In this study, iron-based powder-metal (PM) compacts were sintered using a medium-frequency induction-heating system. The effects of copper amounts on mechanical properties were investigated. Iron-based powders were mixed with mass fractions \( w = 1\% \) to \( 6\% \) copper (Cu) and \( 0.8\% \) zinc stearate in a V-type mixer. During the sintering process, PM compacts were sintered at a frequency of 30–50 kHz (medium frequency), at 12 kW and 1120 °C for 400 s in an atmospheric environment. Mechanical properties, microstructural properties, densities and microhardness values were investigated for the sintered material. The highest mechanical properties were obtained for the iron-based PM compacts including \( 3\% \) Cu.

**Keywords:** induction sintering, powder metal, iron, copper

**1 INTRODUCTION**

Powder metallurgy (PM) is the most diverse manufacturing approach among various metalworking technologies. PM makes it possible to fabricate high-quality, complex parts to close tolerances in an economical manner.\(^1\) Sintering, which is one of the oldest human technologies, is a technique of consolidating powder compacts using mechanical and thermal energy.\(^2\) Mixtures of elemental iron powders are commonly used for PM applications. A small amount of copper powder is always added to develop the mechanical properties of sintered alloys owing to its relative ease of dissolving and diffusing in an iron matrix upon sintering. Extensive investigations on the sintering properties of the Fe-Cu alloy made from elemental powders are well reported.\(^3\)–\(^7\) However, few studies have been conducted to investigate the effect of copper amounts on the microstructures of sintered iron compacts. Several sintering operations are carried out using medium-frequency induction.\(^8\)–\(^10\) The high-frequency induction-heated sintering method (HFIHS), allowing a fabrication of dense materials within two minutes, has been shown to be effective in achieving this goal.\(^11\)–\(^33\)

PM compacts are heated via heat transfer during sintering in conventional sintering furnaces or continuous mesh-belt furnaces. However, PM compacts can also be heated with the magnetic current, which passes over a PM compact in an induction sintering process. The advantage of medium frequency is the improved penetration depth, which is deeper than at a high frequency. This depth, known as the reference depth or skin depth, depends on the frequency of the alternating current through a coil and the electrical resistivity and relative magnetic permeability of a work piece. The medium-frequency induction sintering process involves rapid sintering of a powder metal in a very short time with a high-temperature exposure. This process has advantages because it allows a rapid densification of the associated materials and inhibits the grain growth in powder metals. Shon et al.,\(^15\),\(^29\),\(^30\) Xiaopeng et al.,\(^16\) Khalil et al.,\(^17\),\(^27\) Kim et al.,\(^21\)–\(^23\) Abdelrazek and Won,\(^26\) Montasser\(^28\) and Park et al.,\(^31\) examined the mechanical properties of high-frequency induction-sintered nano- or powder-metal compacts.

Wang,\(^8\) Shon et al.,\(^30\),\(^33\) and Park et al.,\(^31\) investigated the mechanical properties of high-frequency induction-sintered compacts including nano iron. Çavdar and Atik\(^9\),\(^10\) reported about the mechanical properties of the medium-frequency induction-sintered iron or iron-based powder compacts. Zhang et al.\(^34\) studied a conventionally sintered Fe-Cu compact.

Wang\(^8\) investigated the effect of alloying elements and processing factors on the microstructure and hard-
ness of sintered and induction-hardened Fe-Cu alloys. He determined that the volume dilation increases with the increasing compacting pressure. The hardness of sintered Fe-Cu-P alloys increases with the increasing compacting pressure and carbon amount. A further strengthening resulted from a strong solution-hardening effect of the phosphorus in iron. The hardness variation of the sintered alloys with carbon amounts depends on the compacting pressure. During induction hardening the surface hardness also increases with the increasing carbon amount and compacting pressure, but in a different mode compared to the as-sintered state. This is caused by a phosphorus addition.

The swelling of the Fe-Cu materials sintered at the temperatures above the copper melting point during sintering has been studied for many years. It has been shown that the penetration of liquid copper into the iron inter-particle boundaries is the dominant mechanism. Zhang et al. investigated the modelling of the swelling of the Fe-Cu compacts sintered at the temperatures above the copper melting point. In the model, the combined effect of copper amount, porosity, particle size and heating rate on the swelling is analyzed. The calculated volume and dimensional growths show a qualitative agreement with the published data. In addition, the calculated results can be used to predict the swelling of the Fe-Cu compacts with different copper amounts and green densities. In this model, the effect of copper amount, particle size and heating rate on the swelling is described using the particle coordination number to present the role of the porosity. The model can describe the observed influence of copper amount, porosity, particle size and heating rate on the swelling.

