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## IMPROVING GRINDING BALL LIFESPAN AND EFFICIENCY THROUGH HARDENABILITY MODELLING AND OPTIMIZATION

### ABSTRACT

Grinding balls are spherical or cylindrical components used in grinding and milling operations to reduce the size of particles and achieve a finer product. They are made of high chromium white cast iron (HCWCI) and used in a variety of industrial processes. The efficiency of the grinding process is heavily influenced by the properties of the grinding balls, including their composition, size, and hardness. As such, there is ongoing research and development to improve the performance and durability of grinding balls, with the aim of countering the extreme conditions of wear and impact that cause a reduction in their lifespan. This study involved austenitizing balls with diameters of 50 mm and 70 mm at temperatures of 950°C and 1050°C, followed by quenching using both oil and compressed air. By exploiting the experimental HRC hardness results obtained in this work, the study aims to find a mathematical model relating the response (hardenability) to the main effects (austenitization temperature, quenching medium, and diameter balls) and their interactions. Analysis of variance (ANOVA) was used to establish the statistical significance parameters and an optimization of response by the best sub-models method and by the desirability function is realized in the second part of this work. It seems that the austenitization temperature and the size of the balls have a stronger impact on the hardenability of the balls than the cooling rate (quenching medium) by reducing the hardness difference between the surface and the medium of the ball to minimal values.

**Keywords:** *Grinding ball; HCWCI; Hardenability; Optimization; Desirability function*

### INTRODUCTION

High chromium cast irons (HCWCI) are a type of wear-resistant material that are commonly used in the mining, cement, and power generation industries, where they are used in a variety of applications such as grinding balls, liners, and hammers. [1-3]. High-chromium white cast irons are ferrous alloys containing 11-30% Cr and 1.8-3.6% C along with other alloying elements such as molybdenum and nickel [4,5]. The high chromium content in these cast irons provides them with excellent wear resistance, as chromium carbides are formed in the microstructure of the material. The  $(Cr, Fe)_7C_3$  or  $M_7C_3$  hard eutectic carbides act as a barrier against the abrasive particles and prevent them from causing damage to the surface of the material. The initial morphology of the material can be changed significantly by using different heat treatments. Specifically, utilising critical and subcritical heat treatments can

lead to the precipitation of secondary carbides and the transformation of austenite into a harder structure such as martensite.

Various research efforts have been focused on the formation, morphology and characteristics of the secondary carbides formed during the heat treatments. The formation of secondary carbides depends on a number of factors, including the chemical composition, the temperature and duration of the heat treatment, and the cooling rate after heat treatment. The morphology and characteristics of the carbides can also vary depending on these factors [5,6-12]. These carbides can have different crystal structures, sizes, and distributions within the matrix, and can affect properties such as hardness, wear resistance, and toughness [11,13,14]. Quenching is a heat treatment process that involves rapid cooling of a material from a high temperature to a lower temperature, usually in a liquid or gas medium such as water, oil, or air. By rapidly cooling the material, the atoms within it are forced to solidify in a more tightly packed arrangement, which can result in increased hardness, strength, and other desirable properties. However, it's worth noting that quenching can also introduce some potential drawbacks, such as increased brittleness and the risk of distortion or cracking. For this reason, it's important to carefully control the quenching process to ensure that the material is cooled in a way that produces the desired properties without introducing any negative effects. [2,15-19].

A two-compartment ball mill is a type of grinding mill used in the mining and cement industries for the reduction of particle size of various materials. The mill consists of two compartments or chambers separated by a partition or diaphragm (Figure 1). The first compartment of the mill is shorter where larger balls (90, 80, 70, 60 mm) are used. The second compartment of the mill is longer than the first compartment and is designed to further grind the material to a finer particle size. The grinding balls in the second compartment are usually smaller (below 60 mm) [20]. Grinding balls are subjected to various wear mechanisms, including abrasion, corrosion, and impact. These mechanisms can cause the grinding balls to wear down over time, reducing their effectiveness in the milling process. To mitigate the effects of wear on grinding balls, one common approach is to use harder materials or add alloying elements to increase wear resistance. In addition, controlling the pH level and temperature of the grinding environment can also help reduce corrosion and extend the life of the grinding balls [21].

Hardenability is the capability of a material to be hardened by heat treatment, typically by quenching in a cooling medium such as water or oil. The hardenability is influenced by several factors, including the chemical composition, microstructure, and heat treatment process. Alloy elements such as chromium, molybdenum, and nickel, help to improve the hardenability.

In the case of grinding balls, hardenability is a critical factor because it determines the ball's ability to withstand the wear and tear of grinding operations [6,12,22]. Statistical methods such as the design of experiments (DOE) can be used to model and optimize the hardenability of grinding balls. Design of experiments (DOE) is a systematic approach to planning, conducting, and analyzing experiments. It involves manipulating one or more variables of interest and measuring the effect of those changes on a response variable. The goal of DOE is to identify the factors that have the greatest impact on the response variable and optimize the experimental conditions to achieve the desired outcome [16]. The DOE full factorial is to test and evaluate all combinations of all factors at all levels, allowing any number of factors and levels to be fully combined with the experimental design, taking into account all possible test conditions. The biggest advantage of the DOE full factorial is that the amount of information is large, and the main effect size of each experimental factor and the interaction effect between the various factors can be accurately estimated.

Both the best sub-models method and the desirability function are commonly used techniques for optimizing responses in experimental design. The best sub-models method is an approach to optimization in which a large number of potential models are created, and the best sub-set of these models is selected based on certain criteria such as coefficient of determination, also known as R-squared [23]. The desirability function, on the other hand, involves combining multiple response variables into a single overall "desirability" score. This approach is particularly useful when dealing with multiple objectives that may be in conflict with one another. By assigning weights to each response variable, the desirability function creates an overall score that reflects the researcher's priorities [24,25].

The objective of this research was to model and optimize the hardenability of grinding balls made from high chrome white cast iron. The aim was to identify the factors that influence this property and to obtain a final product with high hardness and wear resistance. The factors considered are austenitization temperature, quenching medium, and diameter balls.

