China Steel Technical Report, No. 38, pp.50 −59, (2025)

Development of Hot Briquetting Technology for Iron-Containing By-Products from the Steel Industry

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This study investigates the application of hot briquetting technology to by-products rich in metallic iron, derived from the steel industry. A novel approach was employed to compress these iron-containing by-products, specifically fine grit, into high-strength briquettes under cost-effective conditions, without introducing impurities (i.e., without the addition of binders), to satisfy transportation requirements during the recycling of ironmaking and steelmaking processes. The influence of various factors-including forming pressure, forming temperature, raw material quality, and briquette size-was examined with respect to key parameters such as briquette height, compressive strength (CS), tumbler index (TI), and shatter index (SI). Experimental results demonstrated that both the briquettes' height and CS improved with increasing forming pressure and temperature. Notably, the effect of forming pressure was found to be more significant than that of temperature. Once the CS reached a certain threshold, higher forming pressure promoted denser packing of metallic iron particles, further enhancing CS. However, this improvement did not necessarily correlate with effective increases in TI and SI values. In conclusion, when the forming pressure exceeds 557 MPa and the temperature exceeds 200°C, the TI and SI values of 15 × 15 mm briquettes (10 g) produced from iron-containing desulfurization slag fine grit can meet the quality standards for sintered ores: TI > 76% and SI > 85%.

Keywords: Iron-containing by-products, Hot briquetting, Compressive strength, Tumbler index, Shatter index

1. INTRODUCTION

As global awareness of environmental issues continues to rise, the demand for sustainable development is also increasing among both businesses and consumers. The pressures faced by the steel industry have necessitated the exploration of more environmentally friendly production methods, making the recycling of iron-containing by-products an essential strategy. Many companies have begun to integrate environmental protection into their core values, actively promoting the circular use of resources. Recent technological advancements have significantly improved the recycling efficiency of iron-containing fine grit. For instance, cutting-edge sorting technologies can accurately separate high-quality iron minerals from waste materials. Additionally, innovations in pelletizing technology have enhanced the conversion of fine grit into usable raw materials. These advancements not only increase recycling rates but also contribute to lower production costs, thereby supporting the industry's transition toward more sustainable practices.

Desulfurization in steelmaking is a critical step aimed at removing sulfur elements from molten iron to enhance its quality and performance. The iron present in desulfurization slag primarily originates from the molten iron itself, with some iron not being completely separated during the process and coexisting with the slag. The metallic iron within the desulfurization slag can be recycled directly back into the ironmaking process after dry crushing and sorting. Larger particles (greater than 50 mm) can be reused as they are, while particles smaller than 50 mm undergo wet grinding and magnetic separation to remove most slag components before being returned to the process. However, metallic iron fine grit smaller than 5 mm must be agglomerated through sintering before recycling. This agglomeration process leads to oxidation of the metallic iron due to the high temperatures involved, necessitating a reduction reaction (involving the addition of coke, reducing gases, etc.) to regenerate the metallic iron. This recycling pathway consumes significant energy and generates carbon emissions. Therefore, developing non-combustion pelletizing technologies to replace high-temperature agglomeration methods, such as sintering and pellet roasting, is essential. Traditional non-sintered agglomeration technologies utilize various types of cements or inorganic/organic binders (such as liquid glass, molasses, resins, and starches) along with molecular dispersion systems to harden small particles.

In terms of equipment used to produce non-combustion agglomerates, the primary methods include roll press, cold-bonded pellet production, vibration compaction, and extrusion, all of which have been successfully implemented in industrial metallurgy. Regarding raw material requirements, the most commonly employed method is the roll press. It is noteworthy that binders can be omitted, as demonstrated by Thyssen Stahl AG. The company employs hot roll press technology, operating at temperatures between approximately 500 and 700°C, to agglomerate BOF dust and directly return it to the converter. Thus, the commercial viability of hot briquetting technology has been confirmed.

This study aims to develop a low-temperature agglomeration technology as an alternative to the traditional sintering process. By utilizing the interlocking effect between metallic iron particles without the need for binders, this method converts iron-containing fine grit into briquettes that are suitable for reuse in both ironmaking and steelmaking processes. This approach facilitates the direct recycling of metallic iron from the fines back into the ironmaking process, thereby enhancing resource utilization and contributing to energy conservation and carbon emission reduction.

2. EXPERIMENTAL METHODS AND PROCEDURES

2.1 Iron-Containing Desulfurization Slag Fine Grit

The study focuses on iron-containing desulfurization slag fine grit with a diameter of less than 5 mm. Its appearance and composition are illustrated in Figure 1 and Table 1. The metallic iron (M-Fe) content constitutes 62.3%, while CaO accounts for 5.6%, and SiO_2 comprises 2.48%.

