Effect of nickel addition on mechanical properties of powder forged Fe-Cu-C

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Abstract: Fe-Cu-C system is very popular in P/M industry for its good compressibility and dimensional stability with high strength. Fe-Cu-C is a structural material and is used where high strength with high hardness is required. The composition of powder metallurgy steel plays a vital role in the microstructure and physical properties of the sintered component. Fe-2Cu-0.7C-Ni alloy with varying nickel composition (0%, 0.5%, 1.0%, 1.5%, 2.0%, and 3.0%) wt. % was prepared by powder metallurgy (P/M) sinter forging process. The present work discuss the effect of varying nickel content on microstructure and mechanical properties.

1. Introduction
Fe-Cu-C system is known in powder metallurgy industry for its good compressibility and dimensional stability for high strength material. Iron and copper powder in Fe-Cu-C system has very important role. Copper melts at 1083°C which is below the conventional sintering temperature (1120°C). The melted copper, rapidly infiltrate the pore system of compact where it diffuses easily into iron powder. During sintering the Cu melts, and leave its original position creating very small pores in its wake [1]. The liquid phase sintering promotes efficient bonding of powder particle. The solubility of copper in austenite (γ-iron) is up to 9wt % but in ferrite (α-iron) the solubility of copper is only 0.4 wt. % at room temperature. Therefore iron-copper alloy can be precipitation hardened in low temperature annealing followed by sintering. While copper liquid penetrates through the grain boundaries, it leads to swelling of component which causes high dimensional change. This is due to the low contact angle of copper that enables it to wet the iron particles surface completely [2]. Liquid Cu phase improves particle bonding by forming a semi-permeable liquid layer around the Fe particle, and also hinders the carbon diffusion in iron [3]. Carbon added in the form of graphite increases the contact angle and reduces the wetting. If the carbon addition is high then the liquid copper does not flow along the particle surface and into grain boundary, therefore copper diffusion is reduced [4].

2. Experimental Procedure
The elemental powders of Fe-2Cu-0.7C were admixed with different Nickel content (0, 0.5, 1.0, 1.5, 2.0, 3.0) wt. % in double cone mixer for 40 minutes. After mixing, the powders were filled in mild steel ‘can’ (10cm length and 2 ½ inch diameter). Sintering was carried out in tubular furnace under 90% N2 +10% H2 atmosphere at 1140°C for 40 minutes. The Can was then forged followed by sintering. After the forging process the samples were homogenized for 40 minutes for proper diffusion of nickel powder. After the homogenization the samples were heated to 900°C in 90% N2 +10% H2 atmosphere for 30 minute and then air cooled. The samples were then sectioned into small specimen. The microstructure of samples were analyzed using an optical microscope. Tensile properties were
determined using universal testing machine. The density of the samples was determined using Archimedes test.

3. Result and Discussion

3.1 Powder Characterization

Iron powder showed rounded shape with an average size of 25μm as shown in figure 1(a). Copper powder procured was also round in shape with average particle size of 40μm as shown in figure 1(b). Nickel powder in as received condition was round in shape with average particle size of 80μm as shown in figure 1(c). The milled nickel powder has average particle size of 10μm and is flattened and irregular in shape. The milled powders showed surface deformation and size reduction as shown in figure 1(d). After milling the structure of powder was changed to globular and lamellar. On an average, the particle size of milled nickel was 10 μm due to agglomeration.

![Figure 1: SEM micrograph of (a) Iron Powder (b) Copper powder (c) As received Nickel powder and (d) Milled Nickel powder.](image)

3.2 Microstructural Studies

Optical microscope was used to analyze the microstructure of the samples. Figure 2(a)-(f) showed mainly ferritic phase in its microstructure. Small secondary pores are also visible in these microstructure. 1% Ni steel showed few region of fine bainite as shown in figure 2(c). As the Ni content in the steel is increased it showed increased austenitic phase in the microstructure.

3.3 Density Calculation

Density calculation was done using Archimedes principle as:

$$\delta_a = \frac{W_a}{W_a - W_w}$$
The relative density was increased as the amount of Nickel content of the steel was increased as shown in table 1.