Based on the experimental results of HRC hardness obtained in this work, a full factorial Design of Experiments (DOE) was selected with three factors at two levels each. The purpose of this DOE is to develop a mathematical model that correlates the response (hardenability of grinding balls) to the main effects and interactions that were withheld. In this work, the response (hardenability) was optimized using both methods (best sub-models method and desirability function).

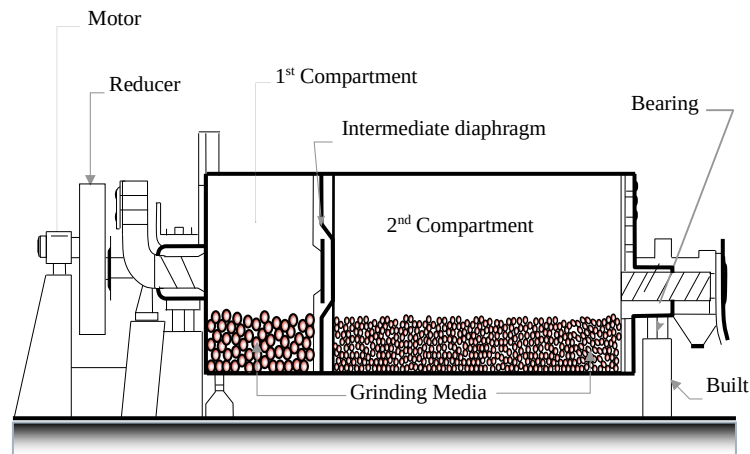


Fig. 1. Two-compartment ball mill

## PROCEDURES AND TECHNIQUES

### *Material used and structure*

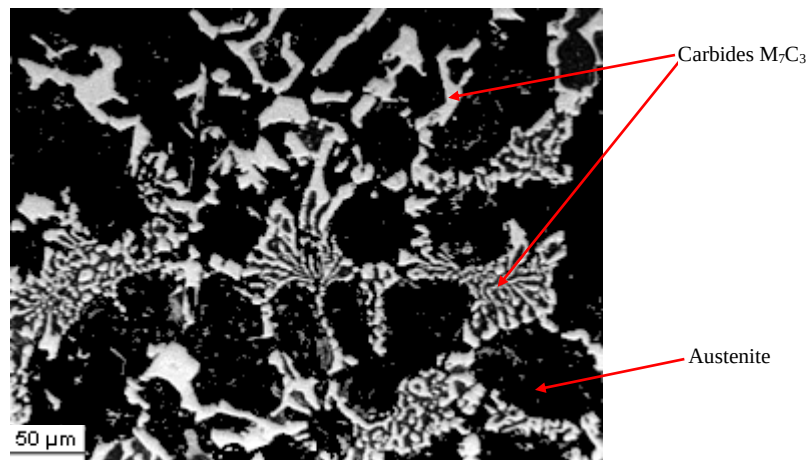
In the current investigation, grinding balls having dimensions of 50 mm and 70 mm in diameter were employed. These balls' chemical make-up is shown in Table 1 based on result from an X-ray fluorescence examination.

**Table 1.** Chemical composition (wt %) of HCWCI

| C    | Si   | Mn   | P    | S     | Cr   | Mo   | Ni   | Cu   | Fe  |
|------|------|------|------|-------|------|------|------|------|-----|
| 2.68 | 0.50 | 0.58 | 0.06 | 0.075 | 13.0 | 0.52 | 0.27 | 0.15 | Bal |

The as-cast structure of high chromium white cast iron typically consists of a matrix of austenite interspersed with eutectic carbides. Depending on the material's chromium content, eutectic carbides are typically of two types:  $M_7C_3$  carbides and  $M_{23}C_6$  carbides.

The as-cast structure of the material investigated in this study (with a carbon content of 2.68% and chromium content of 13.0%) comprises an austenite matrix that is interspersed with  $M_7C_3$  carbides, as depicted in Figure 2.

**Fig. 2.** As-cast structure of HCWCI (Grinding balls, C%=2.68; Cr%=13.0)

### Heat treatments

The heating of balls at 950°C and 1050°C was carried out in a muffle electric furnace with silicon carbide rod heaters and an isothermal holding at these temperatures.

The aim of these treatments is twofold. They allow in the first step, to study the influence of the mass effect on the hardness of grinding balls, on the one hand, and on the other, to study the repercussions of the size of balls on the mass effect. The treated balls were quenched in compressed air and in oil used at room temperature.

### Hardness tests

The hardness test is frequently used to evaluate the hardness of many cast parts and in particular the grinding balls, because it is easy to achieve, non-destructive and it directly provides information on the overall hardness of these parts.

The Rockwell hardness HRC measurements, carried out in this work, are made on the treated balls 50 and 70 mm in diameter starting from the outer surface to the middle of the ball and this by a progressive decrease in the thickness of ball. The test surface is carefully prepared and made smooth and flat.

These tests were carried out using a hardness tester of the HP250 type (220 V / 50 HZ / 6 A) equipped with a conical diamond indenter with an angle at the top of 120° and rounded at its top (R = 0.2 mm).

## Methodology

To model and optimize the hardenability of grinding balls, several steps can be taken, Figure 3.

