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# Modern methods for investigating hot cracking susceptibility in metallic materials

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**Abstract.** The development of modern science and technology has shown that ensuring high product quality depends not only on the operational characteristics of materials, but also on their technological properties. In the production of aluminum alloys, ingots are most commonly used as the initial material for wrought alloys, while shaped castings are used for casting alloys. One of the most widespread defects occurring during the production of castings and ingots is hot cracking, which is the tendency of a material to form crystallization cracks during solidification. The problem of hot cracking is particularly relevant in the development and production of new high-strength and heat-resistant aluminum alloys, since the ranges of their chemical compositions often coincide with regions of increased hot cracking susceptibility. A pronounced tendency of alloys to hot cracking during casting and fusion welding significantly complicates, and in many cases makes practically impossible, their introduction into mass production despite their valuable service properties. As a rule, reducing hot cracking susceptibility in the development of new alloys is achieved through lengthy and labor-intensive experimental studies. This paper considers a method for evaluating the hot cracking susceptibility of aluminum alloys using the pencil test. The physical nature of the hot cracking phenomenon is described, the principle of the method is presented, and the testing procedure and analysis of the results are outlined. In addition, a schematic representation of the hot cracking test according to the pencil test method and a list of references are provided.

***Keywords:*** *aluminium alloy, eutectic, hot-cracking indices, alloying, casting, hot cracks, effective solidification interval.*

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## 1. Introduction

Aluminum alloys are rightfully regarded as among the most significant materials in modern engineering. This is обусловed by the possibility of achieving a unique combination of key service properties, including strength, ductility, corrosion resistance, and others. The development of economically alloyed compositions requires precise control of alloying element concentrations. Improper dosing or the inability to regulate the composition of secondary aluminum significantly complicates the production of secondary economically alloyed aluminum alloys.

Depending on the alloy system, alloying elements are classified as principal elements, minor additions, and impurities. In most cases, strengthening is achieved through solid-solution hardening and precipitation hardening. Furthermore, the content of alloying elements influences the casting properties of the alloy, which in turn determine its processability and suitability for industrial applications [1, 2].

An analysis of research findings on alloying elements indicates a broad spectrum of their influence on alloy characteristics, depending on processing conditions. Aluminum alloys in which magnesium is the principal alloying element belong to the class of non-heat-treatable alloys strengthened predominantly by solid-solution hardening. These alloys are characterized by low density, good machinability and weldability, and excellent corrosion resistance. The Mg content has a pronounced effect on the grain size in cast Al–Mg alloys. In direct chill (DC) casting, a fine-grained microstructure of the as-cast material is generally desirable. Grain refinement affects the mechanical properties of the solidified material, the kinetics of homogenization treatment, formability, defect formation during subsequent thermomechanical processing, and the quality of anodizing. During solidification, grain refinement directly influences porosity formation, susceptibility to hot cracking, the nature of macrosegregation, and the scale of microsegregation. At low temperatures, aluminum alloys with submicron grain sizes have been shown to exhibit higher elongation and yield strength compared to their coarse-grained counterparts [3, 4].

In recent years, improvements in strength and ductility of aluminum alloys have been achieved through the development of complex microstructures incorporating either reduced grain sizes (ultrafine-grained and nanocrystalline materials), grain size distributions (bimodal microstructures),

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strengthening particles, or combinations thereof. Optimization of such microstructures requires a fundamental understanding of the properties of conventional coarse-grained base alloys [5]. Furthermore, Mg retards dynamic recrystallization and suppresses the growth of recrystallized grains during annealing. Magnesium is recognized as the primary solid-solution strengthening element in Al–Mg alloys. Within a certain compositional range, both strength and ductility increase with increasing Mg content. The susceptibility of Al–Mg alloys to corrosion and stress corrosion cracking is associated with the precipitation of the Mg-rich β-phase ($Al_3Mg_2$), rather than with mere elemental magnesium enrichment at grain boundaries below the critical enrichment level [6, 7].

