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ПОДБОР ОПТИМАЛЬНЫХ РЕЖИМОВ ЦИАНИДНОГО ВЫЩЕЛАЧИВАНИЯ ЗОЛОТА ИЗ РУДЫ МЕСТОРОЖДЕНИЯ РЕСПУБЛИКИ КАЗАХСТАН

Переработка золотомедных руд с повышенным содержанием меди и золота вкрапленного в сульфидные минералы цианидными растворами, связана с рядом трудностей. Так медь, вступая в реакцию с цианидом вызывает его повышенный расход, а вкрапление золота в сульфидные минералы вызывает потери золота с хвостами. Таким образом подбор оптимальных режимов выщелачивания необходим для рационального использования реагентов, что ведет к удешевлению гидрометаллургических процессов цианидного выщелачивания золотомедных руд и уменьшению экологических рисков. В работе исследуется возможность переработки золотомедной руды с высоким содержанием меди, и золота внедренного в сульфидные минералы (пирит, халькопирит). Целью работы является установление оптимальных параметров цианидного выщелачивания путем проведения тестов в бутылочных агитаторах. В результате проведенных экспериментов было установлено что при увеличении степени измельчения руды извлечение золота возрастает, а расход цианида несколько снижается. Добавлением угля при выщелачивании существенно увеличивает извлечение золота, до 7%. Отмечено что высокий расход цианида натрия не может быть снижен без существенного снижения извлечения золота. Снижение расхода цианида натрия на $\approx 20\%$ также снижает извлечение золота на $\approx 20\%$. Лабораторно-промышленный эксперимент показал что уже после 16 часов выщелачивания руды достигается переход золота в раствор на 85,8%, через 18 часов – на 86,7%. При дальнейшем увеличении продолжительности процесса повышения извлечения золота не происходит.

Ключевые слова: золотомедные руды, оптимальные параметры, цианидное выщелачивание, золото, медь.

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STUDY OF ENERGY ASPECTS OF COLD BRIQUETTING FOR SHH15 STEEL DUST UNDER VARYING PRESS CONDITIONS

The article reports the outcomes of a practical study into the cold briquetting of powdered residue ShH15 steel cutting debris. Through the analysis of compaction behavior, three sequential stages were identified: an initial elastic compression phase, followed by fragmentation and densification, and concluding with plastic consolidation forming a solid briquette structure. The pressing procedure was conducted at ambient temperature using equipment equipped with an adjustable matrix configuration. Resultant compacts achieved relative densities in the range of 90–91% of theoretical values under forces up to 850 kN and corresponding pressures of 450–500 MPa. The specific energy input required for material deformation was estimated at 2.6–2.8 kJ/g. The results validate the feasibility of utilizing unprocessed steel waste through energy-efficient compaction, eliminating the need for thermal pretreatment.

In addition to improving material utilization efficiency, the proposed method supports broader sustainability goals by enabling low-cost, low-energy recycling of industrial residues. These findings may serve as a foundation for scaling cold briquetting processes to industrial applications, especially in contexts where thermal methods are economically or environmentally impractical.

Keywords: briquetting, ShH15 steel, steel dust, energy efficiency, deformation diagram, recycling, pressing pressure, compaction behavior.

Introduction

Accurate assessment of energy demand and pressing force when compacting ferrous metal machining waste is essential for selecting appropriate briquetting technologies and equipment. According to prior studies [1, p. 43; 2, p. 70], a more energy-efficient method involves the application of press tools with movable matrices, which substantially reduce deformation resistance, minimize wear on the tooling, and improve the structural integrity of the resulting briquettes.

However, most existing research on briquetting of steel and cast iron residues [3; 4; 5; 6; 7; 8; 9; 10] has been carried out using dies with fixed matrices, where the

frictional interaction between the pressing walls and the work piece contributes to higher forming loads and increased wear on the components.

The primary goal of this study is to examine how various pressing modes and mold designs affect the energy flow and compaction characteristics during low-temperature compaction ShH15 steel particles. An additional objective is to enhance the operational efficiency of the process by selecting optimal design parameters that reduce tool degradation and improve the mechanical performance of the briquetted products, thereby supporting sustainable reuse of metallurgical waste [11; 12; 13; 14; 15; 16; 17; 18].