2.2 Lab-scale Equipment for Hot-briquetting

The laboratory briquetting equipment consists of a high-frequency generator paired with a hydraulic press (see Figure 2). The experimental procedure involves placing a 10 g sample of desulfurized iron fine grit into a mold. Under a fixed high-frequency power condition of 13 kW, different heating durations are applied to achieve predetermined briquetting temperatures of 200, 400, and 600°C. Subsequently, a uniaxial hydraulic press is utilized to apply a specific forming pressure ranging from 186 to 1114 MPa, with a holding time of 10 seconds, in order to produce briquettes at various forming temperatures and pressures.

Fig.1. Photo of iron-containing desulfurization slag fine grit.

Table 1 Compositions of iron-containing desulfurization slag fine grit.

Element	C	P	S	CaO	MgO	Al_2O_3	SiO_2	MnO	M-Fe	T-Fe
Content (%)	2.80	0.136	0.326	5.60	0.395	0.840	2.48	0.412	62.30	81.20

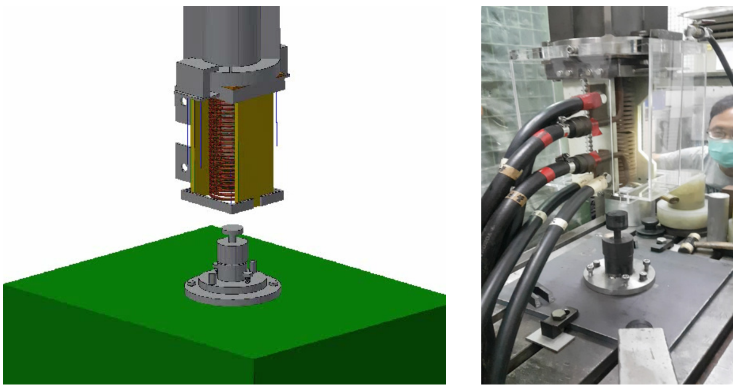


Fig.2. Lab-scale hot-briquetting equipment, (a) Scheme; (b) photo.

2.3 Analysis of Briquettes' Properties

The briquettes produced from iron-containing desulfurization slag fine grit must meet the strength requirements necessary for transportation, including compressive strength (CS), tumbler index (TI), and shatter index (SI). In this study, the TI and SI of sintered ore are established as quality standard targets for the briquette material. The compressive strength analysis is conducted using the COMETECH QC-526M1F tensile (compressive) testing machine, averaging the strength of 10 briquettes. According to the standard methods for tumbler index and shatter index (ISO 3271:2015 and JIS M 8711:2023), the required sample weights are 15 kg and 20 kg, respectively. Due to the limitations of the laboratory briquetting equipment in producing sufficient samples, a small-scale tumbler and shatter test apparatus was utilized to analyze the characteristics of 10 briquettes produced under various conditions, yielding their respective TI and SI values. The results from the small-scale equipment analysis are detailed in Section 3.1, along with the corresponding conditions of the standard methods.

3. RESULTS AND DISCUSSION

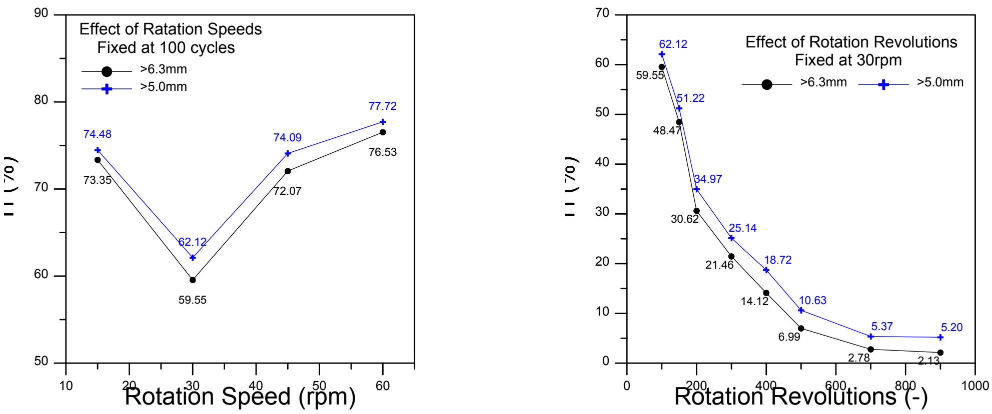
3.1 Establishment of Small-Scale TI and SI Measurement Equipment

Due to the limited output capacity of the laboratory's hot-briquetting equipment, it cannot provide the block weights required for standard methods (15 kg for tumbler index (TI) tests and 20 kg for shatter index (SI) tests). Consequently, this study developed a small-scale TI and SI measurement device to analyze the characteristics of the hot briquettes produced in the laboratory, as illustrated in Figure 3.