Alloying elements such as Zn, Mn, Cu, Cr, Si, and others added to aluminum alloys can effectively modify the microstructure, refine the grain structure, remove dissolved gases and harmful impurities, reduce crack initiation sites, and thereby enhance the overall performance of aluminum. The addition of chromium to 6061 aluminum alloy may lead to the formation of α-$Al_{12}(Fe,Cr)_3Si$ dispersoids during homogenization. However, continuously cast ingots do not undergo a homogenization stage and are rolled directly after casting. Therefore, it is of interest to determine the effect of chromium addition on the microstructure and mechanical properties of continuously cast 6061-T6 rod. Microstructural examination of a 0.5-inch diameter continuously cast and rolled 6061 w/Cr T6 rod revealed a fully recrystallized microstructure with pancake-shaped grains, indicating the presence of dispersoids in the aluminum alloy. Transmission electron microscopy (TEM) analysis confirmed the presence of α-$Al_{12}(Fe,Cr)_3Si$ dispersoids in the T6 rod microstructure. X-ray diffraction (Guinier method) showed that the 6061 w/Cr T6 rod contained α-$Al_{12}Fe_3Si$ and α-$Al_{12}(Fe,Cr)_3Si$ phases, whereas the chromium-free 6061-T6 rod contained only the β-$Al_9Fe_2Si_2$ phase. Tensile test results demonstrated that the addition of chromium to the 6061-T6 rod significantly improved its ductility [8].

The principal strengthening mechanisms in aluminum alloys are strain hardening, solid-solution strengthening, and precipitation hardening; in many cases, one of these mechanisms predominates. In most applications of Al–Mn (3XXX) and Al–Mg (5XXX) alloys, both strain hardening and solid-solution strengthening are significant, while minor additions of Cu can further increase strength through limited precipitation hardening. These alloy systems have been extensively used for decades in beverage can production. In addition, aluminum alloys are increasingly employed as automotive body sheet materials to reduce vehicle weight and thereby improve fuel efficiency and reduce emissions. For this application, 5XXX alloys with Cu additions are considered highly promising candidates due to their excellent formability, adequate strength, and the benefits of precipitation hardening during paint-bake treatment resulting from Cu additions. Alloys used in beverage can and automotive applications are typically subjected to hot and/or cold rolling to produce sheet products. During processing of Cu-containing alloys, precipitation of strengthening phases occurs both during hot and cold rolling and during post–cold-rolling heat treatment. In both cases, precipitation alters the yield strength and work-hardening behavior, thereby influencing subsequent processing steps. For beverage can applications, cold-rolled alloys are used in the strain-hardened condition. In contrast, for automotive body sheet applications, the alloys are supplied to manufacturers in the O temper (annealed condition) due to stringent requirements for superior formability during panel forming. For both applications, further thermal exposure occurs during coating/painting and subsequent baking. During these processes, both recovery and precipitation reactions take place [9].

Alloys of the composition Al–5.8Mg–0.4Mn–0.25Sc–0.1Zr (wt.%) were produced by conventional metallurgical processing using water-cooled copper molds under active flux protection. The recrystallization temperature and nucleation mechanism were investigated by hardness testing, optical microscopy, and transmission electron microscopy (TEM). The results indicate that the recrystallization resistance can be significantly improved by adding small amounts of Sc and Zr to the Al–Mg–Mn alloy. This is evidenced by a substantially higher recrystallization temperature (450 °C) compared to that of the Sc- and Zr-free Al–Mg–Mn alloy (150 °C). The pronounced increase in recrystallization temperature is primarily attributed to the strong pinning effect exerted by highly dispersed $Al_3(Sc,Zr)$ particles on dislocations and subgrain boundaries. The recrystallization process reveals a nucleation mechanism involving not only subgrain coalescence but also subgrain growth [10].