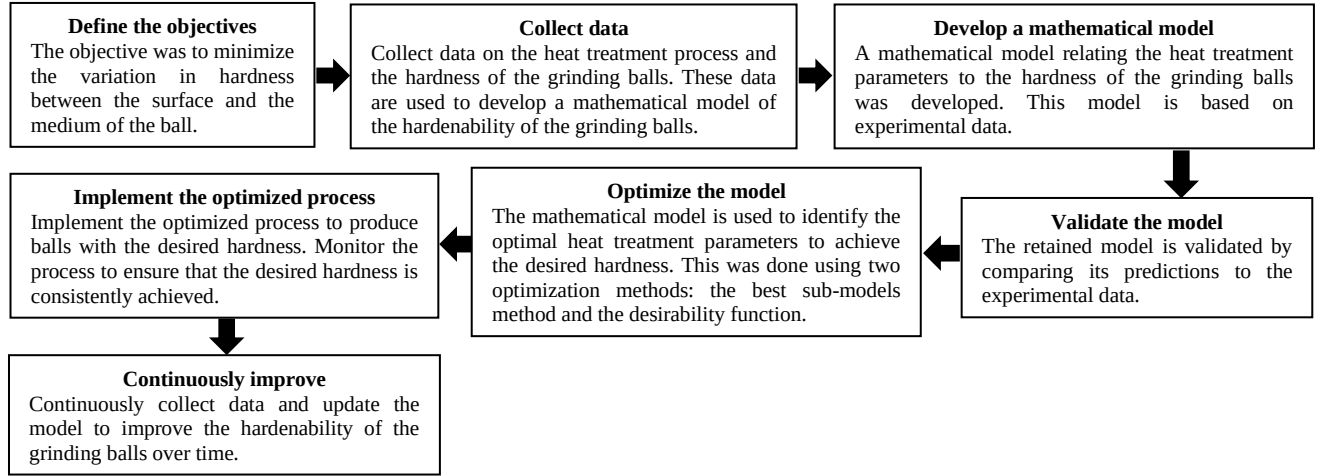


Fig. 3. Steps for modelling and optimizing the hardenability of grinding balls

## EXPERIMENTAL RESULTS

### Influence of the austenitization (destabilization) temperature

The mass effect, which results in a reduction in ball surface hardness towards its core ( $E_H$ : hardness deviation), is evaluated based on the austenitization temperature. This evaluation is performed for 50 mm diameter balls that have been quenched in compressed air and oil, as depicted in Figures 4 and 5.

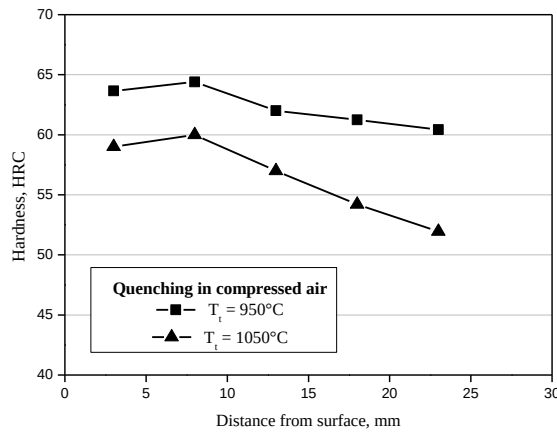


Fig. 4. HRC as a function of the austenitization temperature for balls 50 mm in diameter

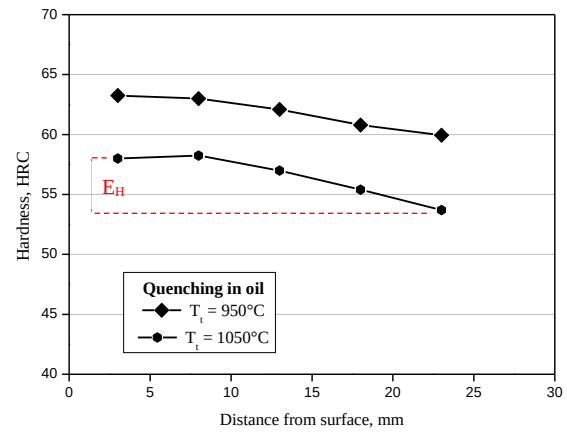
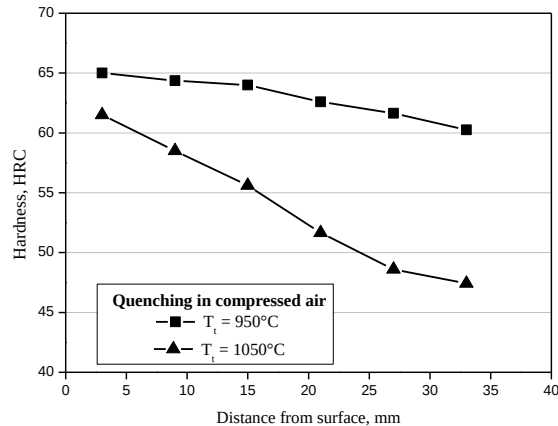


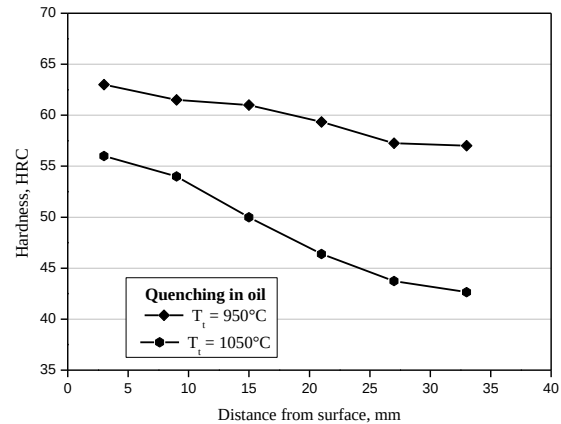
Fig. 5. HRC as a function of the austenitization temperature for balls 50 mm in diameter

Figures 6 and 7 shows the variation of the hardness HRC as a function of the austenitization temperature for balls 70 mm in diameter. The disparity in hardness between the outer and inner layers of balls 50 and 70 mm in diameter heated at  $1050^\circ\text{C}$  and cooled

with compressed air and oil is more important compared to that of balls with the same diameters heated at 950°C and cooled in compressed air and oil.



**Fig. 6.** HRC as a function of the austenitization temperature for balls 70 mm in diameter



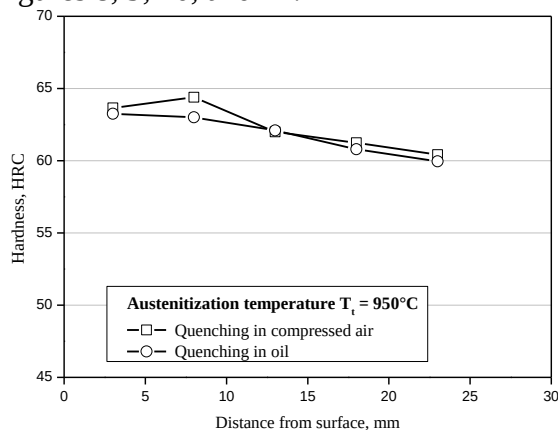
**Fig. 7.** HRC as a function of the austenitization temperature for balls 70 mm in diameter

When the 50 mm and 70 mm diameter balls are heated to 950°C and then cooled using compressed air and oil (Figures 4, 5, 6, and 7), the impact of thermal gradient is minimized. As a result, there is a reduced temperature difference between the outer and inner layers of the balls. This leads to a lesser contrast in hardness between these layers. Consequently, a harder and more brittle microstructure, is formed between the outer and inner layers, its martensite.