The constructed TI measurement device features a barrel diameter of 30 cm, significantly smaller than the 100 cm diameter utilized in standard methods. This study investigates the use of briquettes made from iron-containing desulfurization slag fine grit, produced using a roll press under ambient conditions. The primary objective is to establish operational conditions that correlate the small-scale TI measurement device with the standard measurement method. The relevant results are illustrated in Figure 4.

(a) (b) (c)

Fig.3. (a) TI measurement device; (b) SI measurement device; (c) Thick steel plate at the bottom of the SI measurement device.



(a) (b)

Fig.4. (a) Curve of TI vs. Rotation speed; (b) Curve of SI vs. rotation revolution.

Initially, ten briquettes were selected, and each was subjected to 100 rotations at varying speeds to assess the influence on the TI value (Figure 4(a)). The results indicated that the maximum destructive effect on the briquettes, corresponding to the lowest TI, occurred at a speed of 30 rpm. Figure 4(b) presents the TI variation curve of the briquettes after different numbers of rotations at a fixed speed of 30 rpm. It was observed that the TI progressively decreased with an increase in the number of rotations. According to the standard method (ISO 3271:2015), the TI of the briquettes made from iron-containing desulfurization slag fine grit, produced by the roll press, was measured to be between 1% and 2%. Consequently, the measurement parameters of 30 rpm and 900 rotations were selected as the operational conditions for comparison with the standard method. However, given the inferior strength of briquettes produced under lower forming forces and temperatures, the measurement conditions of 30 rpm and 200 revolutions were adopted to elucidate the impact of operational factors on the TI of the briquettes.

In a similar manner, ten briquettes were tested using the small-scale SI measurement device. The SI value, following four drops from a height of 2 meters, was recorded at 63.8%, which is comparable to the 65.3% obtained using the standard method (JIS M 8711:2023). This result confirms the validity of the small-scale device for analyzing the SI characteristics of the briquettes when utilizing ten briquette samples.

3.2 Briquetting of Iron-Containing Desulfurization Slag Fine Grit

This study focuses on iron-containing desulfurization slag fine grit, which amounts to approximately 70,000 tons per year, as the raw material. It investigates the effects of factors such as forming pressure, forming temperature, raw material quality, and briquette size on the quality characteristics—CS, TI, and SI—of the hot briquettes produced from iron-containing desulfurization slag fine grit.

3.2.1 Effect of Forming Pressure and Temperature

Forming pressure and temperature are critical factors influencing the quality of briquettes. Increasing the forming pressure can enhance the density of the briquettes, thereby improving the strength and durability of the material. Raising the temperature during forming can soften the metallic iron components, enhancing their deformability and resulting in denser briquettes. Figure 5 illustrates the variations in height, CS, TI, and SI of briquettes (10 g, dimensions 15 × 15 mm) under different forming pressures and temperatures.

Figure 5(a) shows that as the forming pressure and temperature increase, the height of the briquettes decreases (indicating an increase in the briquette's density). Moreover, the effect of forming pressure on briquette height is more significant than that of temperature, indicating that to effectively increase the density of the briquettes, increasing the forming pressure is the optimal method. The CS of the briquettes also increases with rising forming pressure and temperature (Figure 5(b)). At a temperature of 200°C and a forming pressure of 186 MPa, the CS of the briquette is 58.72 Kg_f/pcs; when the forming pressure is increased to 1114 MPa at the same temperature, the CS rises to 182.7 Kg_f/pcs, an increase of 3.1 times. However, when the temperature is raised from 200°C to 600°C under a fixed forming pressure, the increase in CS is only between 20% and 47%. Therefore, to effectively enhance the compressive strength of the briquettes, a roller press that can provide the necessary forming force is the preferred solution.

In terms of the TI of the briquettes, the strength of the briquettes is relatively low at forming pressures of 186 MPa and 371 MPa. Using measurement parameters of 30 rpm and 900 revolutions (aligned with standard operational conditions) does not effectively clarify the influence of operational factors on TI. Therefore, a measurement parameter of 30 rpm and 200 revolutions was adopted instead. Figure 5(c) shows that when the forming pressure is 186 MPa, the TI value of the briquettes (200 revolutions) increases from 51.7% to 95.1% with rising temperature. This indicates that under low forming pressure, the effect of temperature can significantly enhance the TI value (200 revolutions) of the briquettes. At a forming pressure of 371 MPa, the TI values of the briquettes at temperatures between 200°C and 600°C (200 revolutions) are all greater than 95%. This suggests that even at low forming pressures, the briquettes of iron-containing desulfurization slag fine grit can exhibit good TI characteristics at a temperature of 200°C.

