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Optimization of Mechanical and Tribological Performance of Powder Metallurgy Processed Cobalt Chromium Reinforced Bronze Hybrid Composites Using the Taguchi Technique

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Abstract:

The effect of material composition, compaction pressure, sintering time and sintering temperature on the mechanical and tribological properties of powder metallurgy bronze based composites were investigated. Fabrication of pure bronze, bronze reinforced with 5% of Co, 5% of Cr and hybrid reinforcement of 2.5 % of Co + 2.5 % of Cr was done by powder metallurgy technique. The processing parameters were optimized using Taguchi L16 orthogonal array and responses were evaluated in term of Vickers hardness, compressive strength and wear rate;. Statistical analysis such as ANOVA, Taguchi signal to noise ratio analysis, regression modeling and Gray Relational Analysis were performed to find out the significant factors and to optimize the overall performance. The results indicated that the most influential parameter was the material composition followed by the compaction pressure. The hybrid Co-Cr reinforced composite showed the best overall performance with a maximum hardness of 132 VHN, compressive strength of 382 MPa, and minimum wear rate of 0.0032 mm³ /m under the optimized processing conditions. The improved properties are attributed to the increased densification, reduced porosity, enhanced inter-particle bonding, effective load transfer and complementary Hall-Petch and Orowan strengthening mechanisms that also contributed to the superior wear resistance. The results show that hybrid reinforcement using Co–Cr is an effective strategy for improving mechanical strength and wear resistance of bronze-based composites for advanced engineering applications.

Keywords: Bronze, Powder Metallurgy, Sintering. Compaction Pressure, Hardness, Wear.

1. Introduction:

Composite substances are created through mixing two or more different materials to create a material with particular characteristics. They frequently offer greater performance, such as increased mechanical strength, decreased weight, and enhanced physical characteristics, and their design is easily configurable. They also offer cost and maintenance advantages [1], [2]. These days, they are frequently utilized in numerous applications.

In an attempt to enhance their mechanical and physical qualities, materials known as metal-matrix composites (MMC) [3] are created by combining one or more reinforcements with a metallic matrix [4], [5]. Since they are able to offer enhanced electrical, mechanical, and magnetic capabilities, ceramic reinforced MMCs have attracted a lot of attention [6]. The

following are typical matrix metals: Fe [7], Cu [8], Mg [9], Zn [10], and Al [11]. The purpose of the extra reinforcements is to adjust the characteristics and strengthen the base metal [12]. Ceramics are typically used as reinforcement for MMCs due to their high melting point, low density, high strength, and resistance to wear. are carbides of silicon, chromium, titanium, boron, niobium, cobalt, chromium, and aluminum nitride [13].

With its high melting point, low coefficient of thermal expansion, superior electrical and thermal conductivities, and strong resistance to corrosion, copper is a promising material for industry. The automotive, aerospace, electrical sliding contact, and heat sink industries make substantial use of copper matrix composites (CMCs).

Cu-based MMCs are made incorporating various methods, such as powder metallurgy, stir casting, and ingot metallurgy. Three basic steps make up the powder metallurgy (PM) process: compaction, sintering, and mixing (blending) particles. To create a homogenous composite powder, the necessary ratios of the component powders were combined in a ball mill. After that, a die cavity is filled with the prepared composite powder, and a punch is used to compact it. The mechanical bonding of free powder particles is facilitated by the high compaction pressure, producing a solid with the desired shape. This solid component is known as the green compact. It is quite sensitive by nature and lacks the strength to work. The Green compact is heated to between 0.75 and 0.85 of the melting point of the principal element in order to facilitate solid-state diffusion during sintering. At high temperatures, solid state diffusion results in the replacement of weak mechanical bonds with strong metallic bonds. PM is one method for producing metal parts with a uniform, small microstructure. The approach facilitates the creation of unique property combinations by combining different types of materials [14], [15]. The PM methodology offers several benefits over alternative manufacturing techniques. Compared to melting methods, PM requires a lower manufacturing temperature. Unwanted stages are eliminated as a result. Another important factor is how affordable it is to produce near-net form parts [16]. Many materials, such as electrical contact materials [17], [18], copper alloys [19], metal matrix composites [20], [21], and most intermetallics [22], can be produced efficiently using the PM process. Density, hardness, and electrical conductivity all rise with increasing compaction pressure [23]. The effects of compaction pressure at 300, 400, 500, and 600 MPa on the microstructural properties, oxide content, hardness, and sintered iron surface topography were investigated by De Mello et al. As the compaction pressure increases, the porosity decreases and the powder particles become closer together. The findings show that high compaction pressure is invariably correlated with low porosity. Similarly, the pore dimensions of the composite is greatly influenced by the compacting pressure. When ductile-phase powder experiences permanent deformation under high compaction pressure, dense packing of powder particles occurs. Moreover, an increase in the effective particle contact area may lead to a decrease in the volume and porosity of the pores [24]. The impact of compacting pressure on the sintering behavior and pre-sintering density of fine molybdenum powder is investigated by Pranav Garg et al. Relative densities of 63%, 73%, and 79% were obtained at compaction pressures of 280, 560, and 840 MPa, respectively. Using dilatometer analysis, the master sintering curves (MSCs) for different compaction pressures are obtained experimentally. This study reduces the number of necessary sintering experiments and optimizes the process. Finer molybdenum particles densifies

significantly at each compaction pressure levels, with enhanced density increasing in proportion to the degree of compaction. [25]. Wen-Fung Wang claims that the hardness, sintered density, and green density of the composite are all greatly influenced by the compaction pressure [26]. At 500 MPa of compaction pressure, iron powder reaches its maximum density and hardness. According to Yongping Jin et al., the Cu-graphite composite shows exceptional mechanical parameters at 700 MPa of compacting pressure and 30 seconds of dwell time. When the compaction pressure rises above 700 MPa, the compaction effect is diminished and powder particles may begin to break. This study examines how powder milling affects many processes and traits [27]. In their investigation of the sliding wear characteristics of Cu+Sn+Cr composites made by powder metallurgy, Sreenivasa et al. discovered that the friction and wear characteristics of the material are improved by adding chromium metal powders as a reinforcement in the bronze matrix [28–30]. Tao et al. examined the effects of different oxygen concentrations on the mechanical characteristics and deformation mechanism of Ti-6Al-4V manufactured at low temperatures using powder metallurgy. According to the investigation, powder metallurgy Ti-6Al-4V shows remarkable mechanical property synergy with oxygen levels ranging from 1300 ppm to 4600 ppm. In particular, it attains greater elongation and strength at room temperature. Despite the significant suppression of basal dislocations, the significant improvement in dislocations is probably due to the significant increase in oxygen content between 1300 ppm and 4600 ppm [31], [32].