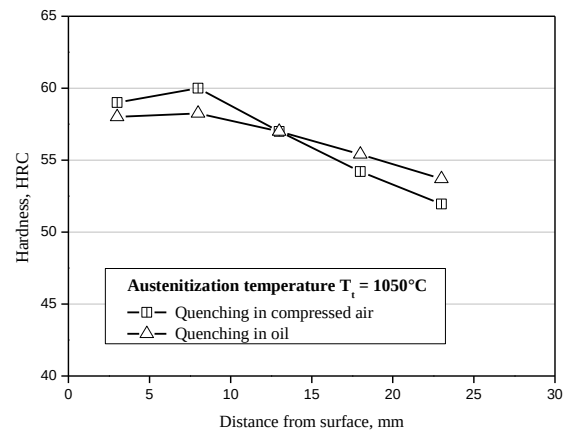
However, when larger balls with a diameter of 70 mm are heated to higher temperatures of 1050°C, the thermal gradient effect becomes more evident, as depicted in Figures 6 and 7. Despite the use of two different cooling fluids amplifies the discrepancy in hardness between the layers, resulting in the formation of softer phases like bainite within the inner region of the balls.

### *Influence of quenching medium*

The results that highlight the influence of the quenching medium on the variation of the hardness of the surface towards the core of balls 50 and 70 mm in diameter are shown in Figures 8, 9, 10, and 11.



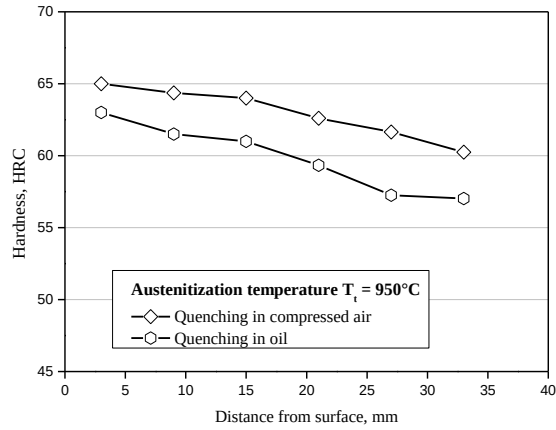
**Fig. 8.** Influence of quenching medium of the hardness of balls 50 mm in diameter



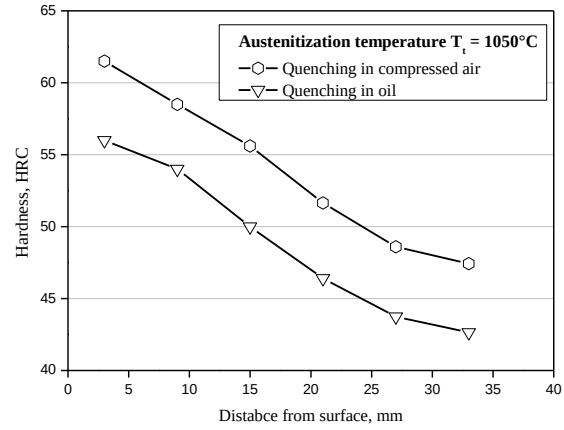
**Fig. 9.** Influence of quenching medium of the hardness of balls 50 mm in diameter

There is no significant variation in hardness between the surface and core of 50 mm diameter balls when they are heated to 950°C and quenched in both compressed air and oil (Figure 8). However, when the balls are heated to 1050°C and rapidly cooled using compressed air and oil, a noticeable increase in the difference in hardness is observed (Figure

9). This increase in hardness difference is more pronounced from the outer layer to the inner layer. Compressed air provides a relatively rapid cooling rate, leading to the formation of harder microstructures. However, oil as a cooling medium provides a slower cooling rate, allowing for partial transformation of austenite into other phases less hard.



**Fig. 10.** Influence of quenching medium of the hardness of balls 70 mm in diameter

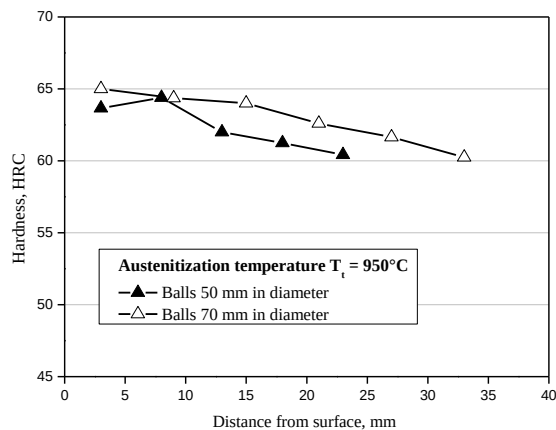


**Fig. 11.** Influence of quenching medium of the hardness of balls 70 mm in diameter

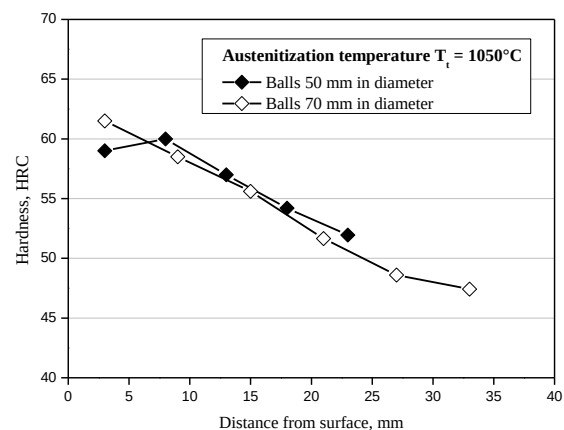
The smaller variations in hardness between the surface and the core are evident when balls with a diameter of 70 mm are heated to a temperature of  $950^{\circ}\text{C}$  and then rapidly cooled in compressed air and oil (Figure 10). Those heated at  $1050^{\circ}\text{C}$  and quenched in compressed air and oil show very significant variations in the hardness between the surface and the core, due to higher thermal gradient effects (Figure 11). This temperature facilitates the growth of austenitic grains, leading to a decrease in the required transformation time and impacting the resulting microstructure. It is also noted that the austenitization temperature at  $1050^{\circ}\text{C}$  has a more significant impact on the hardenability, than the influence of the quenching medium choice.