When the forming pressure exceeds 557 MPa, the strength of the briquettes can be measured using the standard operational conditions of 30 rpm and 900 revolutions. At a forming pressure of 557 MPa, the TI shows better performance, ranging from 82.1% to 94.9%. At higher forming pressures (>557 MPa), the TI values of the briquettes at a temperature of 600°C are comparable (88.0% to 96.4%), but there is an overall declining trend. Notably, at a temperature of 400°C and forming pressures of 743 to 1114 MPa, the TI values of the briquettes range from 76.8% to 81.7%. This result indicates that once the compressive strength of the briquettes reaches a certain level, higher forming pressures, while compressing the metallic iron particles more densely and thereby increasing compressive strength, do not necessarily lead to a significant improvement in TI values. This phenomenon is also observed in the variation curve of the SI values of the briquettes with forming pressure and temperature (Figure 5(d)). However, when the forming pressure

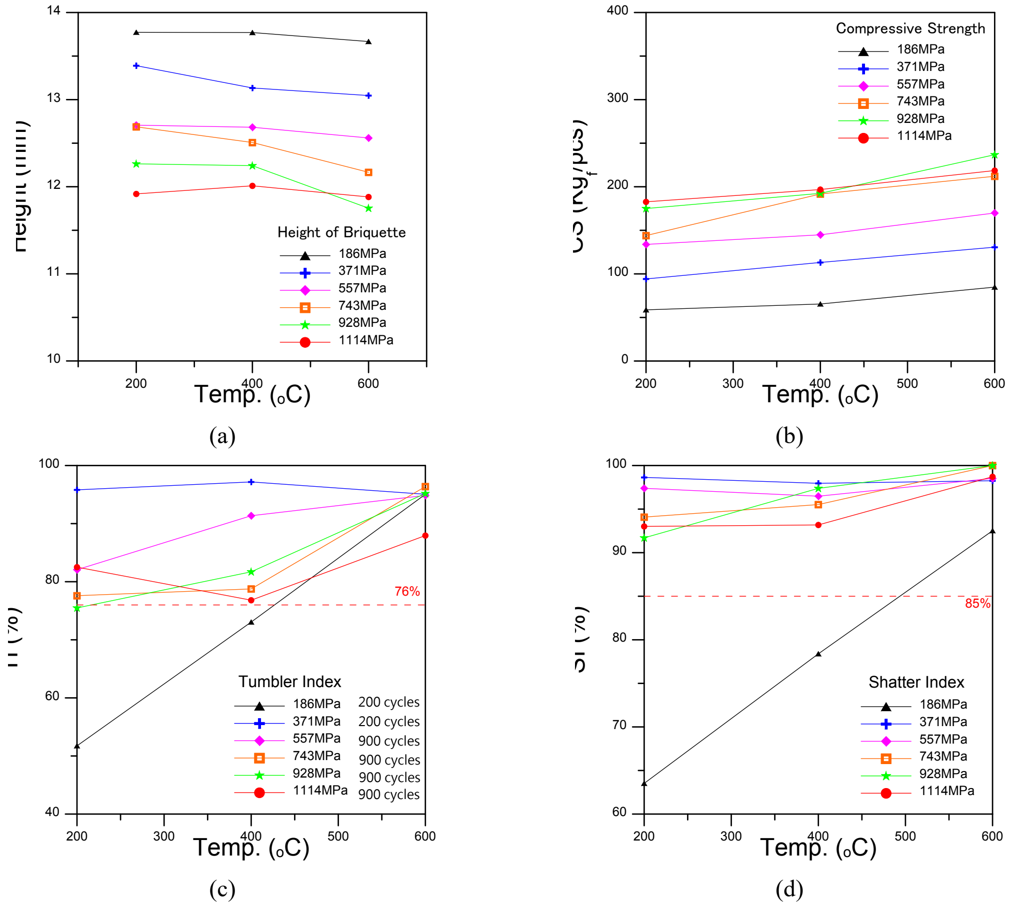


Fig.5. Characteristics of briquettes produced under different forming pressures and temperatures.

exceeds 371 MPa, the SI values of the briquettes are all greater than 90%, with relatively small differences in values.

In summary, when the forming pressure exceeds 557 MPa and the temperature exceeds 200°C, the TI and SI values of the 15 × 15 mm briquettes (10 g) produced by iron-containing desulfurization slag fine grit meet the quality targets for sintered ore: TI > 76% and SI > 85%.

Cross-sectional analysis of the briquettes under different forming pressures and temperatures is shown in Figure 6. At a forming pressure of 186 MPa and a temperature of 200°C, the cross-section of the briquettes exhibits very few metallic glossy areas, and the briquettes appear brown. As the temperature increases, the metallic luster gradually increases, indicating enhanced bonding among the metallic particles within the briquettes, which also improves the CS, TI, and SI characteristics of the briquettes.

When the forming pressure reaches 317 MPa, the brown coloration of the briquettes nearly vanishes, transforming into a black hue akin to that of briquettes produced by roller press. This phenomenon indicates that the particle density within the briquettes has achieved a critical level. In comparison to the cross-section of briquettes formed at 186 MPa, the cross-section at 317 MPa reveals a significantly greater presence of metallic glossy areas, reflecting a substantial improvement in briquette density, with no notable flaking observed during cutting. However, as the temperature increases, the changes in the metallic glossy areas of the briquettes remain minimal, suggesting that at this forming pressure, elevating the temperature does not substantially enhance the quality of the briquettes.