The literature mentioned above makes it evident that a number of PM process variables, including compaction pressure, sintering duration, and sintering temperature, have a greater impact on the hardness, microstructure, and tribological properties. The goal of the current project is to use PM to create a hybrid composite made of bronze that is strengthened with cobalt and chromium particles. The DOE technique is used to analyze extra wear rates and mechanical properties of the composites using different powder metallurgy process settings.

2. Experimentation:

2.1 Materials

Cobalt and chromium powders, each with an average particle size of 40 μm and a purity of 99.9%, were utilized as reinforcing materials, while bronze powder with an average particle size of 40 μm and a purity of 99.9% served as the matrix material. Every powder was purchased from M/s. Parashwamani Metals in Mumbai, India.

2.2 Fabrication Technique

Chromium, cobalt, and bronze powders are heated to 150⁰C for an hour in a hot air oven. It will eliminate the moisture from the powders. After being cooled to room temperature, the powder is put into a specially designed double-acting die for compaction. Zinc stearate is used as a die lubricant to facilitate the removal of green compacts and the 10 mm inside diameter of the die punch. Compaction is done at different compaction pressures of 450, 550, 650, and 750 MPa using a Universal Testing Machine. A three-minute relaxation interval is followed by a gradual application of force during compaction. After limited compression, the bronze, cobalt, and chromium particles are mechanically bonded together to form a un-sintered compact. Four samples are compacted for each combination of compaction pressure. The un-sintered compact

forms have little mechanical strength after pressing. Sintering strengthens Green Compact. Sintering was done in a tube furnace at 700, 750, 800, and 850°C for 2, 4, 6, and 8 hours in an inert argon atmosphere to prevent oxidation. The relevant properties of the bronze powder at ambient conditions are summarized in Table 1. Figure 1 shows the different stages of the powder metallurgy method and Figure 2 shows sintered specimens. Table 2 represents the parameters and levels of the powder metallurgy process.

Table 1. Characteristics of bronze powder

Properties	Bronze powder
Visual morphology	Reddish - Brown
Lattice configuration	FCC (copper-rich α phase)
Coeff. of thermal expansion	$18 \times 10^{-6}/^{\circ}\text{C}$
Density in g/cm^3	8.77
Melting Point in $^{\circ}\text{C}$	950

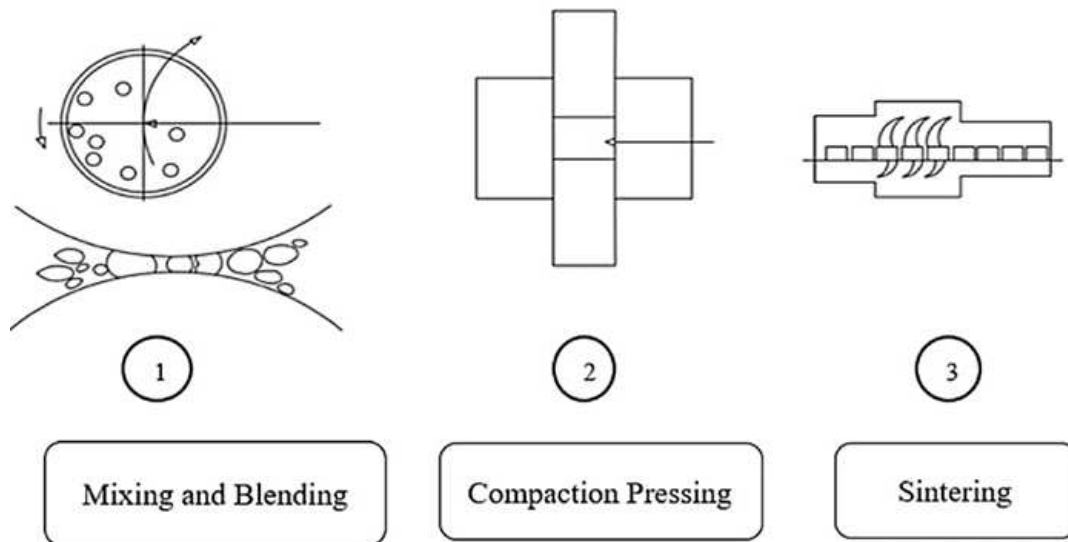


Figure 1. Powder metallurgy method Stages [33]



Figure 2. Sintered Specimens

Table 2. The parameters and levels of the powder metallurgy process.

Parameters	L1	L2	L3	L4
Material Composition (wt. %)	(S1) Pure Bronze	(S2) Bronze + 5 wt.% Co	(S3) Bronze + 5 wt.% Cr	(S4) Bronze + 2.5 wt.% Co + 2.5 wt.% Cr
Compaction Pressure (MPa)	450	550	650	750
Sintering Time (hr)	2	4	6	8
Sintering Temperature (°C)	700	750	800	850

2.3 Hardness Test

At the end of the powder metallurgy process, the samples' hardness is evaluated using the Vickers hardness test machine. The specimens were subjected to a 10 kg force for 30 seconds using a square-based pyramidal diamond indenter, and the Vickers hardness test was carried out in compliance with ASTM E92 standards. Each specimen was measured three times at three different places in order to mitigate the effects of particle segregation. The Vickers hardness number is determined using the following formula.

$$\text{VHN} = (2F \sin \theta / 2) / D^2$$

$$\text{VHN} = (1.8544F) / D^2$$

Where F = force applied (kgf),

θ = 136° face angle of diamond

D = mean diagonal of impression (mm)

2.4 Compression Test

Cylindrical specimens with a length of 25 mm and a diameter of 13 mm were tested for compression testing in a Universal Testing Machine (UTM) according to ASTM E9.