Materials and methods

The research focused on cold briquetting of finely dispersed ShH15 steel waste, generated during the machining of bearing components. The raw material, in the form of powder-like chips, was used without prior removal of lubricants or oil-based residues, thereby simulating real-world production conditions as closely as possible. To ensure a relatively uniform particle size distribution, the chips were sieved through a 1 mm mesh prior to blending.

To facilitate particle adhesion during compaction, a binder system consisting of bentonite clay, sodium silicate (commonly referred to as liquid glass), and a small amount of water was employed. These components were selected due to their low cost, environmental safety, and capacity to enhance the structural stability of the resulting briquettes. The proportion of binders varied between 10% and 20% relative to the steel base mass, depending on the experimental series. The mixtures were prepared manually to achieve a homogeneous distribution of binder throughout the metal matrix.

Table 1 – Composition of experimental samples of briquettes with varying binding components

| Sample | Mass of ShH15, g | Bentonite, % | Liquid glass, % | Water, % | Total mass of binders, r | Briquette mass, g |
|--------|------------------|--------------|-----------------|----------|--------------------------|-------------------|
| 1A | 17 | 5 | 5 | 5 | 15 | 20 |
| 2A | 16 | 10 | 5 | 5 | 20 | 20 |
| 3A | 16 | 5 | 10 | 5 | 20 | 20 |
| 4A | 16 | 5 | 5 | 10 | 20 | 20 |
| 5A | 16 | 7 | 7 | 6 | 20 | 20 |
| 6A | 18 | 3 | 4 | 3 | 10 | 20 |

The mass of pulverized steel chip ShH15 is 20 g in all series. The mass proportions of additives are given as a percentage of the mass of the chip.

The compaction of specimens was performed using a vertical hydraulic press of the RP-50 model. The die assembly was mounted on the worktable, with the lower punch rigidly fixed and connected to a hydraulic ejector mechanism. The design geometry of the mold was selected to provide a uniform distribution of pressure across the cross-section of the briquette, while also minimizing potential heat loss during further processing stages. The external view of the forming assembly is presented in Figure 2.

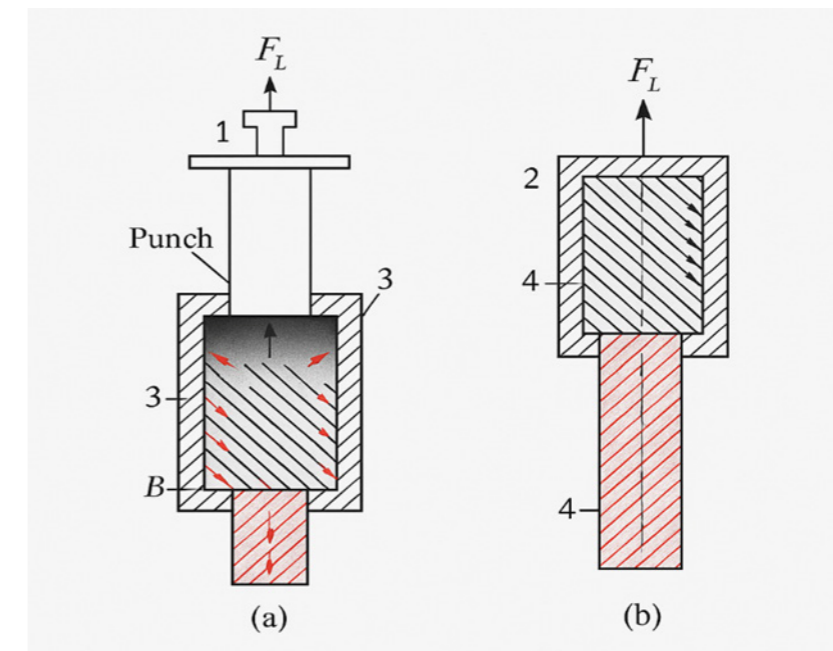


Figure 1 – Schematic structure of metal extrusion in a die: a – RP50 press; b – extrudate

The RP-50 hydraulic press was utilized to simulate the pressure conditions required for the formation of a dense metallic structure, replicating real-world compaction scenarios for fine and powdered ferrous materials. The compaction tooling consisted of a cylindrical die with a fixed matrix, creating standard deformation conditions under applied axial load. The feed material—a homogeneous mixture of SHH15 steel dust, bentonite clay, liquid glass, and water—was manually prepared and dosed before being introduced into the die cavity.