Except for the briquettes produced under the conditions of 557 MPa and 200°C, which display a noticeably looser metallic glossy area, the cross-sectional structures under other forming pressures and temperature conditions do not exhibit significant differences. The interconnections between the metallic iron particles within the briquettes are highly effective, leading to superior tensile and compressive strength characteristics.

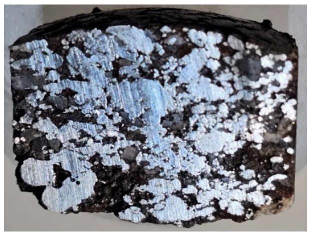
3.2.2 Effect of Raw Material Quality

The raw materials for agglomeration consist of fine grit containing metallic iron derived from the company's iron/steel production processes. The composition, particle

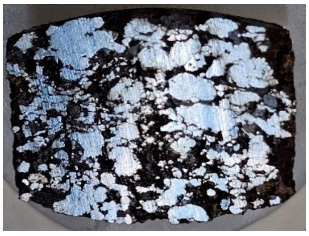
(a) 186MPa, 200°C

(b) 186MPa, 400°C

(c) 186MPa, 600°C



(d) 317MPa, 200°C

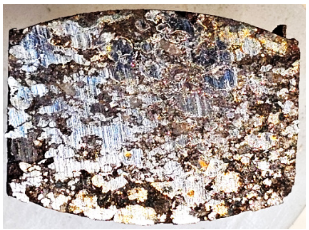


(e) 317MPa, 400°C

(f) 317MPa, 600°C

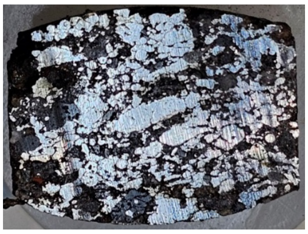
(g) 557MPa, 200°C

(h) 557MPa, 400°C

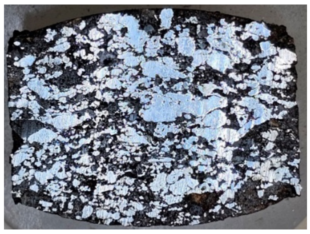


(i) 557MPa, 600°C

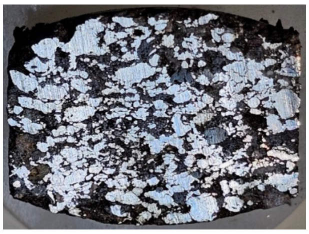
(j) 743MPa, 200°C



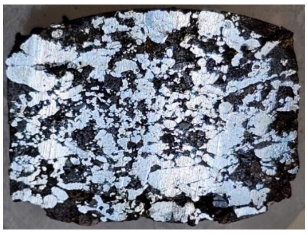
(k) 743MPa, 400°C



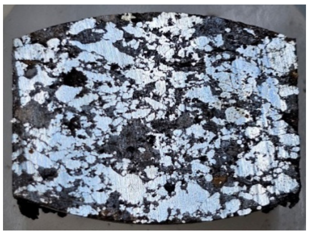
(l) 743MPa, 600°C



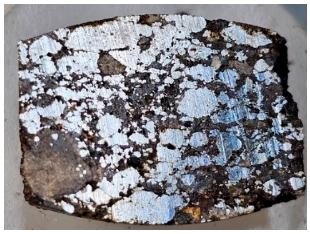
(m) 928MPa, 200°C



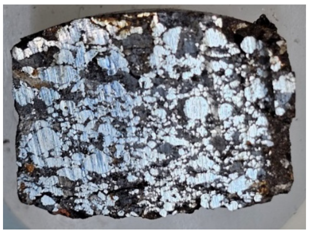
(n) 928MPa, 400°C



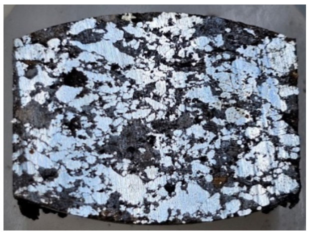
(o) 928MPa, 600°C



(p) 1114MPa, 200°C



(q) 1114MPa, 40°C



(r) 1114MPa, 600°C

Fig.6. Cross-section of briquettes produced under different forming pressures and temperatures.

size, and uniformity of these materials cannot be effectively controlled, which impacts the quality of the briquettes. Previous studies have shown that excessive impurity powder, lower metallic iron content, and high moisture content are detrimental to the quality of the briquettes.

In this study, to address the variability between batches of raw materials (impurity and metallic iron content), the iron-containing desulfurization slag fine grit was screened using a 2 mm sieve. The grit less than 2 mm was selected for hot-briquetting at a forming pressure of 557 MPa. The experimental results are shown in Figure 7.