2.5 Wear Test

In compliance with ASTM G99, a pin-on-disc tribometer was used to assess the composites' dry sliding wear behavior. Sixteen samples were tested using a 20 N applied force, a 3 m/s sliding velocity, a 1500 m sliding distance, and 30 minutes. The sample's original weight was measured using an electronic balance with a single pan and a precision of 0.0001g. During the

test, the pin was pressed by spinning on a 65HRC EN32 steel disk with weight on the opposite side. The specimens were removed, cleaned with acetone, dried, and subsequently weighed after being exposed to a predefined sliding distance in order to measure the weight loss resulting from wear. The difference in weight computed prior to and following the test is used to assess the composite specimen's dry sliding wear behavior. [34] Figure 3 shows the pin-on-disc setup schematic diagram. The wear rate was calculated using the following equation.

$$\text{Wear Rate} = \frac{\text{weight loss}}{\text{distance}} \text{ g/m}$$

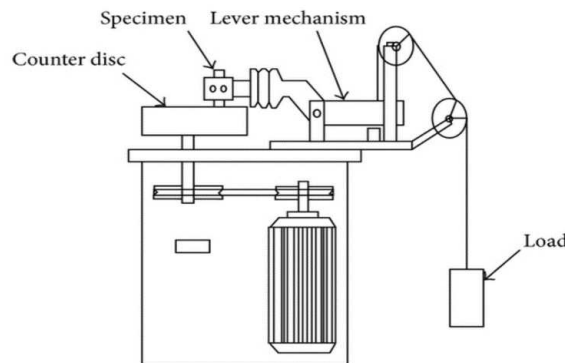


Figure 3. Set-up of pin-on-disc

3. Results:

3.1 Scanning electron microscopy (SEM)

Using a SEM, the shape and microstructure of the sintered objects are examined. Figure 4 depicts the features of the microstructures of the Bronze + 2.5 weight percent Co + 2.5 weight percent Cr composite at different compaction pressures. Powder particles have a lower effective contact area at low compaction pressure due to their weak plastic deformation. The separation of pores along the gaps between the particles results from low compaction pressure. A cluster may emerge as a result of the pores building up along the interstices. This may be due to the large, irregular pores [35].

Figure 4a shows that the holes are irregular in size and appear as voids under low compaction pressure. The micrograph reveals an distorted hollow at 450 MPa. When compaction pressure is minimal, the creation of cavities verifies the separation of pores. Enhanced plastic deformation at the contact surfaces occurs when the 450 MPa pressure is exceeded because the effective stresses at the grain boundaries reach the elastic limit. Reduced pore segregation, which results in fewer cluster forms, is the cause of the observed phenomena.

At 550 MPa, microscopic pores and voids appear in the microstructure, as seen in Figure 4b. Due of their ductility, bronze particles experience higher plastic deformation. When the compaction pressure reaches 650 MPa, clusters of pores vanish due to the intense plastic deformation, leaving only microscopic pores. The SEM picture in Figure 4c indicates the presence of fine pores. It is expected to be connected to chilly strain-induced hardening due to

the elevated pressure. Because of the increasing stress brought on by work hardening, which also promotes plastic deformation, the pores' width decreases and they become tiny. The significant reduction in porosity at a high compaction pressure of 750 MPa is shown in Figure 4d.