Fe is generally regarded as an impurity element in aluminum alloys because it promotes the formation of brittle intermetallic compounds during solidification, such as needle-like and platelet morphologies, which increase susceptibility to cracking during subsequent plastic deformation. This behavior is associated with the formation of the Fe-containing β-Al–Fe–Si intermetallic phase during solidification. This phase tends to form coarse plate-like particles whose sharp edges act as stress concentrators, thereby reducing ductility. In addition, pre-eutectic β-Al–Fe–Si platelets hinder effective feeding by blocking liquid metal flow, which promotes shrinkage porosity. The presence of solid intermetallic particles also decreases melt fluidity. The formation and growth of Fe-containing intermetallic phases strongly depend on solidification conditions, particularly the cooling rate and the presence of other alloying elements. A common approach to modifying the morphology of Fe-containing intermetallics is the addition of manganese to the melt, which transforms the platelet β-phase into the cubic α-Al–(Fe,Mn)–Si phase with a “Chinese script” morphology that is less detrimental to mechanical properties [11, 12].

Currently, approximately 75% of all aluminum ever produced remains in circulation. In Europe, more than half of total aluminum production originates from secondary sources (European Aluminium Association, 2018). According to IndexBox Marketing research data, up to 100% of new scrap (production waste, stampings, rejected parts, etc.), up to 90% of aluminum from the transport sector (end-of-life automotive components and body panels), up to 85% of scrap from the construction sector (structures, fittings, etc.), and up to 80% of scrap from the electrical industry (cables, conductors, equipment) are recycled. If aluminum scrap is not properly refined, exogenous factors such as dissolved gases, oxide inclusions, and impurity elements may lead to stress concentration and significantly deteriorate mechanical properties while simultaneously reducing service life. The presence of iron as a major impurity element in secondary aluminum alloys further aggravates these adverse effects on mechanical performance, casting characteristics, and corrosion resistance.

Alloy behavior during casting is governed by various physicochemical properties (liquidus and solidus temperatures, heat capacity, thermal conductivity, gas solubility, etc.), which in turn determine technological casting properties such as fluidity, volumetric and linear shrinkage, susceptibility to hot tearing, and macrosegregation.

To quantitatively evaluate casting properties, various technological tests have been developed. During casting, the solidification period is of primary importance, and most casting characteristics are closely associated with alloy behavior in this interval. The processes occurring during crystallization depend on the type of phase diagram and the alloy's position within it. Consequently, chemical composition has a decisive influence on casting performance [13].

Accordingly, the development of new alloys and the improvement of existing ones require a scientifically grounded approach that ensures not only high strength, heat resistance, and other service properties but also high resistance to hot cracking. Over recent decades, several criteria have been proposed to assess hot cracking susceptibility, including strength-based, ductility-based, and strain-rate-based criteria, as well as alternative criteria for semi-continuous ingot casting. All of these criteria are determined either experimentally or through combined experimental-analytical approaches. The selection (or development) of an appropriate criterion depends on the specific casting technology, available material parameters, and must be validated experimentally. However, none of the existing criteria enables prediction of hot cracking susceptibility of casting alloys directly from technological test data. Therefore, the search for a universal criterion capable of predicting hot tearing susceptibility based on alloy composition remains a highly relevant task. Such a criterion would provide an essential complement to mathematical modeling and thermodynamic calculations, which are increasingly used in the development of new alloys for comprehensive prediction of service properties.

The influence of composition and structure on hot cracking susceptibility is commonly evaluated using specialized technological tests. Many of these are ring-type tests. Another widely used method, often referred to as the "pencil test," employs a permanent metal mold (die) for casting rod-shaped specimens with enlarged heads. These dumbbell-shaped specimens have identical circular or square cross-sections and differ only in the length of the gauge section between the heads. The greater the length, the larger the restrained linear shrinkage, which promotes hot cracking under the constraint imposed by the rigid mold. The minimum (critical) specimen length at which a crack appears serves as a measure of the alloy's resistance to hot cracking. In another variant of the pencil test, specimens have identical lengths but different diameters; in this case, the smallest diameter at which a crack forms is used as the measure of hot tearing susceptibility. The geometry of the test creates non-uniform cooling and shrinkage conditions: the thinner section solidifies more rapidly, while the thicker section cools more slowly. As a result, tensile stresses arise in the transition zone, promoting hot crack formation when the alloy exhibits insufficient strength and ductility during solidification.

