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Experimental Study Of The Effect Of Salt Content In Cooling Media On The Mechanical Properties Of Alloy Materials Resulting From Copper Casting With Used Cylinder Blocks

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Abstract— Casting of cylinder block metal with copper is a process of making objects by melting/melting metal with copper at a certain temperature. This study aims to evaluate the effect of variations in the concentration of water and salt solution-based quenching medium on the mechanical properties of metals including hardness and impact toughness after heat treatment. Three variations of quenching medium used were 90% water: 10% salt, 80% water: 20% salt, and 70% water: 30% salt. The test results showed that increasing the salt concentration in the quenching medium caused a significant increase in material hardness, with the highest value of 27.3 kg/mm² obtained in quenching medium using 70% water: 30% salt. This increase in hardness was associated with the acceleration of martensite phase formation due to the higher quenching rate. However, the increase in hardness was accompanied by a decrease in impact toughness. The highest toughness value of 6300 J/m² was recorded in a quenching medium of 90% water: 10% salt, while a drastic decrease occurred at a salt concentration of 30%, which only reached 5733 J/m². This decrease is caused by the dominance of the martensitic structure which is hard but brittle, thus reducing the material's ability to absorb shock energy.

Keywords— heat treatment, quenching medium, hardness, impact toughness, salt solution.

I. INTRODUCTION

Copper alloys play a crucial role in various industrial applications, particularly those that prioritize thermal and electrical conductivity. The mechanical properties of copper alloys are highly dependent on the heat treatment process applied, particularly the cooling rate after heating. Quenching techniques using various cooling media have become an important strategy for obtaining desired microstructures, such as martensite or other fine-grained phases, which can increase the hardness and tensile strength of modern metallurgical materials [1].

In the domain of non-ferrous metal materials, such as copper alloys, quenching in saline solutions (brine/NaCl) has become an attractive option due to its ability to offer faster cooling rates than plain water, yet quieter than water with high distortion effects [2]. Research on carbon steel has shown that increasing the salt concentration in the cooling solution is directly proportional to the increase in hardness, although toughness may decrease slightly at higher concentrations [3].

However, literature on the application of salt cooling media to non-ferrous alloys, particularly cast copper alloys, is still limited. On the other hand, studies on aluminum-iron powder and carbon steel alloys have revealed that brine heat treatment can significantly modify the microstructure and mechanical properties such as hardness and toughness [4]. Therefore, expanding the application of this technique to copper alloys merits further investigation. Furthermore, the overall processing of secondary metal waste, in this case used cylinder blocks as raw material for copper alloys, requires a thorough study of the effects of the heat treatment process and cooling media on the final properties of the material. This recycling approach is not only relevant for maintaining resource sustainability but also requires optimal mechanical quality for its application [1].

Conceptually, heat treatment involving heating to austenite or homogenization temperature, followed by an appropriate holding time, and then rapid cooling through a salt solution, has the potential to produce a finer microstructure and a high dislocation density, thereby increasing the hardness and tensile strength of copper alloys. This mechanism is in line with the theory of the influence of quenching rate on the formation of metastable phases such as martensite or bainite in ferrous and non-ferrous metals.

However, it should also be noted that very high cooling rates (for example, at very high salt concentrations) can lead to a decrease in toughness or other mechanical properties. In the context of carbon steels such as S45C and ST 60, research indicates a trade-off between high hardness and reduced toughness at maximum salt concentrations. A similar pattern likely occurs in copper alloys, so experimental analysis is essential to achieve the optimal balance.

The goal of heat treatment is to obtain or improve mechanical properties such as hardness, toughness, and ductility to meet the desired characteristics for use. Heat treatment begins with heating or austenitization to a temperature above the critical austenite temperature [5]. In heat treatment, quenching plays a crucial role. Quenching is the rapid cooling of a material after heating to a certain temperature, followed by cooling using various cooling media, such as water, oil, or other organic fluids. In the quenching process, the cooling medium is used to lower the temperature of the metal after heat treatment, changing its structure. Cooling typically uses air, oil, and salt to cool the sample material, achieving the desired results [6].

To determine the quality of a casting product, macro and micro observations, mechanical testing, and product quality control can be carried out. Macro observations can be carried out using several methods, such as direct observation or using a microscope with magnification up to mm to see defects in the resulting product. Meanwhile, microstructural observations can use a metal optical microscope which aims to see the size of the grains formed in order to determine the mechanical properties of the resulting casting product [7].