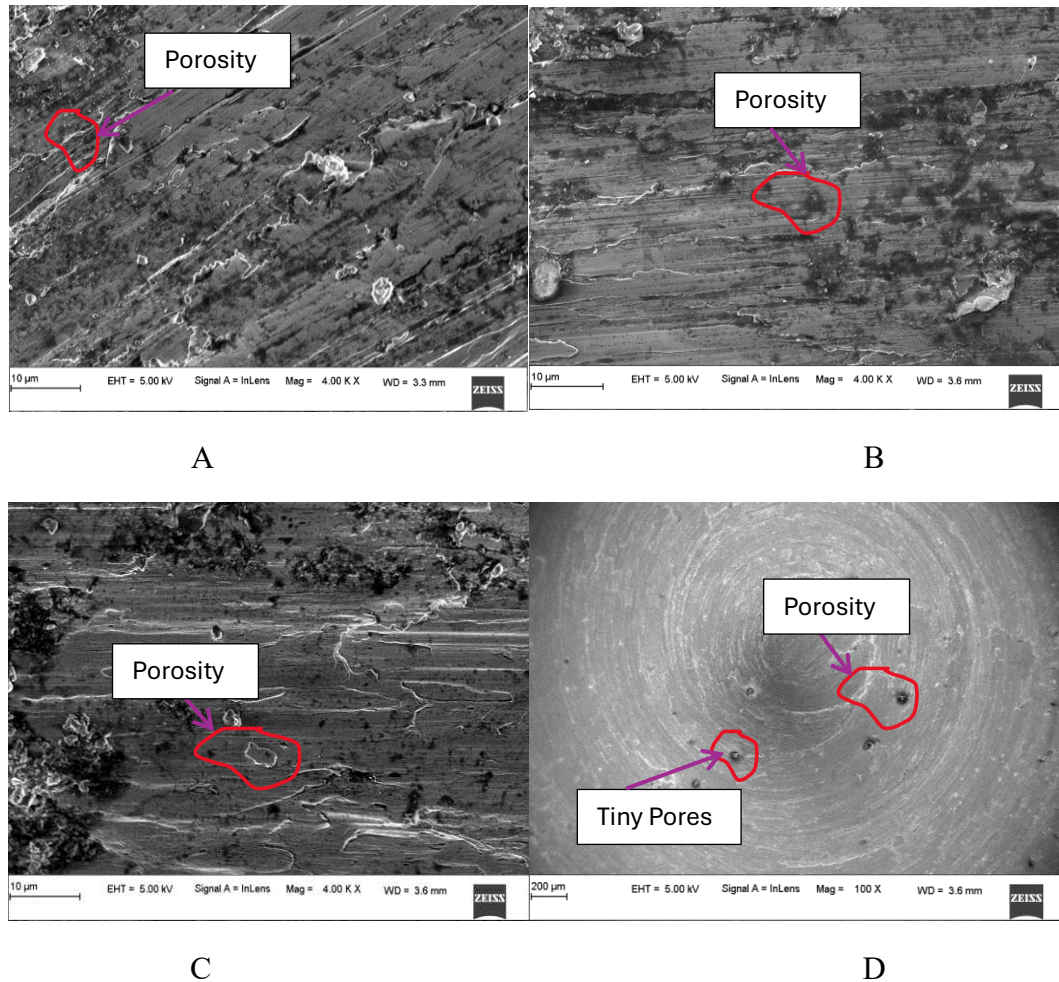


Figure 4. The unetched SEM pictures of Bronze + 2.5 wt.% Co + 2.5 wt.% Cr under compaction pressures of A. 450, B. 550, C. 650, and D. 750 MPa.

3.2 Hardness

The hardness of sintered bronze is measured using Vickers Hardness Tests. The hardness value is determined by averaging a minimum of three test results under each compaction pressure. Figure 5 depicts the relationship between hardness and compaction pressure. The hardness value is comparatively low at a low compaction pressure of 450 MPa. As shown in Figure 4a, the microstructure study indicates that pores at low pressure have uneven diameters and resemble massive voids. The establishment of a stress concentration center in the void formation region causes hardness to decrease.

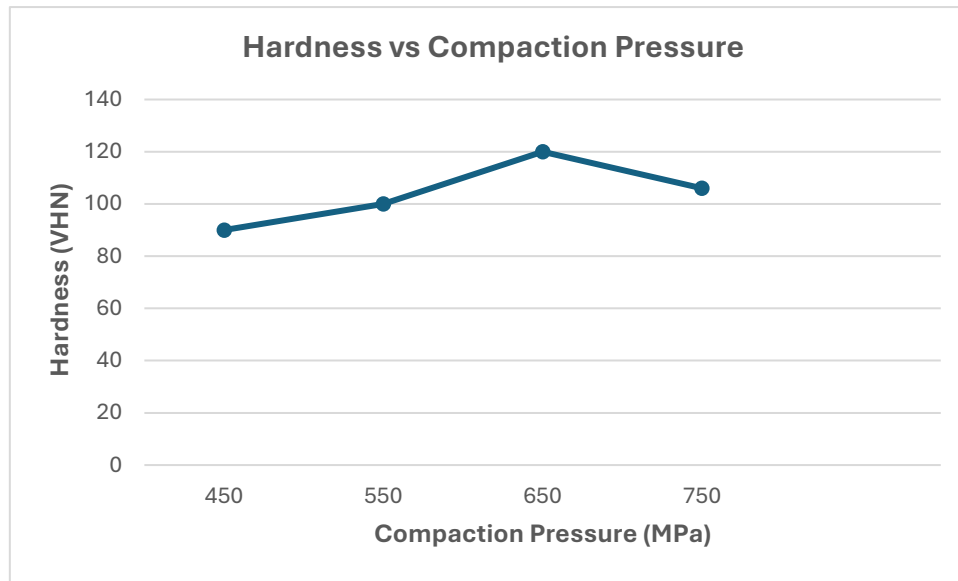


Figure 5. The impact of compaction pressures on the hybrid bronze's composite hardness

As the compaction pressure increases, the pore size shrinks. Figure 4c makes it clear that the pores are quite tiny at 650 MPa. As a result, the hardness will increase because there won't be a stress concentration point at the surface. The greatest hardness rating is associated with a compaction pressure of 650 MPa. The hardness value drops when the compaction pressure is 750 MPa as opposed to 650 MPa. significant compaction pressure may initiate the breakage of bronze particles, and significant plastic deformation may be the cause [36]. As a result, the hardness will decrease. High compaction pressure is typically linked to high hardness.

Four factors with L16 OA were taken into consideration when designing the tests for this work, and the results and summaries of each trial were displayed in a table.5. Composites that had lower PM parameter values were more difficult. The hardness improved from 450 MPa to 650 MPa due to better inter-particle bonding, higher green density, and better particle packing. Nevertheless, density gradients, microcrack formation, elastic recovery, and restricted sintering diffusion are all brought on by excessive compaction at 750 MPa, all of which reduce hardness. Consequently, 650 MPa is the optimal compaction pressure to achieve maximum hardness in the bronze+2.5% wt. Co+2.5% wt. Cr composite.

Table 3 represents average hardness value of bronze based composites. Hybrid composite exhibit more harder than single reinforced composite and pure bronze.