The effect of impurities on hot tearing susceptibility is manifested primarily through changes in ductility. Impurities may broaden or narrow the brittle temperature range and increase or decrease elongation within this interval. Control of impurity content, including specification of both upper and lower limits, can raise the solidus temperature, alter the quantity and distribution of low-melting constituents, and significantly reduce hot cracking susceptibility.

Grain refinement, particularly the transition from a columnar to an equiaxed structure, narrows the brittle temperature range, increases elongation within this range, lowers the temperature of onset of linear shrinkage, and reduces its magnitude within the solidification interval. These factors increase the ductility reserve in the solid–liquid state and reduce hot tearing susceptibility. Conversely, grain coarsening and the development of a columnar crystal zone, caused by excessive melt superheat and prolonged holding, generally increase hot cracking susceptibility. Grain modification by minor alloying additions can substantially reduce hot tearing tendency [14].

## 2. Materials and methods

The objects of investigation were alloys based on the nanocomposite Al–Zn–Mg system with varying Zn and Mg contents up to 6 wt.%, containing eutectic-forming additions such as nickel, iron, and manganese, provided that these elements participate in eutectic phase formation. Thermodynamic calculations were performed using the Thermo-Calc software package, which has demonstrated reliability in the analysis of phase composition in economically alloyed aluminum alloys. Software for phase diagram calculation and thermodynamic property evaluation has been developed since the 1970s. The Thermo-Calc package is produced by Thermo-Calc Software (TCS), founded in 1997 as a spin-off from the Department of Materials Science and Engineering at the Royal Institute of Technology (KTH, Stockholm, Sweden). The software is the result of many years of research conducted at KTH and through international collaborative R&D projects. Thermo-Calc Software is one of the most experienced providers of numerical simulation tools in the field of materials development and research.

Thermo-Calc is widely used worldwide and is among the most frequently applied tools for thermodynamic modeling. Its advantages include not only standard equilibrium calculations and evaluation of thermodynamic quantities based on assessed databases, but also advanced simulation capabilities. For example, the DICTRA module enables accurate diffusion modeling in multicomponent alloys. The program operates on a universal Gibbs energy global minimization algorithm, allowing calculations for multicomponent systems (up to 40 components) without predefined initial approximations. In addition to phase diagram construction, the software enables calculation of thermodynamic properties of phases (Gibbs energy, enthalpy, heat capacity, etc.), metastable equilibria, and related quantities. Thermo-Calc also allows the use of multiple thermodynamic databases employing different phase models within a given system [15, 16]. Hot tearing susceptibility (HTS) was evaluated using the pencil test.

In this test, molten aluminum alloy is poured into a permanent metal or sand mold of specified geometry. After complete solidification, the casting is removed and subjected to visual inspection. Particular attention is paid to the transition region between the thin and thick sections, where crack initiation is most likely. Assessment is based on the presence, length, and morphology of cracks. In some cases, a rating scale is applied to enable quantitative comparison of hot tearing susceptibility

among different alloys. The pencil test is characterized by procedural simplicity, clarity of results, and rapid comparative evaluation of various aluminum alloy compositions. The method does not require complex equipment and is widely used in both academic and industrial practice.