### *Influence of the size of balls*

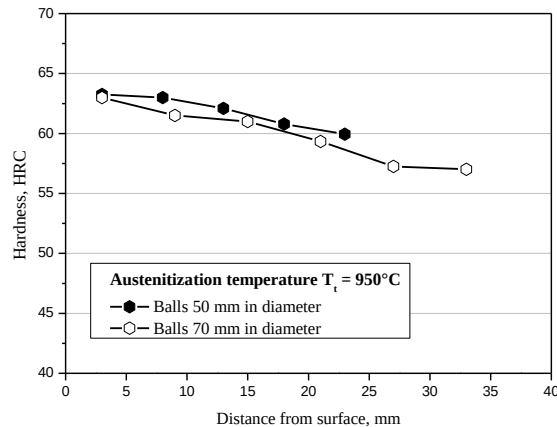
Figures 12 and 13 depict the results of hardness HRC measurements conducted on 50 mm and 70 mm diameter balls that were subjected to quenching in compressed air. The results concerning balls quenched in oil are the subject of Figures 14 and 15.



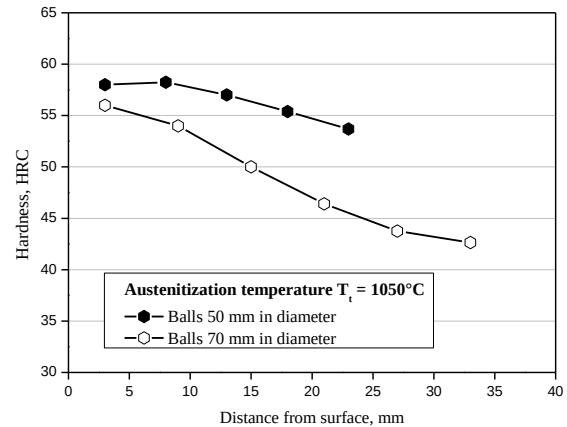
**Fig. 12.** Comparison of the hardness of balls cooled in compressed air



**Fig. 13.** Comparison of the hardness of balls cooled in compressed air



**Fig. 14.** Comparison of the hardness of balls cooled in oil



**Fig. 15.** Comparison of the hardness of balls cooled in oil

The suitability to take the quench or to harden in the depth of balls 50 and 70 mm in diameter treated at  $950^\circ\text{C}$  and cooled in compressed air and oil is greater as a result of the hardness values levied, which remains excellent between the surface and the core.

However, balls 50 mm in diameter heated at  $1050^\circ\text{C}$  and quenched with compressed air and oil have higher hardness differences from the surface to the core.

These deviations become more pronounced for balls 70 mm in diameter, which have low hardenability.

Thus, the differences in hardness in balls 50 and 70 mm in diameter treated at  $950^\circ\text{C}$  and quenched in compressed air and oil are lower, and the martensite transformation is almost uniform throughout the mass (Figures 12 and 14).

An increase in the size of balls causes the degradation of the hardenability of these balls (Figures 13 and 15), especially those with 70 mm in diameter heated at  $1050^\circ\text{C}$ .

It is noted that disparity in hardness becomes more pronounced as the balls diameter increases and is further accentuated with higher austenitization temperatures.

## STATICAL ANALYSIS

### *Design of Experiments (DOE) adopted*

The several factors considered in this study that can affect the disparity in hardness (response) between the outer layer and the inner core of the balls are described in Table 2. The proposed plan consists of conducting eight distinct trials without any repetition. This design is built upon three independent factors, each with two different levels.

**Table 2.** Factors and levels (actual and codes)

| Factor                                                                                   | Symbol | Type of factor | Coded levels | Actual levels  |
|------------------------------------------------------------------------------------------|--------|----------------|--------------|----------------|
| Austenitization temperature (°C)                                                         | F1     | Numeric        | -1           | 950 °C         |
|                                                                                          |        |                | 1            | 1050 °C        |
| Quenching medium                                                                         | F2     | Categoric      | -1           | Compressed air |
|                                                                                          |        |                | 1            | Oil            |
| Diameter of grinding balls (mm)                                                          | F3     | Numeric        | -1           | 50 mm          |
|                                                                                          |        |                | 1            | 70 mm          |
| Response (y): Difference of hardness between the surface and the core of the balls (HRC) |        |                |              |                |

### Response values

The experimental results expressing the difference in hardness between the surface and the core of balls are shown in Table 3.

**Table 3.** Experimental results

| Experience | F1 | F2 | F3 | Response (y) (HRC) | Corresponding figure |
|------------|----|----|----|--------------------|----------------------|
| 1          | -1 | -1 | -1 | 3.24               | Figure 4             |
| 2          | 1  | -1 | -1 | 7.05               | Figure 4             |
| 3          | -1 | 1  | -1 | 3.3                | Figure 5             |
| 4          | 1  | 1  | -1 | 4.3                | Figure 5             |
| 5          | -1 | -1 | 1  | 4.75               | Figure 6             |
| 6          | 1  | -1 | 1  | 14.07              | Figure 6             |
| 7          | -1 | 1  | 1  | 5.98               | Figure 7             |
| 8          | 1  | 1  | 1  | 13.35              | Figure 7             |

### Factors influencing the hardenability

The results of the analysis of variance (ANOVA) are presented in Table 4.