Table 3. Bronze based composites average hardness value

Material Composition (wt. %)	Average Hardness (VHN)
(S1) Pure Bronze	82
(S2) Bronze + 5 wt.% Co	112
(S3) Bronze + 5 wt.% Cr	115
(S4) Bronze + 2.5 wt.% Co + 2.5 wt.% Cr	132

The addition of hard Co and Cr particles to the comparatively soft bronze matrix is the main reason for the increase in Vickers hardness. These reinforcing particles boost resistance to indentation by limiting localized plastic deformation and dislocation movement during compaction and sintering. Improved particle packing, less residual porosity, a better metallurgical link between the matrix and reinforcement, and efficient load transmission from the bronze matrix to the tougher reinforcement particles are the key causes of the increased hardness. Through the Hall-Petch process, where finer grains increase grain boundary density and obstruct dislocation motion, grain refinement brought on by the scattered particles also aids in strengthening. Furthermore, Orowan strengthening—in which dislocations bow around non-shearable particles—is produced by the finely dispersed Co and Cr particles, raising the stress necessary for plastic deformation. Nevertheless, these processes work in tandem; enhanced densification and interparticle bonding attained during powder metallurgical processing are the primary sources of strengthening. [37]

3.3 Compressive Strength

Table 4 represents average compressive strength of bronze based composites. Hybrid composite exhibit more compressive strength than single reinforced composite and pure bronze.

Table 4. Bronze based composites average compressive strength

Material Composition (wt. %)	Compressive Strength (MPa)
(S1) Pure Bronze	235
(S2) Bronze + 5 wt.% Co	326
(S3) Bronze + 5 wt.% Cr	338
(S4) Bronze + 2.5 wt.% Co + 2.5 wt.% Cr	382

Due to particle rearrangement and plastic deformation, the green density rises with increasing compaction pressure, and the porosity decreases during sintering. Reduced porosity allows for an effective transfer of compressive loads through the composite and reduces stress concentration locations. A portion of the applied load is successfully carried by the hard Co and Cr reinforcements, which also limit matrix deformation. This postpones the start and spread of cracks. When compared to single particle reinforcement, the hybrid reinforcement produces a more uniform microstructure, improves the distribution of stress, and increases compressive strength. However, elastic spring-back, die-wall friction, residual stresses, or microcrack formation during ejection may cause the strength to be significantly lowered if the compaction pressure is too high (e.g., 750 MPa), which could negate the benefits of higher densification.

3.4 Wear Rate

Table 5 represents average wear rate of bronze based composites. Hybrid composite exhibit less wear rate than single reinforced composite and pure bronze.

Table 5. Bronze based composites average wear rate

Material Composition (wt. %)	Wear Rate (mm ³ /m)
(S1) Pure Bronze	0.0068
(S2) Bronze + 5 wt.% Co	0.0045
(S3) Bronze + 5 wt.% Cr	0.0042
(S4) Bronze + 2.5 wt.% Co + 2.5 wt.% Cr	0.0032

As hardness and compressive strength rise, wear resistance improves. Archard's wear law states that the wear volume is inversely related to the material's hardness; hence, the harder the composite, the less material is removed while sliding. As strong load-bearing components, the scattered Co and Cr particles limit the bronze matrix's severe plastic deformation and decrease the actual contact area between the sliding surfaces. Particle pull out, a frequent cause of abrasive wear in powder metallurgy composites, is also avoided by improved interfacial bonding. Additionally, cobalt enhances the thermal stability and load-carrying capability while chromium creates a stable oxide film during sliding, resulting in a mild oxidative wear regime rather than a severe adhesive wear regime. As a result, of all the compositions, the hybrid composite had the lowest wear rate. [38]

Table 6. An overview of powder metallurgy experiments and their outcomes

Exp. Runs	Material Composition (wt.%)	Compaction Pressure (MPa)	Sintering Time (hr)	Sintering Temperature (°C)	Hardness (VHN)	Compressive Strength (MPa)	Wear Rate (mm ³ /m)
1	S1	450	2	700	82	235	0.0068
2	S1	550	4	750	90	252	0.0062
3	S1	650	6	800	98	270	0.0056
4	S1	750	8	850	95	265	0.0059
5	S2	450	4	800	108	315	0.0048
6	S2	550	2	850	112	326	0.0045
7	S2	650	8	700	118	338	0.0042
8	S2	750	6	750	116	333	0.0043
9	S3	450	6	850	104	305	0.0050
10	S3	550	8	800	111	322	0.0046
11	S3	650	2	750	115	335	0.0043
12	S3	750	4	700	113	330	0.0044
13	S4	450	8	750	121	350	0.0039
14	S4	550	6	700	126	365	0.0036
15	S4	650	4	850	132	382	0.0032
16	S4	750	2	800	129	376	0.0034

4. Statistical Analysis:

4.1 ANOVA for Hardness

Table 7 presents the findings of the ANOVA test, which was employed to assess the influence of various parameters on the hardness. In this study, the sum of squares was calculated by examining the difference between the mean value and the outcome of each empirical trial, with a significance level set at 5%. Among the four parameters, material composition had the greatest impact, accounting for 78.60% of the contribution, followed by compaction pressure at 15.10%, sintering time at 1.60%, and sintering temperature at 1.20%. [39]

Table 7. Statistical analysis of variance for hardness

Source	DF	Adj SS	Adj MS	F - Value	P - Value	Contribution
Material Composition (wt.%)	3	2748.00	916.00	85.24	0.002	78.60
Compaction Pressure (MPa)	3	528.00	176.00	16.38	0.021	15.10
Sintering Time (hr)	3	56.00	18.67	1.74	0.312	1.60
Sintering Temperature (°C)	3	42.00	14.00	1.30	0.382	1.20
Error	3	122.00	40.67	—	—	3.50
Total	15	3496.00	—	—	—	100.00

4.2 ANOVA for Compressive Strength

Table 8 presents the findings of the ANOVA test, which was employed to assess the influence of various parameters on the compressive strength. Among the four parameters, material composition had the greatest impact, accounting for 76.90% of the contribution, followed by compaction pressure at 16.10%, sintering time at 1.90%, and sintering temperature at 1.50%. [40]

Table 8. Statistical analysis of variance for compressive strength

Source	DF	Adj SS	Adj MS	F - Value	P - Value	Contribution
Material Composition (wt.%)	3	20680	6893.3	92.5	0.001	76.90