The inner diameter of the die was 20 mm, giving a base area of approximately 0.0007065 m². Pressure during compaction was determined using the formula $P=F/SP = F/SP=F/S$, where force FFF is calculated as the product of pressure and base area. Under standard loading and fill weight conditions, the compaction pressure was estimated at 45 MPa, equivalent to an applied force of roughly 317 N. Across the experimental series, the actual applied pressure ranged from 100 to 300 MPa, depending on the formulation and processing mode.

After placing the mixture into the mold, pressure was applied using a manual hydraulic drive and maintained for 10 seconds to allow the formation of a cohesive, high-strength briquette. Upon completion of the pressing cycle, the sample was removed for post-processing.

To stabilize the internal structure and remove residual moisture, the formed briquettes were subjected to thermal treatment in a chamber-type SPLL-1.6.2.5.1/11-I2M muffle furnace. Drying was conducted at 350 °C for 1.5–2 hours, which was selected as the upper thermal limit for removing physically bound water while avoiding decomposition of the binders. This drying regime helped preserve the structural integrity provided by

bentonite and liquid glass, while minimizing oxidation of the steel particles. The samples were placed in thermally stable metallic containers to ensure uniform heat distribution and prevent oxidation from atmospheric exposure.

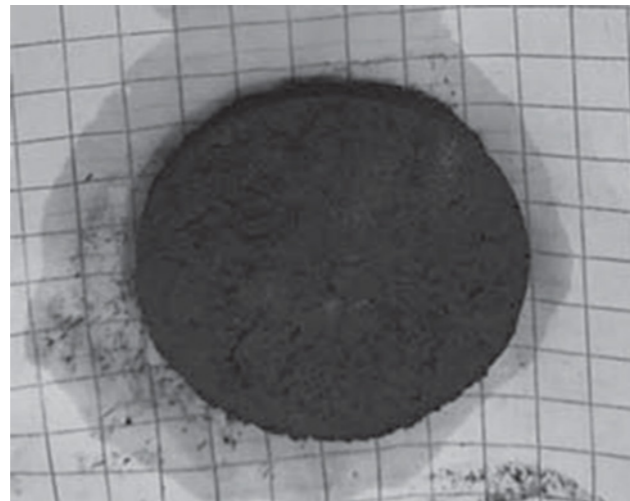


Figure 2 – Briquettes after pressing on the press RP50

The final stage of the experiment involved mechanical testing of the fabricated samples to evaluate their compressive strength and actual density. These measurements were taken only after complete cooling and structural stabilization of the briquettes. The data collected at this stage made it possible to assess both the technological viability and the effectiveness of the applied compaction regime, as well as to determine how the pressure and binder composition affected the resulting material quality.

Results and discussion

The adopted cold compaction approach using the RP-50 press demonstrated high reproducibility of outcomes. It also enabled the observation of direct relationships between key processing parameters—such as compaction pressure and binder content—and the resulting physical properties, including strength and density of the briquettes.

To quantify the energy demand during pressing, force readings from the hydraulic system were monitored throughout the process. Using the known cross-sectional area of the mold and the displacement of the punch, both the applied force and the specific energy input were calculated. These calculations allowed for identifying a working range of parameters that ensures an optimal trade-off between energy consumption and mechanical performance.

Figure 3 illustrates a representative deformation diagram obtained from a staged compression of ShH15 steel dust briquettes formed in a movable-matrix die system. The graph plots the relationship between the pressing force and the vertical displacement of the pressing punch, allowing for detailed analysis of compaction behavior under cold forming conditions.