Figure 2: Optical micrograph of Fe-2Cu-0.7C-Ni sample with (a) 0% Ni (b) 0.5% Ni (c) 1% Ni (d) 1.5% Ni (e) 2% Ni and (f) 3% Ni
Table 1: Relative Density of the samples

| S.No | Sample       | \( W_a \) (gm) | \( W_w \) (gm) | \( W_a-W_w \) (gm) | Density (gm/cc) | Relative Density (%) |
|------|--------------|----------------|----------------|-------------------|-----------------|---------------------|
| 1    | Fe-Cu-C-0%Ni| 7.34           | 6.3            | 1.04              | 7.05            | 90.56               |
| 2    | Fe-Cu-C-0.5%Ni| 10.26        | 8.82           | 1.44              | 7.12            | 91.57               |
| 3    | Fe-Cu-C-1%Ni| 7.01           | 6.03           | 0.98              | 7.15            | 92.01               |
| 4    | Fe-Cu-C-1.5%Ni| 10.11        | 8.68           | 1.43              | 7.06            | 92.90               |
| 5    | Fe-Cu-C-2%Ni| 1.98           | 1.71           | 0.27              | 7.33            | 94.43               |
| 6    | Fe-Cu-C-3%Ni| 6.86           | 5.93           | 0.93              | 7.37            | 95.00               |

3.4 Tensile Test
Sample showed increase in the yield strength with increasing nickel content in the sample. Sample containing 3% Ni content showed maximum yield stress of 701 MPa. Ductility of the material was also improved with the increased Ni content. Nickel acts as the austenitic stabilizer which is responsible for the good strength and ductility of the material as shown in table 2.

Table 2: Tensile properties of the sample

| S.No | Sample          | Yield Stress (MPa) | Proof Stress (MPa) | Ultimate Tensile Stress (MPa) | % Elongation |
|------|-----------------|--------------------|--------------------|--------------------------------|--------------|
| 1    | Fe-2Cu-0.7C-0%Ni| 345                | 397.5              | 482.5                          | 6.24         |
| 2    | Fe-2Cu-0.7C-0.5%Ni| 512.5            | 555                | 637.5                          | 7.28         |
| 3    | Fe-2Cu-0.7C-1%Ni| 550                | 625                | 650                            | 8.86         |
| 4    | Fe-2Cu-0.7C-1.5%Ni| 575               | 625                | 700                            | 9.68         |
| 5    | Fe-2Cu-0.7C-2%Ni| 645                | 712.5              | 837.5                          | 14.58        |
| 6    | Fe-2Cu-0.7C-3%Ni| 701                | 725.78             | 885                            | 17.40        |

3.5 Fracture Morphology
Fracture mode for 0% Ni was observed to be cleavage type which shows its brittle nature as showed in figure 3(a). With increase in the nickel percentage the ductile mode increases which can be seen by its dimple mode of fracture as shown from figure 3(b)-(f). SEM analysis in figure 4(a)-(b) shows that the fracture propagation initiated from the larger or bigger pores. These bigger pores are called Primary pores. The size of the primary pores was measured using SEM. The pores area was greater than 25 \( \mu m^2 \). Primary pores are developed during the compaction of the powder before sintering. Smaller pores
or secondary pores are less severe because of its more rounded shape. The pore area of secondary pores is less than 25 μm².

Figure 3: Fractography of samples containing (a) 0% Ni (b) 0.5% Ni (c) 1.0% Ni (d) 1.5% Ni (e) 2% Ni (f) 3% Ni
4. Conclusion

i. Increase in density was observed with increasing Ni content. This is due to the formation of austenite phase in the steel as Nickel addition. As Nickel is austenitic stabilizer. Austenite phase has the high density.

ii. The microstructures showed ferrite, pearlite and few bainite. Sample with higher Nickel content showed mostly austenite phase. Primary and secondary pore was observed in all the microstructure. Secondary pore was developed as the copper leave its wake during the sintering process.

iii. Higher Y.S and UTS was observed in 3% Ni steel. This composition of steel showed good percentage elongation of 17.40%. This is because the Nickel contribute in the toughness of the material. The copper added in the sample increase the strength by solid solution hardening. So, material showed both good strength and toughness.

iv. The mode of fracture of all the samples was mixed mode. But 0% Ni steel showed brittle fracture. This may be the reason for low Y.S and UTS for 0% Ni steel. Crack was initiated from the primary pores because of its bigger size and irregular shape.

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