**Table 4.** Analysis of variance (ANOVA)

| Factors and interactions | SS      | DF | MS      | F        | P < 0.05 | Model terms     |
|--------------------------|---------|----|---------|----------|----------|-----------------|
| F1                       | 57.7812 | 1  | 57.7812 | 625.0000 | 0.025451 | Significant     |
| F2                       | 0.5940  | 1  | 0.5940  | 6.4256   | 0.239211 | Not Significant |
| F3                       | 51.3085 | 1  | 51.3085 | 554.9859 | 0.027007 | Significant     |
| F1 by F2                 | 2.8322  | 1  | 2.8322  | 30.6349  | 0.113792 | Not Significant |
| F1 by F3                 | 17.6418 | 1  | 17.6418 | 190.8253 | 0.046005 | Significant     |
| F2 by F3                 | 1.2800  | 1  | 1.28000 | 13.8453  | 0.167142 | Not Significant |
| Error                    | 0.0925  | 1  | 0.0925  |          |          |                 |
| Total SS                 | 131.530 | 7  |         |          |          |                 |

The first factor (austenitization temperature), the third factor (diameter of grinding balls), and their interaction (F1F3) are shown to have statistically significant effects, as illustrated in Table 4. The impact of the second factor and the interactions between factors F1F2 and F2F3 are moderately influential. Interaction F1F2F3 is completely absent.

### Modelling of the hardenability of grinding balls

The complete model of the hardness deviation as a function of all coded factors and interactions is given by equation (1):

$$y = E_H = b_0 + b_1F1 + b_2F2 + b_3F3 + b_{12}F1F2 + b_{13}F1F3 + b_{23}F2F3 \quad (1)$$

This model with the respective actual values takes the form (equation 2):

$$y = 7.005 + 2.6875T_t - 0.2725Q_m + 2.5325D_b - 0.595T_tQ_m + 1.485T_tD_b + 0.4Q_mD_b \quad (2)$$

With  $y = E_H$ : Hardness deviation (response),  
 $F1 = T_t$ : Austenitization temperature ( $^{\circ}\text{C}$ ),  
 $F2 = Q_m$ : Quenching medium

$F3 = D_b$ : Diameter of ball (mm).

### Optimization of the hardenability of grinding balls

The choice of sub-models is based on the model's quality and a search for the simplest model that nonetheless accurately describes the data. These latter are deduced from the complete model by removing at least one monomial, apart from the constant component  $b_0$ . The possibility that the sub-model is only equal to  $b_0$  was excluded.

The sub-models were sorted in a descending order based on the coefficient of determination  $R^2$  value, as shown in Table 5. Among the best sub-models, those without monomials were identified. This allows deducing the factors and the corresponding interactions, having the least influence on the quality loss of the complete model. They can therefore be considered as regarding little influence on the response since their absence has little effect on the quality and the predictive aspect of the modelling.

For an initial model with  $p$  coefficients (therefore with  $p$  monomials),  $(p-1)!$  sub-models are found [23].

**Table 5.** Determination of best sub-models

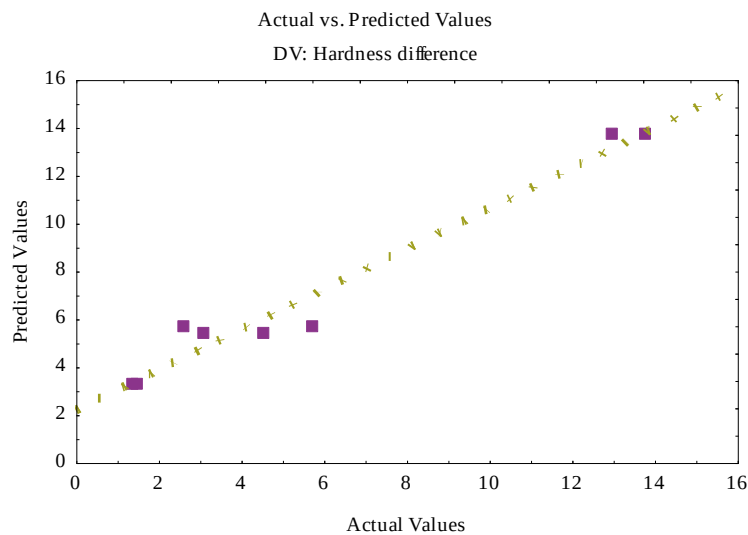
|                            | Sub-models formed                                                                                | R-squared   |
|----------------------------|--------------------------------------------------------------------------------------------------|-------------|
| Best Sub-models            | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m + 2.5325 D_b - 0.595 T_t Q_m + 1.485 T_t D_b + 0.4 Q_m D_b$ | 0.999297120 |
|                            | $y = 7.005 + 2.6875 T_t + 2.5325 D_b - 0.595 T_t Q_m + 1.485 T_t D_b + 0.4 Q_m D_b$              | 0.994780666 |
|                            | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m + 2.5325 D_b - 0.595 T_t Q_m + 1.485 T_t D_b$               | 0.989565514 |
|                            | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m + 2.5325 D_b + 1.485 T_t D_b + 0.4 Q_m D_b$                 | 0.977764422 |
|                            | $y = 7.005 + 2.6875 T_t + 2.5325 D_b + 1.485 T_t D_b$                                            | 0.963516364 |
|                            | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m + 2.5325 D_b - 0.595 T_t Q_m + 0.4 Q_m D_b$                 | 0.865169748 |
|                            | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m + 2.5325 D_b - 0.595 T_t Q_m$                               | 0.855438143 |
|                            | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m + 2.5325 D_b + 0.4 Q_m D_b$                                 | 0.843637051 |
| Moderately good Sub-models | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m - 0.595 T_t Q_m + 1.485 T_t D_b + 0.4 Q_m D_b$              | 0.609208380 |
|                            | $y = 7.005 + 2.6875 T_t - 0.595 T_t Q_m + 1.485 T_t D_b + 0.4 Q_m D_b$                           | 0.604691926 |
|                            | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m - 0.595 T_t Q_m + 1.485 T_t D_b$                            | 0.599476774 |
|                            | $y = 7.005 + 2.6875 T_t + 1.485 T_t D_b$                                                         | 0.573427623 |
|                            | $y = 7.005 + 2.5325 D_b - 0.595 T_t Q_m + 1.485 T_t D_b + 0.4 Q_m D_b$                           | 0.555480414 |
|                            | $y = 7.005 + 2.5325 D_b + 1.485 T_t D_b$                                                         | 0.524216112 |
|                            | $y = 7.005 + 2.6875 T_t - 0.2725 Q_m - 0.595 T_t Q_m + 0.4 Q_m D_b$                              | 0.475081008 |
|                            | $y = 7.005 + 2.6875 T_t$                                                                         | 0.439300252 |
|                            | $y = 7.005 + 2.5325 D_b$                                                                         | 0.390088740 |
| Less good Sub-models       | $y = 7.005 + - 0.2725 Q_m - 0.595 T_t Q_m + 1.485 T_t D_b + 0.4 Q_m D_b$                         | 0.169908128 |
|                            | $y = 7.005 + 1.485 T_t D_b + 0.4 Q_m D_b$                                                        | 0.143858977 |
|                            | $y = 7.005 - 0.2725 Q_m + 1.485 T_t D_b$                                                         | 0.138643825 |
|                            | $y = 7.005 - 0.2725 Q_m - 0.595 T_t Q_m + 0.4 Q_m D_b$                                           | 0.035780756 |
|                            | $y = 7.005 - 0.595 T_t Q_m + 0.4 Q_m D$                                                          | 0.031264303 |
|                            | $y = 7.005 - 0.2725 Q_m + 0.4 Q_m D_b$                                                           | 0.014248059 |
|                            | $y = 7.005 - 0.2725 Q_m$                                                                         | 0.004516453 |

