ВЧ 500-7	500	340	7	0.10	*B*5	ЛО60-1	353	176	40	0.80	*B*2
ВЧ 700-2	700	420	2	0.03	*B*5	ЛС59-1	290	140	36	0.75	*B*2
ВЧ 1000-2	1,000	700	2	0.03	*B*5	ЛЦ4Мц3Ж	390	165	18	0.43	*B*2
СЧ200*	210	172	0.7	0.01	*B*5	ЛЦ35НЖА	345	175	20	0.39	*B*3
СЧ350*	367	265	0.4	0.01	*B*5	ЛЦ16К4	245	115	15	0.32	*B*3
Hypoeutectic white cast iron*	310	302	0.1	0.00	*B*6	ЛЦ40АЖ	335	245	20	0.27	*B*3
Bronze						ЛЦ30А3	275	150	12	0.22	B3
БрА3К2*	315	61	53	2.74	*B*0	ЛЦ38Мц2С2	295	215	10	0.14	*B*4
БрА5К0.6Мц0.6*	309	63	55	2.70	*B*0	ЛЦ14К3С3	270	135	7	0.14	*B*4
БрА3К1Мц1*	276	70	61	2.40	*B*0	ЛЦ23А6Ж3Мц	540	295	7	0.13	*B*4
БрА5	275	68	55	2.22	*B*0	Aluminum Alloys					
БрА6К1*	342	88	52	2.02	*B*0	АМг5	300	130	23	0.53	*B*2
БрА9К1*	470	120	47	1.84	*B*0	АМг3	230	120	25	0.48	*B*3
БрА3Мц2*	249	88	48	1.36	*B*1	АМг2	190	120	25	0.40	*B*3
БрСр0.1	200	80	50	1.25	*B*1	АМц (1400)	110	60	18	0.33	*B*3
БрА9*	448	157	35	1.00	*B*1	АЛ2	170	80	6	0.13	*B*4
БрКМц3-1	340	100	25	0.85	*B*2	АЛ24	240	150	4	0.06	*B*5
БрОЦС4-4-4	315	130	30	0.73	*B*2	***Steel***					
БрО3А3*	330	150	29	0.64	*B*2	Ст3-сп	350	190	37	0.68	*B*2
БрАЖМц10-3-1.5	490	155	20	0.63	*B*2	110Г13Л*	794	498	20	0.32	*B*3
БрА10Ж3Мц2Л	490	157	20	0.62	*B*2	35Л*	608	310	14.5	0.28	*B*3
БрОФ6.5-0.15*	295	140	28	0.59	*B*2	35ХНМЛ	900	775	2	0.02	*B*5
БрОЦ4-3	245	65	15	0.57	*B*2	Magnesium Alloys					
БрА7	295	245	45	0.54	*B*2	Мл2	100	35	4	0.11	*B*4
БрМц5	245	145	30	0.51	*B*2	Мл3	180	55	5.5	0.18	*B*4
БрА9Мц2Л*	440	196	20	0.45	*B*3	Zinc Alloys					
БрА9Ж4Н4Мц1*	595	247	13	0.31	*B*3	ЦАМ 10-5	328	301	1	0.01	*B*5
БрАЖ9-4	345	195	15	0.27	*B*3	ЦАМ 9-1.5	300	255	5.2	0.06	*B*5
БрАЖН 10-4-4	750	295	10	0.25	*B*3	Titanium Alloys					
БрО8Н4Ц2	265	175	14	0.21	*B*3	ВТ1-0	440	310	32	0.45	*B*3
БрОЦС4-4-2.5	185	100	11	0.20	*B*3	ВТ-5Л*	870	690	10	0.13	*B*4
БрО8Ц4	195	115	11	0.19	*B*4	*Notes* * – own data					

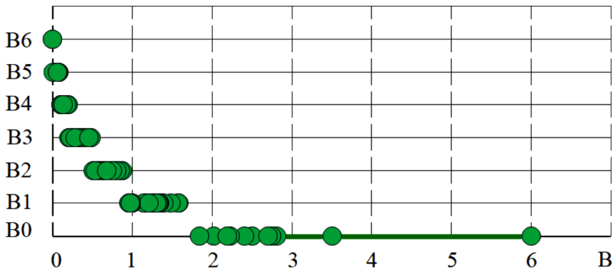


Fig. 3. Cast non-heat-treated metals and alloys (Table 4) division into conditional subgroups according to their criterion B value (suitability for MPP)

ple configuration and under certain conditions. If, for example, alloy has been included in groups *A*3 + *B*4, this means that such alloy is suitable for castings of any size, weight, and shape manufacturing and not limited by casting types number, but has certain conditions and limitations for its processing by MPP processes.

Naturally, this classification (metals and alloys for their casting and/or MPP manufacturability division into groups) has conventional character. Nevertheless, in first approximation, this approach provides certain orientation for enterprise technologists and alloy developers on possible technological problems that will need to be solved during such materials development and implementation into production.

Conclusions.

1. Parametric dimensionless criteria (*A* and *B*) divided into groups have been developed, which, due to such groups combinations, allow, in first approximation, to assess suitability of any alloy or metal for foundry and/or MPP using.

2. Impact strength, hardness, elongation at rupture or area reduction values, as well as yield strength to strength limit ratio of any cast metal (alloy) as cast metal (alloy) or metal (alloy) for MPP suitability only indicators cannot be recommended.

3. Elaborated parametric criteria and their division into groups are recommended for use to pure metals, cast irons, steels and bronzes with low lead content analysis.

4. Further investigations development, devoted to proposed criteria of preliminary assessment, should be expanded to other alloys, including alloys based on Ni, Al, Ti, etc.

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Критерії оцінювання придатності металів і сплавів до лиття та деформування

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Мета. На основі аналізу існуючих критеріїв прогнозування придатності металів і їх сплавів для виготовлення з них виробів деформуванням або литтям розробити комплекс безрозмірних параметричних критеріїв і їх кількісні шкали, використання яких дозволить підвищити точність прогнозування придатності й доцільності металів і сплавів до їх обробки тиском або литвом.

Методика. У роботі використано феноменологічний підхід до інтерпретації результатів системного аналізу механічних та окремих ливарних властивостей металів і сплавів в умовах невизначеності із запозиченням літературних довідкових даних, даних експертних оцінок і результатів власних досліджень. Власні дані отримані експериментально за стандартними методиками визначення механічних властивостей сплавів та оригінальною авторською методикою визначення величини їх абсолютно утрудненої лінійної усадки при литті.

Результати. Авторами вперше запропоновані параметричні безрозмірні критерії та шкали до них (критеріальні групи), застосування яких дозволяє за рахунок комбінацій таких груп провести оцінку придатності будь-якого сплаву чи металу до можливості його використання для виготовлення виробів способами лиття та/або обробки тиском.

Наукова новизна. Уперше розроблені й запропоновані до використання на початкових етапах розробки нових сплавів або технологій виготовлення з них виробів безрозмірні параметричні критерії та їх кількісні шкали для попередньої оцінки (прогнозу) доцільності обробки сплавів тиском або литтям безвідносно від їхнього виду та способу.

Практична значимість. Використання розроблених критеріїв та їх кількісних шкал дозволить розробникам сплавів і працівникам профільних підприємств заощадити час і витрати як на розробку сплаву, так і на його впровадження у виробництво.

Ключові слова: *деформація, видовження, заготовка, пластичність, усадка, лиття, структура, термічна обробка*

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