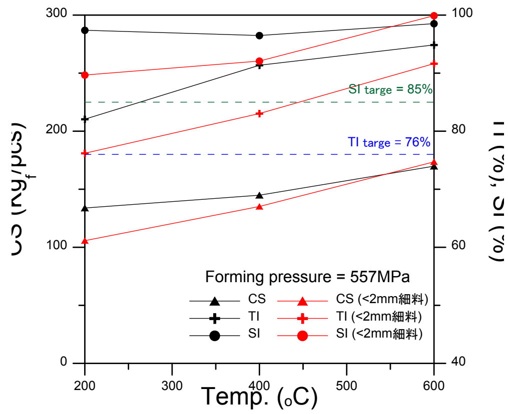


Fig.7. Influence of raw material on the briquette properties.

Due to the lower metallic iron content and higher oxide content in the fine grit (as shown in Table 1), the interlocking effect of metallic iron particles in the briquettes is poor, resulting in inferior CS, TI, and SI of the briquettes. As the briquetting temperature increases, it facilitates the softening of metallic iron particles. Under sufficient forming pressure, these particles can deform, promoting inter-particle bonding and gradually narrowing the quality gap compared to the un-screened materials.

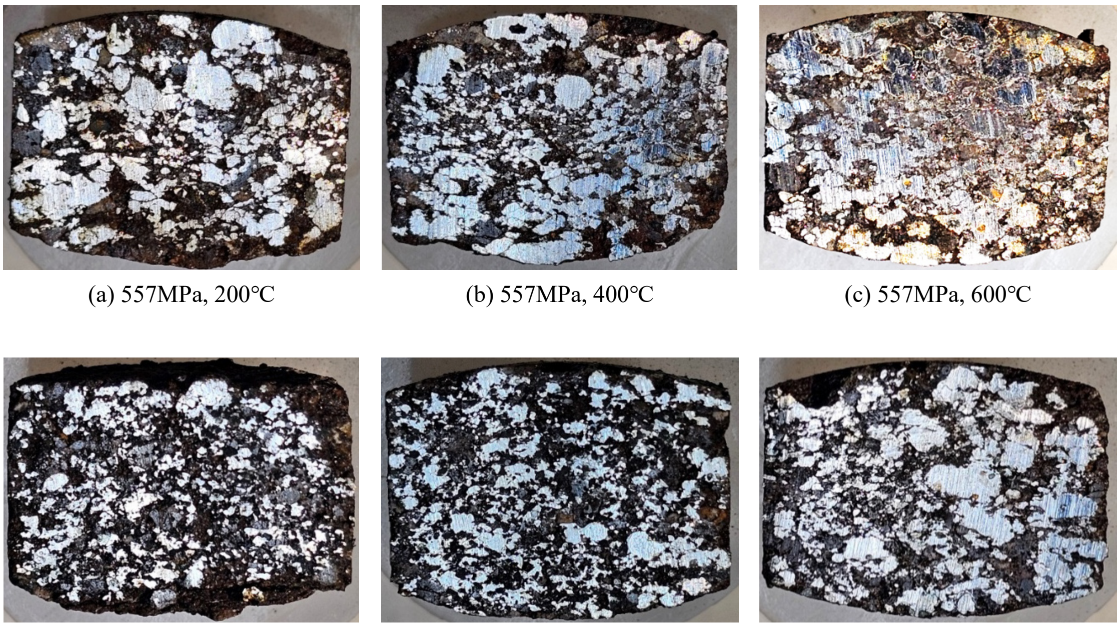
Additionally, it is noteworthy that within the experimental conditions (557 MPa, 200~600°C), the briquettes made from iron-containing desulfurization slag fine grit with a particle size of less than 2 mm still meet the requirements of TI > 76% and SI > 85%.

Figure 8 shows a cross-section of briquettes under different conditions of iron-containing desulfurization slag fine grit (with a forming pressure of 557 MPa). Comparing the cross-sections of briquettes under the same briquetting conditions but different raw material conditions, it can be observed that the briquettes made from grit with a particle size of less than 2mm are noticeably looser, with fewer large areas of metallic luster. This is attributed to the removal of larger metallic iron particles, leaving a higher proportion of oxide components.

Moreover, at a briquetting temperature of 600°C, the cross-section of the briquettes made from grit with a particle size of less than 2mm shows a significant area of metallic luster, indicating that at this briquetting condition, partial fusion among smaller metallic iron particles occurs, enhancing the strength of the briquettes. Consequently, the TI and SI values of the briquettes made from grit with a particle size of less than 2mm show excellent performance (as seen in Figure 7).