Compaction Pressure (MPa)	3	4325	1441.7	19.4	0.017	16.10
Sintering Time (hr)	3	520	173.3	2.33	0.245	1.90
Sintering Temperature (°C)	3	410	136.7	1.84	0.291	1.50
Error	3	970	323.3	—	—	3.60
Total	15	26905	—	—	—	100.00

4.3 ANOVA for Wear Rate

Table 9 presents the findings of the ANOVA test, which was employed to assess the influence of various parameters on the wear rate. Among the four parameters, material composition had the greatest impact, accounting for 74.80% of the contribution, followed by compaction pressure at 16.60%, sintering time at 2.30%, and sintering temperature at 1.70%. [41]

Table 9. Statistical analysis of variance for wear rate

Source	DF	Adj SS	Adj MS	F - Value	P - Value	Contribution
Material Composition (wt.%)	3	9.12×10^{-6}	3.04×10^{-6}	81.7	0.002	74.80
Compaction Pressure (MPa)	3	2.02×10^{-6}	6.73×10^{-7}	18.1	0.019	16.60
Sintering Time (hr)	3	2.80×10^{-7}	9.33×10^{-8}	2.51	0.231	2.30
Sintering Temperature (°C)	3	2.10×10^{-7}	7.00×10^{-8}	1.88	0.287	1.70
Error	3	5.60×10^{-7}	1.87×10^{-7}	—	—	4.60
Total	15	1.22×10^{-5}	—	—	—	100.00

Across all three responses, material composition is the most influential parameter, contributing approximately 75–79% of the total variation. Compaction pressure is consistently the second most significant factor, contributing 15–17%. Within the selected parameter ranges, sintering time and sintering temperature exhibit comparatively smaller effects.

4.4 Taguchi signal-to-noise ratio analysis

For Hardness (VHN) and Compressive Strength (MPa), the objective is Larger-the-Better (LTB):

$$S/N = -10\log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right)$$

For Wear Rate (mm³/m), the objective is Smaller-the-Better (STB):

$$S/N = -10\log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right)$$

Table 10 represents signal-to-noise ratio for all experimental runs.

Table 10. S/N Ratios for All Experimental Runs

Exp. Runs	Material Composition (wt.%)	Compaction Pressure (MPa)	Sintering Time (hr)	Sintering Temperature (°C)	Hardness S/N (dB)	Compressive Strength S/N (dB)	Wear Rate S/N (dB)
1	S1	450	2	700	38.28	47.42	43.35
2	S1	550	4	750	39.08	48.03	44.15
3	S1	650	6	800	39.82	48.63	45.04
4	S1	750	8	850	39.55	48.46	44.58
5	S2	450	4	800	40.67	49.97	46.38
6	S2	550	2	850	40.98	50.26	46.94
7	S2	650	8	700	41.44	50.58	47.54
8	S2	750	6	750	41.29	50.45	47.33
9	S3	450	6	850	40.34	49.69	46.02
10	S3	550	8	800	40.91	50.16	46.74
11	S3	650	2	750	41.21	50.50	47.33
12	S3	750	4	700	41.06	50.37	47.13
13	S4	450	8	750	41.66	50.88	48.18
14	S4	550	6	700	42.01	51.25	48.87
15	S4	650	4	850	42.41	51.64	49.90
16	S4	750	2	800	42.21	51.50	49.37

Table 11,12,13 represents S/N ratio response table for hardness, compressive strength and wear rate of composites respectively.

Table 11. Signal-to-Noise Ratio Response Table (Hardness). Larger is better.

Level	Material Composition (wt.%)	Compaction Pressure (MPa)	Sintering Time (hr)	Sintering Temperature (°C)
1	39.18	40.24	40.67	40.70
2	41.10	40.75	40.95	41.06
3	40.88	41.22	41.01	41.11
4	42.07	41.03	41.17	40.97
Delta	2.89	0.98	0.50	0.41
Rank	1	2	3	4

Table 12. Signal-to-Noise Ratio Response Table (Compressive Strength). Larger is better.

Level	Material Composition (wt.%)	Compaction Pressure (MPa)	Sintering Time (hr)	Sintering Temperature (°C)
1	48.14	49.49	50.17	49.91
2	50.32	49.93	49.91	50.22
3	50.18	50.34	50.19	50.30
4	51.32	50.20	50.29	50.07
Delta	3.18	0.85	0.38	0.39
Rank	1	2	3	4

Table 13. Signal-to-Noise Ratio Response Table (Wear Rate). Smaller is better.

Level	Material Composition (wt.%)	Compaction Pressure (MPa)	Sintering Time (hr)	Sintering Temperature (°C)
1	44.28	45.98	46.75	46.73
2	47.05	46.68	46.86	47.25
3	46.81	47.45	47.25	47.26
4	49.08	47.10	47.29	46.86
Delta	4.80	1.47	0.54	0.53
Rank	1	2	3	4

The Taguchi signal to noise ratio analysis indicated that material composition was the most influential factor on all the three responses followed by compaction pressure. The hybrid reinforced composite (S4) showed higher S/N ratios uniformly for better hardness, compressive strength and wear resistance. The optimum parameter combinations from the S/N response tables were S4 material composition, 650 MPa compaction pressure, 8 h sintering time and 800°C sintering temperature. This combination is the preferred processing condition for the bronze composites studied in powder metallurgy, as it is expected to maximize the hardness and compressive strength, while minimizing the wear rate.