Compression Diagram during Cold Briquetting of ShH15 Steel Chip

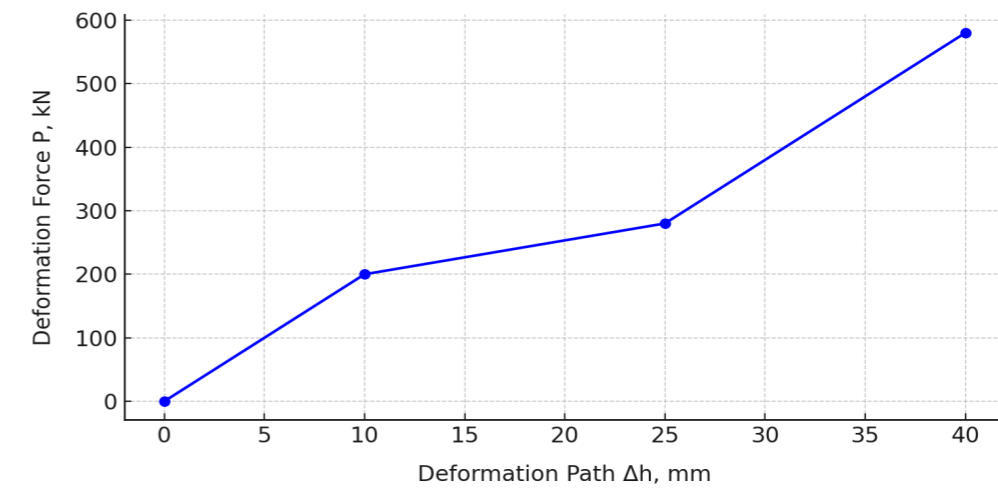


Figure 3 – Dependence of deformation force on the deformation path in cold pressing of ShH15 steel chips. Forming hole diameter 20 mm; fill height 150 mm; fill mass 20 g; temperature 20 °C.

Analysis of the diagram allows to highlight three characteristic stages of pressing:

Elastic compression and structural compaction (up to 10 mm stroke): At the initial stage, the chip is redistributed and compressed, which is accompanied by a rapid increase in force to around 200 kN. , table 2.

Table 2 – Effect of binder composition and pressure on strength and density characteristics of ShH15 steel chip briquettes

| Sample | Binder Content (%) | Pressing Pressure (MPa) | Compressive Strength (MPa) | Density (g/cm ³) | Density (% of theoretical) |
|--------|--------------------|-------------------------|----------------------------|------------------------------|----------------------------|
| 1A | 15 | 150 | 48 | 6.3 | 82.9 |
| 2A | 20 | 200 | 56 | 6.55 | 86.3 |
| 3A | 20 | 200 | 58 | 6.6 | 87.0 |
| 4A | 20 | 200 | 52 | 6.48 | 85.4 |
| 5A | 20 | 250 | 61 | 6.75 | 89.0 |
| 6A | 10 | 300 | 63 | 6.9 | 91.1 |

Fragmentation and Dense Compaction (10–25 mm):At this intermediate stage, the rate of force increase becomes more gradual. This behavior is attributed to the breakdown of protruding particle edges and the progressive filling of internal voids. The material begins transitioning toward a continuous contact structure, which marks the onset of more stable compaction.

Plastic Flow and Maximum Densification (25–40 mm): As the particles come into close contact, a sharp rise in compaction force is observed—reaching up to 850 kN.

During this phase, intense plastic deformation takes place, resulting in the consolidation of the particulate mass into a dense, cohesive structure.

At the conclusion of the compaction cycle, the briquettes demonstrate a theoretical density level of 90–91 %, which corresponds to industry standards for secondary metal products. The applied pressure at this point ranges between 450 and 500 MPa. The specific energy required for deformation falls within 2.6–2.8 kJ/g, which exceeds that typically recorded during hot pressing operations.

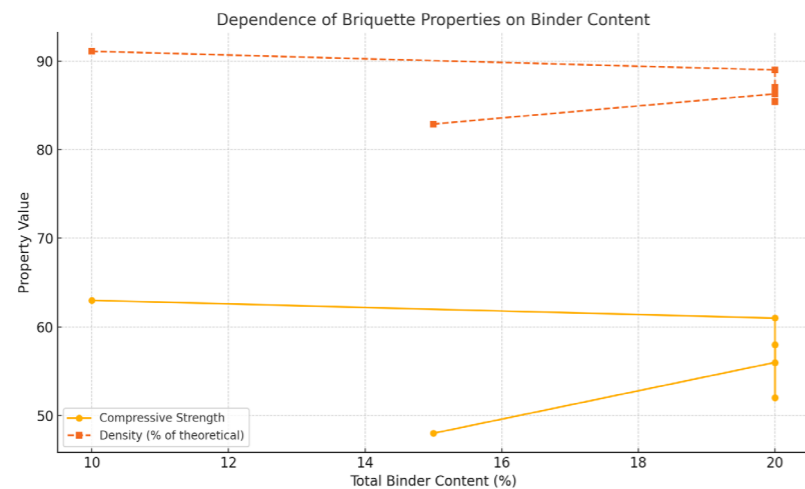


Figure 4 – Dependence of compressive strength and density on binder content in ShH15 steel chip briquettes