3.2.3 Effect of Briquette Size

To maintain the same forming pressure for briquettes, the hydraulic press must provide greater force to produce larger-sized agglomerates. Considering the specifications of the hydraulic press and operational safety, this study selected a forming pressure of 557 MPa to compare the influences of briquette sizes on their



(a) 557MPa, 200°C (b) 557MPa, 400°C (c) 557MPa, 600°C

(d) 557MPa, 200°C (<2 mm) (e) 557MPa, 400°C (<2 mm) (f) 557MPa, 600°C (<2 mm)

Fig.8. Cross-section of briquettes produced with different raw material quality.

characteristics at various temperatures, as illustrated in Figure 9.

The larger briquette (Ø=30 mm, 40 g) and the smaller briquette (Ø=15 mm, 10 g) were produced in proportional sizes. The curvature of the surface decreases inversely with the square of the scale factor as the size increases. This means that as the size of the object increases, its curvature diminishes. Consequently, when measuring the larger briquette (Ø=30 mm, 40 g), the contact area is larger, resulting in a higher measured compressive strength (CS) value (as seen in Figure 9(a)).

However, the weight of larger briquettes is greater, resulting in higher impact energy during the Tumbler Index test. This leads to a poor Tumbler Index (TI) value of only 27.6% at a temperature of 200°C, as illustrated in Figure 9(b). This is significantly lower than the TI value of 82.1% observed for smaller briquettes under the same briquetting conditions. This finding is consistent with the results of Bizhanov and Zagainov (2021)[15] and Nistala et al. (2015)[16]. As the briquetting temperature increases, the TI value of larger briquettes shows a linear increasing trend. At 600°C, the TI value reaches 58.1%, but it still does not meet the target requirement of 76%.

Additionally, as shown in Figure 9(c), the trend of the Shatter Index (SI) for larger briquettes varies from that of the TI with temperature changes. The SI is optimal at 200°C, while higher temperatures lead to a slight decrease. However, the difference in values remains within 10%, which can be attributed to experimental variability. These experimental results indicate that the appropriate briquette size is crucial for hot-briquetting technology.

Cross-sections of briquettes under different forming pressures and temperatures are shown in Figure 10. Compared to Figure 8(a), the larger briquettes produced under the same conditions of 557 MPa and 200°C exhibit a less concentrated distribution of metallic luster areas, with a lower proportion of area coverage. When the temperature is increased to above 400°C, the metallic luster areas in the cross-section of the larger briquettes significantly increase and are more interconnected.