Çivi et al. investigated the reliability of the mechanical properties of induction-sintered iron-based powder-metal parts. They reported that by increasing the sintering time, the reliability of the ultimate stress, the ultimate strain and the Rockwell-B hardness were increased by (10, 50 and 90)% . They found that the Vickers hardness values were generally not increased with the induction sintering time. In addition, they found that the microhardness (HV) test is not appropriate for the powder-metal parts that have porosity. Due to the results of the Rockwell-B hardness tests, it is also suggested that the macrohardness tests such as Rockwell-B and Brinell are more appropriate and more accurate for the powder-metal parts with porosity and alloying elements.

In Wang’s study the blended powder mixtures were compacted, sintered and the P-containing sintered alloys were induction hardened. They showed that the microstructure of sintered Fe-Cu alloys varies with the copper amount. The refined and decreased volume of pro-eutectoid ferrite was observed when the copper amount was increased. The ferrite phase is markedly hardened by the dissolved copper. The P-containing specimens exhibit a significant volume expansion after the sintering.

Kurt and Ates used the same composition as we did in our work. They found that the samples sintered at 1150 °C have a better density. They determined that the thermal conductivity decreases because of a porous microstructure. In addition, Arik and Turker investigated mechanical alloying of the same composition. They reported that mechanical alloying resulted in a formation of finer powder particles containing homogeneously distributed carbon in iron. They maintained that this process also caused a high deformation of the particles which increased the internal energy. They showed that the hardness, the strength and the microstructure of sintered compact specimens were affected by the mechanical-alloying time and sintering temperature. These results are in good agreement with our work.

Feldshtein and Dyachkova investigated the properties and tribological behaviors of P/M iron-based composites reinforced with ultrafine particulates. They obtained friction coefficients on the surfaces of MMCs containing nanocrystalline particulates, reduced by 2–3 times compared to the base material, while the critical seizure pressure was increased from 2 to 5 times. In addition, they observed that the presence of nanocrystalline particulates hinders the appearance of fracture microcracks on the surfaces during friction, preventing the movement of dislocations. The wear resistance of MMCs increases by 2–4 times compared to the base material.

In this study, we investigated the 1–6 % Cu iron-based powder-metal compacts that were sintered using the medium-frequency induction-heated system. The sintered compacts were compared with respect to their fracture strength, deflection at fracture, microhardness and density values. The goal of this research was to find the optimum copper amount for the iron-based powder-metal compacts.

2 EXPERIMENTAL STUDIES

In this study, 1–6 % Cu iron-based powder-metal compacts were used. The chemical compositions of the PM compacts are given in Table 1.

<table>
<thead>
<tr>
<th>Powder</th>
<th>Cu</th>
<th>Fe</th>
<th>Lubricant (Zn stearate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity 1</td>
<td>1</td>
<td>Balance</td>
<td>0.8</td>
</tr>
<tr>
<td>Quantity 2</td>
<td>2</td>
<td>Balance</td>
<td>0.8</td>
</tr>
<tr>
<td>Quantity 3</td>
<td>3</td>
<td>Balance</td>
<td>0.8</td>
</tr>
<tr>
<td>Quantity 4</td>
<td>4</td>
<td>Balance</td>
<td>0.8</td>
</tr>
<tr>
<td>Quantity 5</td>
<td>5</td>
<td>Balance</td>
<td>0.8</td>
</tr>
<tr>
<td>Quantity 6</td>
<td>6</td>
<td>Balance</td>
<td>0.8</td>
</tr>
</tbody>
</table>

All the powders were mixed with 0.8 % Zinc stearate, used as a lubricant during the pressing. The particle sizes
of iron and copper powders were 45–106 μm. The powders were mixed for 20 min at 25 r/min in a V-type mixer to produce a homogeneous mixture. The mixed powders were compacted under 600 MPa using uniaxial pressure. The dimensions of green compacts were 10 mm × 10 mm × 55 mm. Green compacts were introduced into the medium-frequency induction-heated sintering system as shown schematically in Figure 1. PM compacts were sintered using the continuous-induction-heating system as presented in Figure 2. The inner diameter of the coil was 32 mm; the outer diameter was 48 mm.

An induced current (the frequency of around 30 kHz) was then activated. The induced current was a 100% output of the total power capacity. PM compacts were sintered in air environment at 1120 °C for 400 s. The temperatures were measured (± 5 °C) with an infrared pyrometer focused on the center of a compact surface.