Following sub-model classification based on the  $R^2$  coefficient of determination, the following results are reached:

- The best model remains the complete model.
- The best sub-models are those for which the second factor ( $F2$ ) and interactions with other factors (interactions  $F1F2$  and  $F2F3$ ) have been removed. These terms seem to

have a limited role in the adjustment quality. This remark has already been noted by ANOVA (Table 4) and the study of model coefficients.

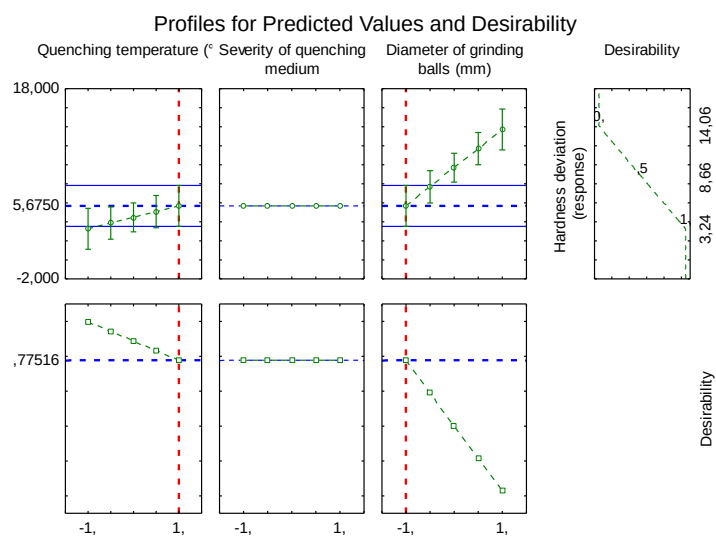
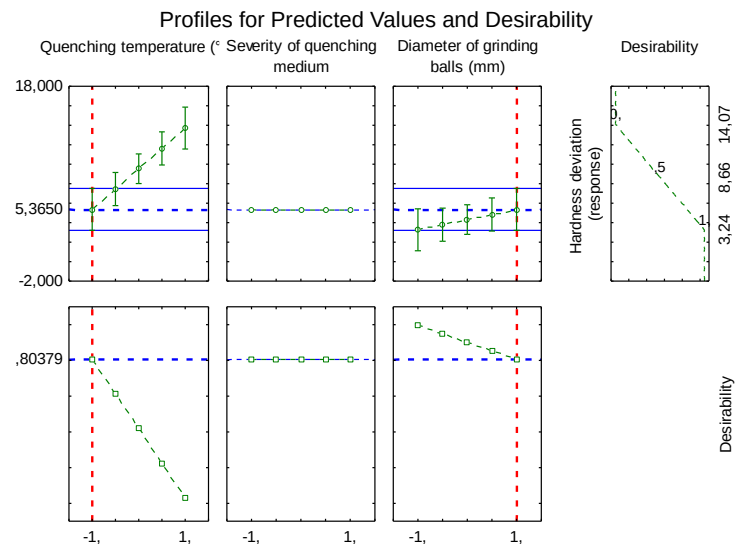
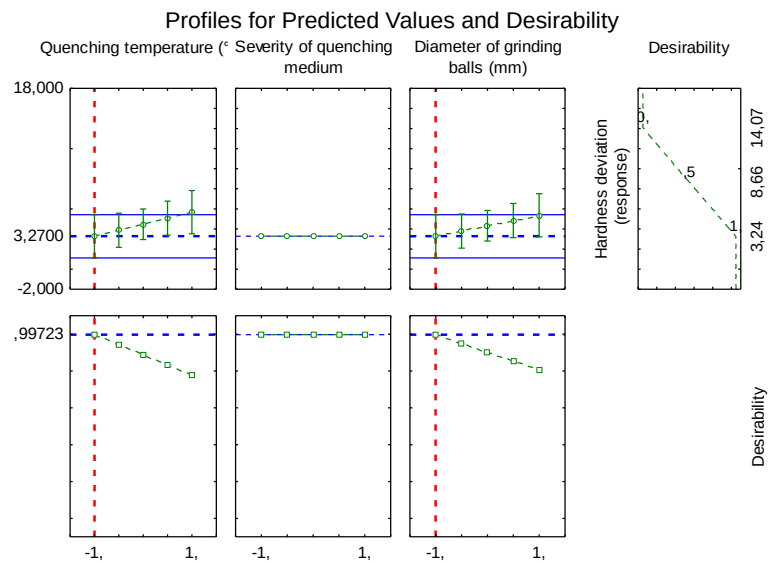
- The sub-model  $y = 7.005 + 2.6875 T_t + 2.5325 D_b + 1.485 T_t D_b$  can be judged of sufficient quality and considered as the model capable to explain the hardenability of grinding balls. Its coefficient of determination is interesting ( $R^2 = 0.963$ ). This model allows us to reduce half the number of experiments.
- The second factor is eliminated from this sub-model because the interactions of this factor with the other factors are insignificant.
- The elimination of one of the main factors ( $F1$ ,  $F3$ ) greatly influences the adjustment quality and strongly decreases  $R^2$ .
- By comparing the sub-models ( $y = 7.005 + 2.6875 T_t + 1.485 T_t D_b$ ) and ( $y = 7.005 + 2.5325 D_b + 1.485 T_t D_b$ ). A greater correlation exists between the response and the first factor ( $T_t$ ) than between the same response and the third factor ( $D_b$ ).
- The experimental data were compared to the predicted values by the maintained model, as shown in Figure 16. According to this graph and the  $R^2$  value (Table 5), the model selected is satisfactory, and the predicted values are in very good agreement with the measured values.