Figure 4 shows the dependence of the compressive strength and relative density of the briquettes on the total content of the binding components (bentonite, liquid glass and water) in the composition of the briquettes. According to the data obtained, there is a steady trend of increasing both strength and density of briquettes with an increase in the total proportion of binder from 10 % to 20 %. The minimum values of strength (48 MPa) and density (6.30 g/cm³, which is about 83 % of theoretical) are observed at 15 % binding content (sample 1A). The best performance is achieved with 20 % binder content (samples 3A and 5A), where strength increases to 61 MPa and density reaches 6.75-6.90 g/cm³, which is up to 91% of theoretical steel density ShH15.

It was also observed that increasing the compaction pressure from 150 MPa to 300 MPa led to a corresponding improvement in both strength and density characteristics of the briquettes. Nevertheless, the rate of enhancement diminished at higher pressure levels, indicating that a saturation threshold of structural compaction had been reached. Notably, Sample 6A—containing only 10% binder—demonstrated strong mechanical properties, which can be attributed to the applied high pressure of 300 MPa. This result confirms that high-density briquettes can be achieved even with minimal binder content, provided the compaction force is sufficiently elevated. Therefore, the most influential parameters affecting briquette quality are the proportion of binder components and the magnitude of pressing pressure. A balanced formulation combined with a minimum

pressure of 250 MPa appears to be optimal for achieving both structural integrity and economic efficiency.

Conclusion

The efficiency of densification during cold compaction of ShH15 steel dust is primarily influenced by the initial material properties, particularly its density and plasticity. Materials with higher bulk density and limited plastic deformation require substantially greater compaction forces to achieve desired densification levels. The inclusion of fine additives—such as bentonite clay and sodium silicate—facilitates the filling of voids between metal particles, thereby enhancing initial packing density and enabling more uniform stress distribution during pressing.

In the case of ShH15 steel chips with inherently low plasticity, both theoretical calculations and experimental data reveal the presence of a defined flow zone during compaction. The extent of this zone is determined by the volumetric strain and residual deformation parameters of the system. The use of a pressing setup with a movable matrix significantly reduces deformation resistance in comparison with traditional fixed-die configurations. For ShH15-type high-carbon steels, this design modification allows for a reduction in pressing force by approximately 30–35%, ultimately contributing to reduced energy input and extended tool life.

The close agreement between experimental results and theoretical predictions—within a deviation margin of 12 %—confirms the validity of the employed physical and mathematical model for describing compaction behavior in particulate metal systems.

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ТҮРЛІ ПРЕССТЕУ ЖАҒДАЙЫНДА ШХ15 БОЛАТ ШАҢЫН СУЫҚ БРИКЕТТЕУДІҢ ЭНЕРГЕТИКАЛЫҚ АСПЕКТІЛЕРІН ЗЕРТТЕУ

Бұл мақалада ұсақ дисперсті ШХ15 болат өңдеу қалдықтарын суық брикеттеу бойынша эксперименталды зерттеу нәтижелері берілген. Тығыздау әрекетін талдау арқылы үш дәйекті кезең анықталды: бастапқы серпімді қысу фазасы, содан кейін фрагментация және тығыздау және қатты брикет құрылымын құрайтын пластикалық консолидациямен аяқталу. Престеу процесі жылжымалы штамппен жабдықталған жабдықты пайдалана отырып, қоршаған орта температурасында жүргізілді. Нәтижелі ықшамдаулар 850кН дейінгі күштер мен 450-500МПа сәйкес қысымдар кезінде теориялық мәндердің 90–91% диапазонында салыстырмалы тығыздыққа қол жеткізді. Материалдың деформациясы үшін қажетті меншікті энергия шығыны 2,6–2,8 кДж/г деп бағаланды. Нәтижелер термиялық алдын ала өңдеу қажеттілігін жоя отырып, энергияны үнемдейтін тығыздау арқылы өңделмеген болат қалдықтарын кәдеге жарату мүмкіндігін растайды.

Материалдарды тиімді пайдалану мүмкіндігін арттырумен қатар, ұсынылған әдіс өнеркәсіптік қалдықтарды төмен шығынмен және энергия үнемдеу арқылы қайта өңдеуге жол ашып, тұрақты даму мақсаттарына жетуге ықпал етеді. Бұл нәтижелер суық брикеттеу технологиясын