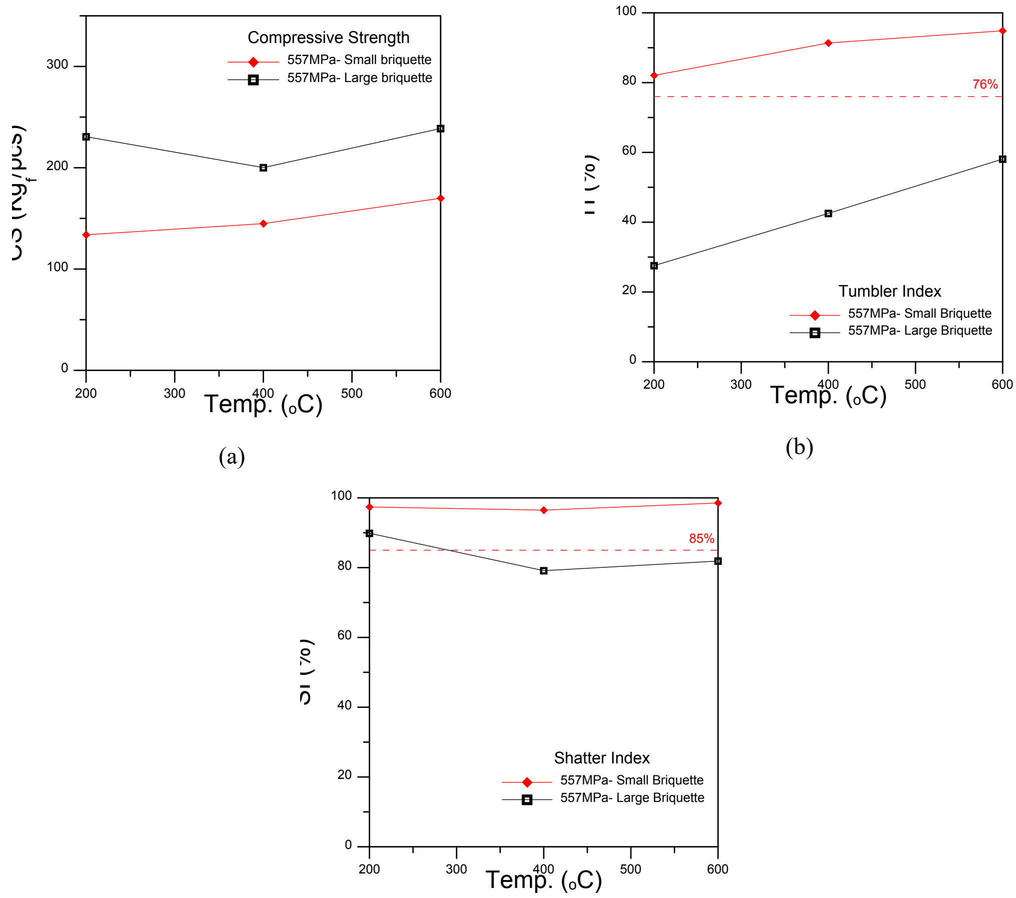
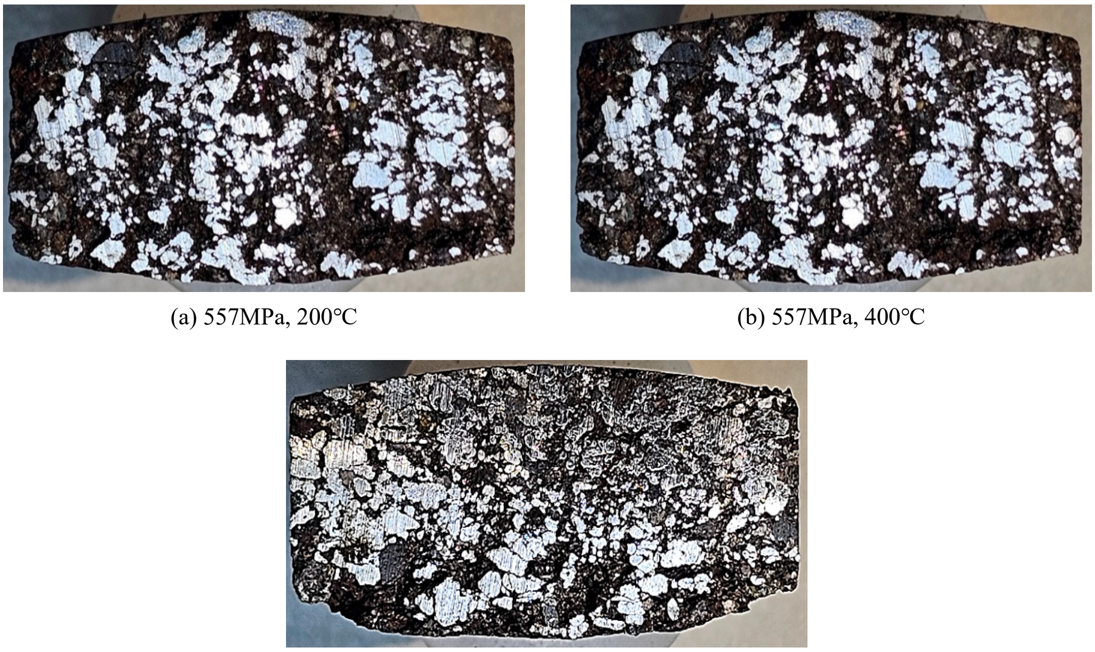


Fig.9. Influence of briquette size on its properties.



(a) 557MPa, 200°C (b) 557MPa, 400°C

(c) 557MPa, 600°C

Fig.10. Cross-section of large briquettes.

3.3 Estimation of Benefits for Recycling Iron-Containing Desulfurization Slag Fine Grit into the Ironmaking Process

The addition of commercially available Hot Briquetted Iron (HBI) in blast furnaces has been verified to provide carbon reduction benefits, with each ton of HBI approximately reducing CO_2 emissions by 1.5 tons (1.5 tons CO_2e per ton of HBI) [17]. The experimental results of this study indicate that under the forming conditions of 200°C and 557 MPa, briquettes that meet the specifications for sintered ore products can be produced. The market price of HBI is approximately NT$15,000 per ton, with a metallic iron content of 83-88% [18]. Simply calculating the value and carbon reduction benefits of the metallic iron content in the briquettes yields NT$10,600/ton and a reduction of 1.06 tons-CO_2e/ton. Therefore, the low-temperature briquetting technology established in this study is expected to create an annual output value of NT$740 million and reduce CO_2 emissions by 74,000 tons-CO_2e per year.

4. CONCLUSION

This study applies hot briquetting technology to desulfurization slag fine grit containing metallic iron. The effects of various factors, such as forming pressure, forming temperature, raw material quality, and briquette size, on the characteristics of the briquettes were studied. The experimental results indicate that when the forming pressure exceeds 557 MPa and the temperature exceeds 200°C, the TI and SI of the 10 g briquettes (15 × 15 mm) can meet the quality targets for sintered ore: TI > 76% and SI > 85%. Thus, this study confirms that the low-temperature hot briquetting process effectively substitutes sintering for transforming fine iron-containing desulfurization slag grit into high-strength briquettes. The method preserves metallic iron content, eliminates binder-induced impurities, and achieves cost efficiency while fulfilling transportation durability specifications.

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