4.5 Regression Modeling

Using the statistical software MINITAB 17, multiple linear regression models were developed. These models generated a linear equation that depicted the connection between an independent variable and the response variable based on the data collected. [42]

Regression Model for Vickers Hardness (VHN)

Linear Regression Equation

$$HV = 31.52 + 12.14M + 0.024P + 0.43t + 0.008T$$

Regression Model for Compressive Strength

Linear Regression Equation

$$CS = 126.34 + 39.72M + 0.083P + 1.48t + 0.026T$$

Regression Model for Wear Rate

Linear Regression Equation

$$WR = 0.01025 - 0.00082M - 2.8 \times 10^{-6}P - 5.6 \times 10^{-5}t - 7.3 \times 10^{-7}T$$

where

- HV = Vickers Hardness (VHN)
- CS = Compressive Strength (MPa)
- WR = Wear Rate (mm³/m)
- M = Material code
- P = Compaction Pressure (MPa)
- t = Sintering Time (h)
- T = Sintering Temperature (°C)

4.6 Grey Relational Analysis

Grey Relational Analysis (GRA) is a multi-criteria decision-making and optimization technique developed under Grey System Theory. GRA can be used to optimize parameters such as material composition, compaction pressure, sintering time, and sintering temperature considering responses like hardness (larger is better), compressive strength (larger is better), and wear rate (smaller is better) together.

The following steps are used in Grey Relational Analysis.

Step 1 – Original Experimental Data

Step 2 – Grey Relational Generation (Normalization)

Larger-the-Better

$$X_i = \frac{Y_i - \min(Y)}{\max(Y) - \min(Y)}$$

Smaller-the-Better

$$X_i = \frac{\max(Y) - Y_i}{\max(Y) - \min(Y)}$$

Step 3 – Deviation Sequence

$$\Delta_i = |1 - X_i|$$

Step 4 – Grey Relational Coefficient (GRC)

The Grey Relational Coefficient is calculated as

$$\gamma_i = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_i + \zeta \Delta_{\max}}$$

where:

- Distinguishing coefficient, $\zeta = 0.5$
- $\Delta_{\min} = 0$
- $\Delta_{\max} = 1$

Step 5 – Grey Relational Grade (GRG)

The Grey Relational Grade is the average of the three coefficients:

$$GRG = \frac{\gamma_1 + \gamma_2 + \gamma_3}{3}$$

Table 14,15,16 represents Grey Relational Coefficient for All Experimental Runs, Grey Relational Grades and Response Table for Grey Relational Grade respectively.

Table 14. Grey Relational Coefficient for All Experimental Runs

Exp. Runs	Material Composition (wt.%)	Compaction Pressure (MPa)	Sintering Time (hr)	Sintering Temperature (°C)	Hardness GRC	Compressive Strength GRC	Wear Rate GRC
1	S1	450	2	700	0.333	0.333	0.333
2	S1	550	4	750	0.373	0.361	0.375
3	S1	650	6	800	0.424	0.396	0.429
4	S1	750	8	850	0.403	0.386	0.400
5	S2	450	4	800	0.510	0.523	0.529
6	S2	550	2	850	0.556	0.568	0.581
7	S2	650	8	700	0.641	0.626	0.643
8	S2	750	6	750	0.610	0.600	0.620
9	S3	450	6	850	0.472	0.488	0.500
10	S3	550	8	800	0.543	0.551	0.563
11	S3	650	2	750	0.595	0.610	0.620
12	S3	750	4	700	0.568	0.586	0.600
13	S4	450	8	750	0.694	0.696	0.720

14	S4	550	6	700	0.806	0.811	0.818
15	S4	650	4	850	1.000	1.000	1.000
16	S4	750	2	800	0.893	0.924	0.899

Table 15. Grey Relational Grades

Run	GRG	Rank
15	1.000	1
16	0.905	2
14	0.812	3
13	0.703	4
7	0.637	5
8	0.610	6
11	0.608	7
12	0.585	8
6	0.568	9
10	0.552	10
5	0.521	11
9	0.487	12
3	0.416	13
4	0.396	14
2	0.370	15
1	0.333	16

Table 16. Grey Relational Grade Response Table

Level	Material Composition (wt.%)	Compaction Pressure (MPa)	Sintering Time (hr)	Sintering Temperature (°C)
1	44.28	45.98	46.75	46.73
2	47.05	46.68	46.86	47.25
3	46.81	47.45	47.25	47.26
4	49.08	47.10	47.29	46.86
Delta	4.80	1.47	0.54	0.53
Rank	1	2	3	4

In Gray Relational Analysis, the three performance characteristics were converted into Gray Relational Grade and it was possible to optimize hardness, compressive strength and wear resistance at the same time. The results showed that the overall performance is most affected by the material composition, followed by compaction pressure, sintering time and sintering temperature. Run 15 had the highest Gray Relational Grade among the sixteen experimental runs, indicating the best overall combination of mechanical and tribological properties. The

best processing condition achieved by GRA from the average of the response table is the hybrid bronze composite reinforced with 2.5 wt.% Co and 2.5 wt.% Cr, processed at 650 MPa compaction pressure, 2 h sintering time and 850°C sintering temperature. This combination is the best compromise between the maximum hardness, compressive strength and minimum wear rate.

4. Discussion:



Figure 6. Experimentation and Outcomes

The trends of the experiments show that the material composition is the most important factor controlling the hardness, compressive strength and wear resistance of the powder metallurgy bronze composites. Among the studied compositions, the hybrid reinforcement (Bronze + 2.5 wt.% Co + 2.5 wt.% Cr) exhibited the best overall properties due to the synergistic effects of cobalt and chromium on microstructure refinement, densification and load-bearing capacity. Figure. 6 shows experimentation, and their results.