Copper is a chemical element with the symbol Cu and atomic number 29. It is a soft, malleable, and ductile metal with very high thermal and electrical conductivity. Freshly exposed pure copper has a pinkish-orange color. The cylinder block is the main part of the engine, housing the pistons and mounting the cylinder head and crankshaft mechanism. It is made of gray cast iron. Over time, this material has been abandoned due to the difficulty of dissipating heat generated by the combustion process, requiring further development [8]. Carbon steel, particularly AISI 1045, is widely used in industry due to its mechanical properties, which can be improved through heat treatment. Variations in temperature and cooling media such as mineral water and oil significantly affect hardness and corrosion rates, with best results achieved with water quenching at 850°C [9].

II. RESEARCH METHODS

This study used a quantitative experimental approach to analyze the effect of varying cooling media on the mechanical properties of used cylinder blocks made from cast copper alloy. This approach was chosen to allow for precise measurements and strict variable control, in accordance with engineering materials testing principles used in thermal alloy research [10].

2.1. Materials and Specimen Preparation

The raw material, used cylinder blocks from motor vehicles, was collected from a local reconditioning workshop. The used cylinder block material was then mixed with copper, with a composition of 85% by weight of used cylinder block and 15% by weight of copper. The two materials were then melted in a heating furnace. Subsequently, specimens were formed with standard hardness test dimensions (10mm × 10mm × 10mm) and toughness test dimensions (10mm × 10mm × 55mm with a 2mm V-notch) using a water-cooled bandsaw to avoid thermal deformation. This cutting procedure was based on practices used in recycled metal research [11].

2.2. Heat Treatment Design

The heat treatment process consisted of three main stages: austenitization, quenching, and tempering. The specimens were heated in an electric furnace at 850°C for 60 minutes to ensure phase homogenization. This temperature and duration are the optimum parameters for Cu–Ti–Fe alloys. After reaching the austenitization temperature, the specimens were immediately quenched in three media: a water–salt mixture (9:1 volume), a water–salt mixture (8:2 volume), and a water–salt mixture (7:3 volume). Quenching was carried out at room temperature (±27°C) in a 5-liter stainless steel tank. Each medium was gently stirred to avoid stagnation and accelerate cooling uniformity; this technique is based on recommendations from bio-quenchant-based cooling experiments [12].

2.3. Hardness and Toughness Testing

After tempering at 300°C for 1 hour, the specimens were tested using a Vickers microhardness tester (10 kgf, 15 seconds) in accordance with ISO 148-1 [13] and ASTM E92-17 [14] standards. Test points were taken three times on different surfaces, and the results were averaged. For toughness, the Charpy impact test method was used based on ISO 148-1 [13] and ASTM E23-23 [15] standards. The testing machine used a 300 J energy pendulum and was conducted at room temperature.

2.4. Validity and Reproducibility

To ensure internal validity, all specimens were tested under identical conditions and by the same operator to reduce human variability. External validity was maintained by using international standards and methodologies proven in previous studies in metallurgy [16]. Replications for each type of cooling medium also aimed to increase the accuracy and reproducibility of this study.

III. RESULTS AND DISCUSSION

Figure 1 shows the relationship between variations in cooling media and the hardness value (Hardness HV) of a metal material after the heat treatment process. Three types of cooling media used consisted of a mixture of water and salt with different concentrations, namely: 90% water: 10% salt, 80% water: 20% salt, and 70% water: 30% salt. Based on Figure 1, there was an increase in the hardness value along with the increase in the salt concentration in the cooling media.

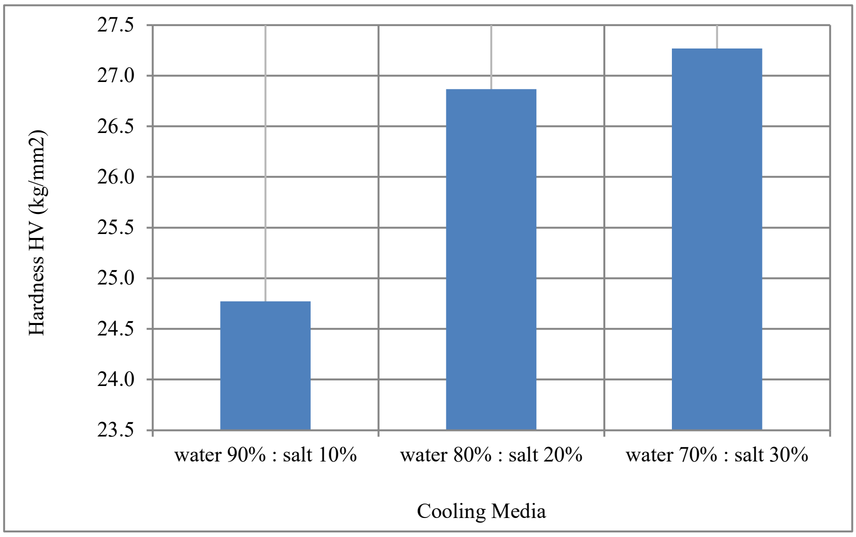


Figure 1. Graph of the relationship between cooling media and HV hardness.