Table 2: Processing parameters of medium-frequency-heated sintering of w = 3 % Cu iron-based PM compacts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Applied value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied pressure</td>
<td>600 MPa</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>1120 °C</td>
</tr>
<tr>
<td>Power capacity</td>
<td>12 kW</td>
</tr>
<tr>
<td>Frequency</td>
<td>30 kHz</td>
</tr>
<tr>
<td>Presintering time</td>
<td>Unavailable</td>
</tr>
<tr>
<td>Duration</td>
<td>400 s</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>1120 °C</td>
</tr>
<tr>
<td>Heating rate</td>
<td>≈ 75 °C/s</td>
</tr>
<tr>
<td>Cooling rate</td>
<td>Natural</td>
</tr>
<tr>
<td>Environment</td>
<td>Atmosphere</td>
</tr>
</tbody>
</table>

Table 3: Flow chart of the sintering process

The three major stages of sintering are shown in Figure 3 and the typical parameters of the process are presented in Table 2. The sintering stages of the induction processes are shown on the flow chart in Table 3. Five different compacts were used for all the processes.

3 RESULTS AND DISCUSSIONS

3.1 Mechanical properties of sintered compacts

The average strength, deflection percentage at fracture, HV hardness and density values for the induction-sintered samples are given in Table 4. Five different compacts were used for all the processes and average results.

The three-point bending results were compared (Figure 4). The rupture strengths of 2–4 % Cu iron-based PM compacts were very similar. The maximum bending strength was obtained for 3 % Cu iron compacts. In the compacts with different Cu amounts the strength values were reduced.
Deflection percentages at fractures were compared (Figure 5). The maximum deflection at fracture was obtained for iron 3% Cu compacts. Deflection percentages at fractures for the components with 2–4% Cu amounts were very similar. The other Cu amounts reduced the breaking-strain values. The highest ductility was obtained for 2–4% Cu compacts.

Microhardness results are compared in Figure 6. The highest HV microhardness results were obtained for 3% Cu PM compacts. Higher or lower Cu amounts decreased the hardness.

Density results are compared in Figure 7. The highest density results were obtained for 6% Cu PM compacts. It is clearly seen that Cu amounts increase the density of iron-based compacts. Cu powders were molten into the compacts at the sintering temperature of 1120 °C.

During the medium-frequency induction-heated sintering 400 s, the maximum fracture strength, deflection percentage at fracture and HV microhardness of the iron-based compacts with 3% Cu were as expected. The incremental Cu amounts reduced the fracture strength, deflection percentage at fracture and HV microhardness.

These results are in good agreement with the previous works. Compared with the references, the density results for the copper-iron PM compacts are quite similar. An increased sintering time increased the fracture strength, microhardness and density of PM compacts and the best values were obtained during medium-frequency induction sintering 500 s. In indu-

Table 4: Mechanical properties and densities of the PM compacts

<table>
<thead>
<tr>
<th>Copper amount (wt%)</th>
<th>Bending strength (N/mm²)*</th>
<th>Deflection at rupture (%)*</th>
<th>Hardness (HV)*</th>
<th>Density (g/cm³)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>148</td>
<td>1.32</td>
<td>172</td>
<td>6.56</td>
</tr>
<tr>
<td>2</td>
<td>296</td>
<td>2.67</td>
<td>187</td>
<td>6.57</td>
</tr>
<tr>
<td>3</td>
<td>303</td>
<td>2.75</td>
<td>189</td>
<td>6.60</td>
</tr>
<tr>
<td>4</td>
<td>302</td>
<td>2.70</td>
<td>185</td>
<td>6.62</td>
</tr>
<tr>
<td>5</td>
<td>225</td>
<td>1.93</td>
<td>176</td>
<td>6.63</td>
</tr>
<tr>
<td>6</td>
<td>177</td>
<td>1.47</td>
<td>171</td>
<td>6.65</td>
</tr>
</tbody>
</table>

* Error range is ±3%
3.2 Microstructural properties of the sintered compacts

Light microstructural images of the polished surfaces of PM compacts are given in Figure 8. SEM microstructural images of the polished surfaces of PM compacts are given in Figure 9. We observed a homogeneous microstructure in the part including 3 % Cu. Melted and bonded Cu grains are observed in this microstructure. Cu grains are uniformly distributed.

More bonding is observed at the edge of the part than in its centre. A brittle fracture is observed on the broken surface of the part. This is presented with a SEM image in Figure 9.

4 CONCLUSIONS

Iron-based powder-metal compacts including \( w = 1\% \) to 6 % Cu were produced using medium-frequency induction system. Based on the results, the conclusions are as follows:

The highest fracture strength, deflection percentage during bending and microhardness were obtained with 3 % Cu amounts. In some tests involving 2–4 % Cu amounts, the results were similar.

In the other medium-frequency induction-sintered PM compacts, the Cu amounts increased the density of the iron-based compacts.

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