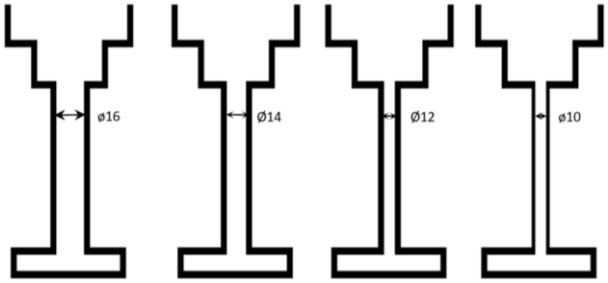



***Figure 1. Schematic representation of the pencil test for hot-cracking susceptibility***

The Al–Zn–Mg–Ni–Mn system is of considerable interest because it allows the incorporation of relatively inexpensive alloying elements such as nickel and manganese. A small amount of iron is also present in the system, contributing to the alloy's properties. The combined presence of Fe, Ni, and Mn promotes the formation of a significant fraction of ternary eutectic constituents, such as (Al)–$Al_6$(Fe,Mn)–$Al_3$Fe, which is expected to enhance the casting properties of the alloys.

## 3. Results and discussion

Alloys based on the Al-Zn-Mg system with varying Zn and Mg contents up to 6%, at a Zn/Mg ratio of 1:1, and with additions of nickel, iron, and manganese-under the condition that these additions enter eutectic-origin phases-were selected as the objects of investigation.

Prior to experiments on the influence of various elements on the structure of the matrix alloys, polythermal sections for alloys with different Zn and Mg contents located within the (Al + T) phase field were constructed using the Thermo-Calc software [16]. Figure 2 presents one of the polythermal sections for different contents of transition metals.

The constructed sections indicate that, with increasing Zn and Mg concentrations in aluminium, alloys containing more than 5% Zn should also contain more than 5% Mg in order to remain within the α-phase field Al-T($Al_2Mg_3Zn_3$), since it is in these alloys that the maximum strength level is achieved.

There is a direct relationship between an alloy's tendency to form cracks under constrained shrinkage and the magnitude of the effective solidification interval (the difference between the temperature at the onset of linear shrinkage and the solidus temperature). Within the same alloy system, as the effective solidification interval increases, the propensity for crack formation increases. At a constant shrinkage development rate, the density and ductility of the surface layer of the casting increase. However, in alloys with a small effective solidification interval (eutectic alloys and pure metals), the heat extracted by the mould promotes the formation of a thin but fully solidified shell. In contrast, in alloys with a large effective solidification interval, the formation of a solid structure proceeds in a dispersed manner within the solidifying, non-ductile and low-strength two-phase region. Therefore, under otherwise equal conditions, such alloys are more prone to hot cracking.

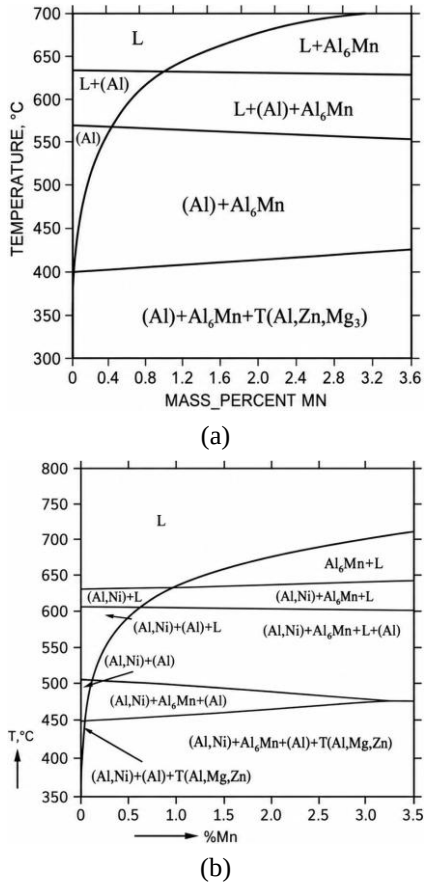



***Figure 2. Polythermal sections of the Al–Zn–Mg-based alloy system with transition-metal additions, calculated using Thermo-Calc software (version TCW-5, TTAL5 database): (a) Al–5Zn–5Mg–Mn; (b) Al–5Zn–5Mg–4Ni–Mn***

The effective solidification interval (ESI) was determined using the Thermo-Calc software package, where curves were generated by the Scheil calculation method for the Al-Zn-Mg-Ni-Mn system with different Zn and Mg contents (Figure 3).