The increase in hardness aligns with the basic principle of metal cooling during quenching, where higher cooling rates tend to form a greater amount of martensite, the hardest structure in low-alloy steel [17]. The mixture of water and salt increases thermal conductivity and accelerates heat transfer from the hot metal to the cooling medium. The higher the salt concentration, the greater the temperature difference between the metal and the solution, and the faster the cooling process.

This faster temperature drop results in the formation of a more dominant and uniform martensite structure in the metal's microstructure. A cooling medium with a high salt content can stabilize the austenite-to-martensite transformation process instantly without allowing the metal to pass through the critical temperature range for too long [18]. Therefore, a 30% water-salt solution produces the highest hardness value of approximately 27.3 kg/mm², compared to solutions with 20% and 10% salt content, which produce hardnesses of approximately 26.9 kg/mm² and 24.8 kg/mm², respectively (Figure 1).

In addition, the ionization effect of salt in water contributes to increasing the thermal conductivity of the solution, which accelerates the cooling rate [19]. Na^+ and Cl^- ions in the solution play a role in reducing surface tension and improving contact between the metal surface and the liquid, so that there is no vapor layer that hinders heat transfer (Leidenfrost phenomenon).

In the context of heat treatment, it is also important to consider the aspect of cooling homogeneity. A more concentrated salt solution medium (30%) shows more uniform cooling, which reduces the possibility of thermal deformation and cracking due to uneven cooling [20]. Therefore, the choice of cooling solution concentration affects not only the hardness but also the structural integrity of the material after quenching.

Figure 2 shows that impact toughness decreases with increasing salt concentration in the cooling medium. The highest value of 6300 J/m² was achieved when quenching with 90% water:10% salt, then decreased to 6033 J/m² for 80% water:20% salt, and reached a lowest value of 5733 J/m² for 70% water:30% salt.

This decrease can be explained by examining the relationship between the microstructure resulting from rapid cooling and the metal's ductility. Rapid cooling due to high salt concentrations tends to form a hard but brittle martensite structure, thereby reducing impact toughness [21]. Impact toughness is the ability of a material to absorb energy before fracturing under dynamic loading conditions. When the martensite structure dominates, the metal becomes harder but more susceptible to fracture under shock loads.

Increasing the cooling rate leads to a reduction in the softer and more ductile ferrite and pearlite phases, and promotes the formation of hard and brittle martensite [22]. Thus, quenching using a 30% brine solution accelerates the transformation and produces a structure less able to absorb impact energy, resulting in a decrease in toughness.

Meanwhile, quenching using a 10% brine solution, the cooling rate is slower, allowing the formation of a mixed structure containing greater amounts of ferrite and pearlite, which supports plasticity and microdeformation when impact loads are applied. This explains why its impact toughness value is higher than other treatments.