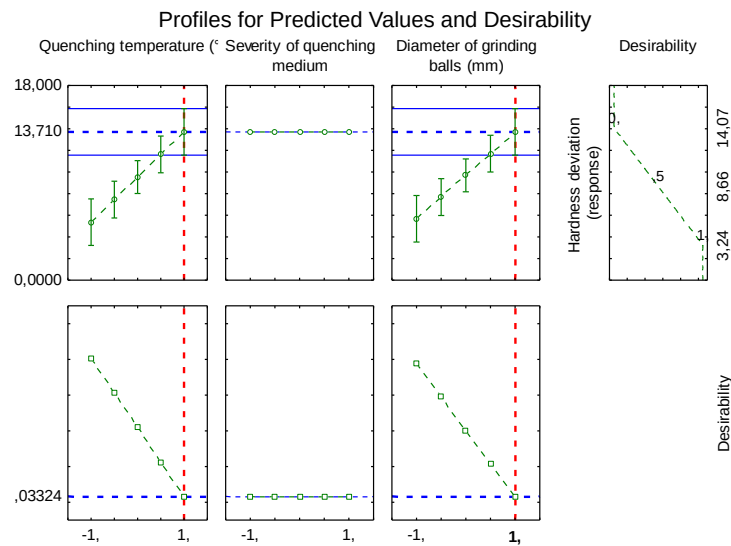


**Fig. 16.** Comparison between actual (observed) and predicted values for hardness difference

To find the optimum hardness deviation between the surface and the core of the ball, the desirability function integrated into the STATISTICA software was used. It makes it possible to determine the levels of selected factors  $F1$  and  $F3$  (Figures 17a, 17b, 17c and 17d).

The value of 0 (zero) is assigned to the desirability when the hardness deviations are very important (unacceptable or undesirable) and that of 1 (one) when these differences are minimum (desirable).





**Fig. 17d.** Desirability of the hardness difference for the considered factors F1 (level: +1) and F3 (level: +1)

Table 6 consolidates the values of the hardness deviation and their corresponding desirability as shown in Figure 17a-d.

**Table 6.** Desirability of the hardness deviation for factors considered F1 and F3 at different levels

|       | Austenitization temperature (F1) | Diameter of grinding balls (F3) | Optimal value of the hardness deviation | Desirability |
|-------|----------------------------------|---------------------------------|-----------------------------------------|--------------|
| Level | -1 (950 °C)                      | -1 (diameter 50)                | 3.27                                    | 0.99723      |
|       | -1 (950 °C)                      | +1 (diameter 70)                | 5.365                                   | 0.80379      |
|       | +1 (1050 °C)                     | -1 (diameter 50)                | 5.675                                   | 0.77516      |
|       | +1 (1050 °C)                     | +1 (diameter 70)                | 13.71                                   | 0.03324      |

Observing Table 6, it is evident that a larger ball diameter leads to a greater disparity in hardness. This difference becomes more pronounced as the austenitization temperature rises. The minimum value of the hardness deviation of 3.27 is obtained for a desirability of 0.99723, in this case, the balls have a low toughness to their central zone i.e., poor resistance to impact. If the hardness deviation increases (5.365 and 5.675), the toughness is moderate in the middle of the ball and the hardness at the surface remains high. For a larger difference (13.71), the ball loses its wear resistance in the central zone.

## CONCLUSIONS

The results obtained in this study allow drawing the following conclusions:

- The austenitization temperature (quenching temperature) and the size of the balls have a greater effect on the hardenability of the balls than the quenching medium (severity of quenching medium). This appears to be caused by the close values of the cooling rates of air and oil.
- The wrong capability of balls to accept quenching or to harden in depth is influenced more by the overheating of balls at the austenitization temperature of 1050°C than by the quenching medium. Heating to this temperature will cause the magnification of austenitic grain and the degradation of the hardenability of the material.

- The mass effect is more significant when the size of balls increases and especially with the increasing austenitization temperature. The quenching medium influences significantly the hardenability of balls by its interaction with the austenitization temperature.
- A mathematical model is established in this work. It only takes into consideration the first factor (austenitization temperature), the third factor (diameter of balls) and the interaction between these two factors.
- The values predicted by this model are in good agreement with the experimental values, which allowed us to judge the sufficient quality of this model and considered it as the model likely to explain the hardenability of grinding balls.
- Finally, to minimize the difference in hardness between the surface and the core of balls (improve hardenability), a wise choice would therefore be that of a low level of the austenitization temperature and the use of compressed air cooling on the small diameter balls.
- To maintain the peripheral hardness of balls, reduce that of their central zone, and increase their toughness, the choice would be between a low level of the austenitization temperature on the large diameter balls, cooled in compressed air, or that of a high level of the austenitization temperature on the small diameter balls, cooled in a more severe quenching medium (cooling in oil).

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### Authors' contributions

Methodology, Ali Safa and Sahraoui Aissat; Analysis and investigation, Ali Safa and Sahraoui Aissat; bibliographical sources, Ali Safa; writing original and review the manuscript, Ali Safa and Sahraoui Aissat. The final published version of the paper has been read and approved by all authors.

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### Conflicts of Interest

The authors declare that there is no conflict of interest.

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