To determine the hot-cracking index (HCI), i.e., the susceptibility of alloys to hot-crack formation during casting, experiments were conducted using the pencil test.

Hot cracking occurs within the temperature range between the liquidus and solidus, when the metal is in a semi-solid state. During this period, the material exhibits low strength and limited ductility. The main causes of hot-crack formation in aluminium alloys include:

– a wide solidification interval;

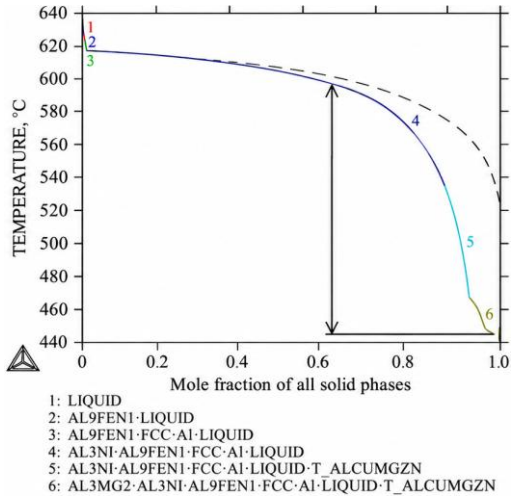
– the presence of alloying elements that form low-melting eutectics along grain boundaries;

– non-uniform shrinkage during solidification;

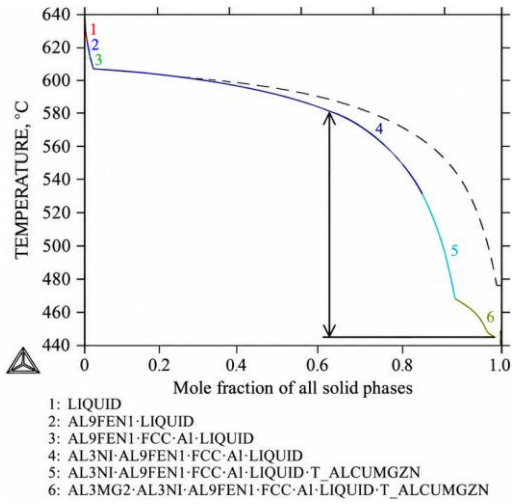
– the development of tensile thermal stresses.

In the pencil test, the thin section of the specimen solidifies more rapidly, whereas the massive section crystallizes more slowly. Tensile stresses develop in the transition zone between the sections; for alloys with high hot-cracking susceptibility, these stresses lead to crack formation.

During the experiments, the alloys were poured into a cold and a preheated mould. The temperature of the cold mould was 25°C, which is considered optimal, while the temperature of the heated mould was 150°C. Conducting experiments at different mould temperatures is motivated by the fact that casting into a cold mould produces higher stresses and a relatively high solidification rate, increasing the probability of cracking.




(a)




(b)

***Figure 3. Effective solidification intervals (ESIs) of Al–Zn–Mg-based alloys with transition-metal additions, calculated using Thermo-Calc software (version TCW-5, TTAL5 database): (a) Al–3.5Zn–3.5Mg–4Ni–1Mn; (b) Al–6Zn–6Mg–3Ni–1Mn***

This procedure makes it possible to determine whether the alloy is weldable. When casting into a heated mould, the conditions are less severe; moreover, most industrial high-strength aluminium alloys are poured into heated moulds in production practice, since otherwise it is impossible to obtain defect-free ingots. Figure 4 shows aluminium alloy specimens cast into hot and cold moulds; at a diameter of 12 mm, a fracture occurred at the base of the head.