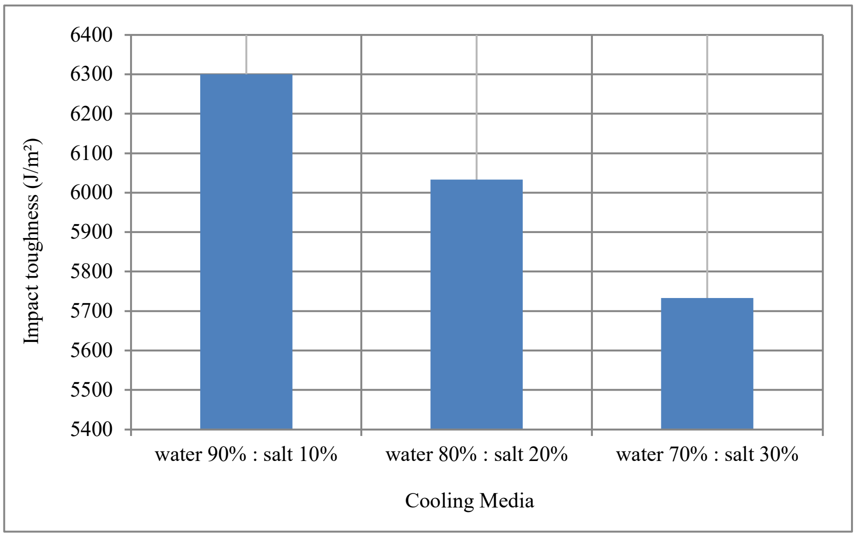
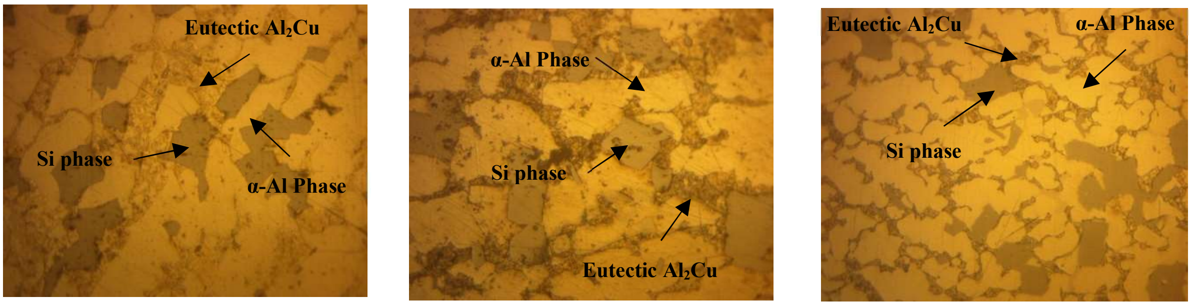


Figure 2. Graph of the relationship between cooling media and toughness

This fact indicates that there is a trade-off between hardness and toughness in steel heat treatment. When hardness increases due to rapid quenching, toughness usually decreases. Therefore, the choice of cooling medium must consider the final function of the component. Components requiring impact resistance (such as axles, agricultural implements, or vehicle frames) are better suited to mediums with moderate cooling rates, such as 10%–20% brine solutions, to maintain a balance between hardness and toughness [23].



(a) (b) (c)

Figure 3. (a) microstructure of water 90% salt 10% magnification 400X, (b) microstructure of water 80% salt 20% magnification 400X, (c) microstructure of water 70% salt 30% magnification 400X.

Figure 3(a) shows the observation of the microstructure formed in a specimen cooled with 90% water and 10% salt at 400X magnification. Figure 3(a) shows three gray, dark, and light regions. The bright yellow microstructure represents the α-Al structure, while the dark region represents the Al2Cu eutectic structure, which is located at the grain boundaries and generally appears non-uniform. The gray region represents the Si phase, which is silicon, often seen between the arms of aluminum dendrites and occupies cavities or gaps. It has an irregular, smoother, net-like shape and finer grain size.

Figure 3(b) shows the observation of the microstructure formed in a specimen cooled with 20% salt at 400X magnification. Figure 3(b) shows three gray, dark, and light regions. The light microstructure represents the α-Al structure, while the dark region represents the Al2Cu eutectic structure, which is located at the grain boundaries or segregation between dendrites and appears non-uniform. The gray area represents the Si phase structure, which is silicon, often seen between the arms of aluminum dendrites and occupies cavities or gaps, as well as dark areas with irregular and rough shapes.

Figure 3(c) shows the results of observations of the microstructure formed in a specimen cooled with 70% water and 30% salt at 400X magnification. Figure 3(c) shows three areas: gray, dark, and light. The light microstructure represents the α-Al structure, while the dark area represents the Al2Cu eutectic structure, which is located at grain boundaries or segregation between dendrites, which appears non-uniform. The gray area represents the Si phase structure, which is silicon, often seen between the arms of aluminum dendrites and occupies cavities or gaps, and has an irregular and rough shape following the eutectic pattern. The microstructure is dominated by large α-Al particles and a small, random Si phase, and the appearance of small, smooth, eutectic Al2Cu particles.

IV. CONCLUSION

The hardness value increases with increasing salt concentration in the cooling medium. The cooling medium of water + 30% salt is the most effective in increasing the hardness of the material. This is due to the high cooling rate and maximum martensite formation. The higher the salt concentration, the lower the impact toughness of the heat-treated metal. The cooling medium of 10% salt water produces the highest toughness due to the formation of a softer and more ductile microstructure. The use of 30% salt water causes the formation of a dominant amount of martensite, reducing the resistance to dynamic impact. The microstructure shows the presence of similar types of structures formed, variations in cooling media affect the distribution and morphology of the phases, which can impact the mechanical properties of the material. The quenching medium affects the morphology and distribution of the phases, where rapid cooling (such as 90% water + 10% salt) produces a sharper eutectic structure and a finer distribution, as well as a larger and dominant α-Al structure.

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