The enhancement in Vickers hardness can be mainly attributed to the introduction of hard Co and Cr particles in the relatively soft bronze matrix. These reinforcement particles help to prevent localized plastic deformation and dislocation movement during compaction and sintering thus increasing indentation resistance. The increase in hardness is mainly due to better particle packing, decreased residual porosity, stronger metallurgical bonding between the matrix and the reinforcement, and effective load transfer from the bronze matrix to the harder reinforcement particles. The dispersed particles also cause grain refinement which contributes to strengthening thru the Hall–Petch mechanism by increasing grain boundary density and hence hindering dislocation motion. In addition, the finely dispersed Co and Cr particles are effective in strengthening of the material by Orowan mechanism, where dislocations bow around non-shearable particles thus increasing stress for plastic deformation. However, these

mechanisms are complementary and the dominant strengthening is due to the improved densification and interparticle bonding which is achieved during powder metallurgy processing. [43]

The increase in compressive strength happens by a similar mechanism. Higher compaction pressure permits particle rearrangement and plastic deformation. This increases the green density and results in lower porosity after sintering. Reduced porosity decreases stress concentration sites and permits an efficient transfer of the compressive loads thru the composite. The hard Co and Cr reinforcements are effectively carrying part of the applied load and constraining matrix deformation. This delays the crack initiation and propagation. The hybrid reinforcement results in a more homogeneous microstructure than the single-particle reinforcement resulting in better stress distribution and higher compressive strength. However, excessive compaction pressure (e.g. 750 MPa) may result in a slight decrease in strength owing to elastic spring-back, die-wall friction, residual stresses or microcrack formation during ejection, which may counteract the benefits of higher densification.

The rise of hardness and the increase of compressive strength enhance the wear resistance. According to Archard's wear law, the wear volume is inversely proportional to the hardness of the material, therefore the harder the composite, the lower the material removal during sliding. The dispersed Co and Cr particles serve as hard load bearing constituents, which reduce the actual contact area between the sliding surfaces and restrict severe plastic deformation of the bronze matrix. Improved interfacial bonding also prevents particle pull out which is a common source of abrasive wear in powder metallurgy composites. Furthermore, chromium promotes the formation of stable oxide films during sliding, and cobalt enhances the thermal stability and the load-carrying capacity, which together favor a mild oxidative wear regime rather than a severe adhesive wear regime. Hence the lowest wear rate is found for the hybrid composite among all compositions.

The influence of compaction pressure is especially important since it directly controls densification. Raising the pressure from 450 MPa to 650 MPa leads to a decrease in pore volume, an increase in interparticle contact area, and an improvement of diffusion bonding during sintering. Such improvements lead to higher hardness, higher compressive strength and lower wear rate. However, excessive densification above the optimum pressure can induce residual stresses and local defects, which accounts for the slight decrease in properties at 750 MPa.

The effect of sintering time and temperature is relatively of less importance in the studied range. The moderate increase of temperature and holding time enhances the atomic diffusion, neck growth between the particles and metallurgical bonding, finally leads to the improvement of mechanical properties. However, prolonged sintering or too high temperature may promote grain coarsening, which will reduce the beneficial effects of grain boundary strengthening, and partially offset the gains from improved densification.

Overall, the combined statistical analyzes (ANOVA, Taguchi S/N ratio, regression modeling as well as Gray Relational Analysis) reveal the material composition as the dominant parameter followed by the compaction pressure, whereas the sintering time and temperature are the

secondary effects. The optimum compromise between hardness, compressive strength and wear resistance is obtained for the Bronze + 2.5 wt.% Co + 2.5 wt.% Cr composite compacted at around 650 MPa and sintered under optimized conditions. This superior performance can be attributed to the synergistic effect of improved densification, strong interparticle bonding, reduced porosity, efficient load transfer, complementary Hall-Petch and Orowan strengthening mechanisms, and the transition from severe adhesive wear to predominantly mild abrasive/oxidative wear due to the presence of cobalt and chromium reinforcements. This combination of microstructural and tribological mechanisms explains the enhanced mechanical and wear properties of the synthesized bronze based powder metallurgy composites.

5. Conclusions:

The research project was successfully completed using powder metallurgy with base alloy bronze with cobalt and chrome particles. Furthermore, the Taguchi optimization was employed to study the influence of PM parameters and response outputs like hardness, compressive strength and wear rate. The study ends with the following conclusion:

- Co and Cr reinforced bronze based composites were successfully fabricated by powder metallurgy technique. The effect of material composition, compaction pressure, sintering time and sintering temperature on the hardness, compressive strength and wear rate was systematically investigated by Taguchi L16 experimental design.
- The most influential factor affecting all three responses was material composition. The ANOVA showed that it accounted for about 75–79% of the total variation, followed by the compaction pressure, whereas the sintering time and sintering temperature had relatively smaller effects.
- The hybrid composite with 2.5 wt.% Co + 2.5 wt.% Cr (S4) exhibited the best mechanical and tribological performance than all the compositions studied. At optimized processing conditions, the composite exhibited a maximum Vickers hardness of 132 VHN, compressive strength of 382 MPa and minimum wear rate of 0.0032 mm³/m.
- Taguchi signal-to-noise ratio analysis, regression modeling and Gray Relational Analysis consistently identified the hybrid-reinforced composite processed at approximately 650 MPa compaction pressure under optimized sintering conditions as the optimum parameter combination for simultaneously maximizing hardness and compressive strength and minimizing wear rate.
- The enhancement in mechanical and tribological properties is due to better densification, reduced residual porosity, improved metallurgical bonding between bronze matrix and reinforcement particles, effective load transfer, and synergistic Hall–Petch and Orowan strengthening mechanisms. The increased hardness also decreased the plastic deformation during sliding, which improved the wear resistance.
- The developed regression models exhibited excellent predictive capability with coefficients of determination ($R^2 > 95\%$) confirming their suitability to predict performance of bronze-based composites within the investigated processing range.
- The current study demonstrates the hybrid Co–Cr reinforcement as an efficient approach to produce high strength and wear resistant bronze composites and potential candidates for bearings, bushes, gears and other tribological engineering components working under moderate to high loading conditions.

Author contributions:

Sreenivasa R, Kallesh S S, Ramesh B T, and Shridhar S. Mendhe have contributed to, read, and approved the manuscript in its current form. All authors conceived of the work, researched the necessary references, produced the scaling analysis, and wrote the manuscript together.

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The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

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The authors declare no conflict of interest.

Ethics Approval:

Not applicable. This study does not involve human participants or animals; therefore, ethical approval was not required. The research is based purely on material fabrication and experimental analysis.

Consent to Participate:

Not applicable. The study does not involve any human subjects or participants requiring consent.

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