***Figure 4. Aluminium alloy specimens tested for hot-cracking susceptibility using the pencil test***

The results of the pencil-test experiments, expressed as the hot-cracking index (HCI), are summarized in Table 1 for the investigated alloys cast into cold (25°C) and preheated (150°C) molds. For comparison, the table also includes the corresponding HCI values reported for the Al–4Zn–Mg and VAL-12 casting alloys [14]. These data provide a basis for evaluating the effects of alloy composition and mold temperature on hot-cracking susceptibility.

***Table 1. Hot-cracking indices (HCI) of the alloys***

| Alloy | HCI at 25°C, mm (cold mold) | HCI at 150°C, mm (preheated mold) |
|---|---|---|
| Al–4Zn–Mg alloy [14] | >16 | 16 |
| VAL-12 aluminum casting alloy [14] | >16 | >16 |
| Al–3.5Zn–3.5Mg–4Ni–1Mn | 14 | 12 |
| Al–6Zn–6Mg–3Ni–1Mn | 16 | 14 |

As shown in Table 1, the Al–3.5Zn–3.5Mg–4Ni–1Mn alloy exhibited the lowest HCI values under both casting conditions, reaching 14 mm in the cold mold and 12 mm in the preheated mold. For the Al–6Zn–6Mg–3Ni–1Mn alloy, the corresponding values were 16 and 14 mm. Increasing the mold temperature from 25 to 150 °C reduced the HCI by 2 mm for both investigated alloys, indicating a decrease in their susceptibility to hot cracking. Compared with the reference Al–4Zn–Mg and VAL-12 alloys, both experimental compositions exhibited lower HCI values under the investigated conditions. These results indicate that the proposed alloy compositions have more favorable hot-cracking characteristics than the reference alloys, with the Al–3.5Zn–3.5Mg–4Ni–1Mn alloy demonstrating the highest resistance among the compositions considered.

## 4. Conclusions

Determination of the hot-cracking susceptibility of aluminium alloys using the pencil test is an effective and accessible approach for assessing the tendency of alloys to form hot cracks. The method makes it possible to identify the influence of chemical composition and process parameters on solidification behaviour and casting quality. Despite its limited accuracy, the pencil test remains relevant as a simple and informative technique for studying hot-cracking susceptibility in aluminium alloys. The results of the pencil test enable a qualitative evaluation of the effects of chemical composition and casting conditions on the hot-cracking tendency of aluminium alloys. Alloys with a narrow solidification interval generally exhibit a lower propensity for crack formation.

As can be seen from the data presented in Table 1, all alloys containing a eutectic constituent show lower hot-cracking indices compared with standard eutectic-free alloys. Accordingly, alloying with eutectic-forming elements made it possible to noticeably improve the casting properties. It is shown that the alloys may be used as casting alloys, since their HCI values are better than those of standard matrix aluminium casting alloys. As a result of the experiments, all alloys containing a eutectic constituent exhibit lower hot-cracking index (HCI = 12 mm) than standard eutectic-free alloys (HCI ≈ 16 mm). In addition, the level of casting properties was assessed from the external appearance of thin-walled castings with respect to the absence of cracks, misruns, and other visible defects.

## Author contributions

Conceptualization: ADM, GMK, DUS; Data curation: ADM; Formal analysis: DUS; Funding acquisition: ADM; Investigation: ADM; Methodology: DUS; Project administration: ADM; Resources: ADM; Software: BDB; Supervision: GMK; Validation: DUS; Visualization: GMK, DUS; Writing – original draft: ADM; Writing – review & editing: GMK. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of interests

The authors declare no conflict of interest.

## Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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# Металл материалдардың ыстық сынғыштығын зерттеудің қазіргі әдістері

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**Аңдатпа.** Қазіргі заманғы ғылым мен техниканың дамуы бұйымдардың жоғары сапасын қамтамасыз етуде материалдардың пайдалану қасиеттерімен қатар олардың технологиялық қасиеттерінің де маңызды екенін көрсетті. Алюминий қорытпаларын өндіруде деформацияланатын қорытпалар үшін бастапқы дайындама ретінде көбінесе құйма слитоктар қолданылады, ал құю қорытпалары үшін фасонды құймалар пайдаланылады. Құймалар мен слитоктарды өндіру барысында жиі кездесетін ақаулардың бірі - ыстық сынғыштық, яғни қату процесінде кристалдану жарықтарының пайда болуына материалдың бейімділігі. Ыстық жарықтардың пайда болу мәселесі әсіресе жоғары берікті және ыстыққа төзімді алюминий қорытпаларын әзірлеу мен өндіру кезінде өзекті болып табылады, себебі олардың химиялық құрам аймақтары көбінесе ыстық сынғыштығы жоғары қорытпалардың құрам аймақтарымен сәйкес келеді. Құю және балқытып дәнекерлеу кезінде қорытпалардың айқын ыстық сынғыштығы құнды пайдалану қасиеттеріне қарамастан, оларды сериялық өндіріске енгізуді айтарлықтай қиындатады, ал кейбір жағдайларда іс жүзінде мүмкін емес етеді. Жаңа қорытпаларды әзірлеу барысында ыстық сынғыштықты төмендету, әдетте, ұзақ әрі еңбек сыйымды эксперименттік зерттеулер арқылы жүзеге асырылады. Мақалада алюминий қорытпаларының ыстық сынғыштығын бағалаудың карандаш сынамасы әдісі қарастырылған. Ыстық сынғыштық құбылысының физикалық мәні сипатталып, әдістің принципі, сынақ жүргізу әдістемесі және алынған нәтижелерді талдау келтірілген. Сонымен қатар карандаш сынамасы әдісі бойынша ыстық сынғыштықты анықтау сызбасы және пайдаланылған әдебиеттер тізімі ұсынылған.

***Негізгі сөздер:*** *алюминий қорытпасы, эвтектика, ыстықжарылғыштық көрсеткіштері, легірлеу, құю, ыстық жарықтар, тиімді кристалдану аралығы.*

# Современные методы исследования горячеломкости металлических материалов

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**Аннотация.** Развитие современных научно-технических направлений показало, что при обеспечении высокого качества изделий решающую роль играют не только эксплуатационные характеристики материалов, но и их технологические свойства. В производстве алюминиевых сплавов в большинстве случаев исходным материалом для деформируемых сплавов служат слитки, тогда как для литейных сплавов применяются фасонные отливки. Одним из наиболее распространённых дефектов, возникающих при получении слитков и отливок, является горячеломкость - склонность материала к образованию кристаллизационных трещин в процессе затвердевания. Проблема возникновения горячих трещин особенно актуальна при разработке и изготовлении новых высокопрочных и жаропрочных алюминиевых сплавов, поскольку диапазоны их химического состава часто совпадают с областями повышенной горячеломкости. Значительная склонность сплавов к образованию горячих трещин при литье и сварке плавлением существенно усложняет, а в ряде случаев делает практически невозможным их внедрение в серийное производство, несмотря на наличие ценных эксплуатационных свойств. Как правило, снижение горячеломкости при создании новых сплавов достигается путем длительных и трудоёмких экспериментальных исследований. В статье рассматривается метод оценки горячеломкости алюминиевых сплавов с применением карандашной пробы. Описана физическая сущность явления горячеломкости, изложен принцип метода, приведена методика проведения испытаний и анализ полученных результатов. Также представлена схема оформления пробы горячеломкости по методу карандашной пробы и приведён перечень использованной литературы.

***Ключевые слова:*** *алюминиевый сплав, эвтектика, показатели горячеломкости, легирование, литье, горящие трещины, эффективный интервал кристаллизации.*

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