4.0 Alloying Elements and Microstructural Phases

There is a direct link between microstructure and properties and if the microstructure is altered by heat treatment, fabrication or composition then the properties will change accordingly.

4.1 Influence of Alloying Elements

4.1.1 Aluminium

Aluminium is the main strengthening element and normally ranges from 8–13% within this family of alloys. At the top end of the range, hardness figures of 30–44 HRC are possible. However, at these very high hardeneses, the ductility is reduced to 1% and these alloys can only be used in wear applications for forming and drawing tooling.

4.1.2 Manganese

Manganese is normally added as a deoxidant but is a major alloy addition to one important alloy, CuMn11Al8Fe3Ni3 (Appendix Tables App5 and App9) which, due to its good fluidity and castability, is used in the marine industry for ships’ propellers. Manganese is a beta phase stabiliser and also has a strengthening effect with 6% manganese being equivalent to 1% aluminium.

4.1.3 Nickel

Nickel is added in quantities ranging from 1–7%. Nickel is soluble in copper at lower levels and is added in conjunction with iron. Its presence improves the corrosion resistance and increases the mechanical strength. It also helps with the erosion resistance in high velocity water flow.

4.1.4 Iron

Iron can refine the structure and gives toughness. It has low solubility at room temperature in these alloys and can provide iron-rich kappa precipitates by controlled heat treatment to strengthen the alloy. It is beneficial for the iron content to be less than that of nickel.

4.1.5 Impurities

This is an important aspect of the specification, particularly those alloys used in military or naval applications where impact toughness is important, and for those alloys involved in welding operations. Low melting point elements such as lead, magnesium and phosphorus, commonly found in copper-based alloys, have a detrimental effect on hot formability, weldability, impact toughness and ductility.

- Lead is normally limited to 0.05% but the preferred limit is 0.01% as it can cause hot shortness in welded structures. A study on castings has indicated that lead and bismuth together caused hot shortness and should be limited to 0.05% bismuth and 0.01% lead when in combination 19.

- Magnesium is sometimes used as a deoxidant prior to adding aluminium and is normally limited to 0.05%. However, even at 0.01% it can have a harmful effect on ductility if present with lead towards the higher impurity limit 19.

- Phosphorus can cause hot shortness when greater than 0.01%.

4.2 Types of Microstructural Phases

The aluminium bronze and nickel aluminium bronze equilibrium phase diagrams shown in Figures 34 and 35 can appear rather complicated with a number of microstructural phases possible. In the binary system of copper and aluminium, Figure 34, for up to approximately 9% aluminium, the equilibrium metal structure is a single α (alpha) phase.
Above approximately 8% aluminium, a second phase known as \( \beta \) (beta) appears in the metal structure at high temperatures, which is stronger and harder. However, on slow cooling below 565°C, the \( \beta \) phase becomes unstable and decomposes to a finely divided structure (eutectoid) containing \( \alpha \) and another stronger, but less ductile, embrittling phase \( \gamma_2 \) (gamma 2). Also \( \gamma_2 \) can be attacked preferentially in seawater and is not desirable.

Nickel and iron additions suppress the \( \gamma_2 \) as in Figure 35. When both iron and nickel are present at nominally 5%, the structure of 9–10% aluminium alloys is modified and, instead of the formation of \( \gamma_2 \), a new phase \( \kappa \) (kappa) is created, which is more beneficial.
The nickel aluminium bronzes are similar to quench hardening steels in their structural morphology as they also undergo a martensitic transformation if cooled quickly from elevated temperatures. Figure 36 shows samples which have been polished and etched to reveal their structures and then examined at magnification under a metallurgical microscope.

![Figure 36 - CuAl10Ni5Fe4Mn DIN 2.0966 Widmanstätten martensitic structure. Water quenched from 900°C. Etched in acidified ferric chloride solution. x100 x500](image)

In the quenched condition, the structure consists of \( \alpha \) and martensitic \( \beta \) and some primary \( \kappa \) phases. In this condition the material has high strength but very limited ductility and is highly stressed, having been water quenched. This can be improved by a heat treatment called tempering. Tempering of the structure with aluminium >10% is normally conducted whilst the material is still warm to prevent stress cracking.

At the tempering temperature in the region of 500–715°C, the \( \beta \) transforms to \( \alpha + \kappa \) eutectoid (Figure 37) and further secondary \( \kappa \) precipitates from the structure. As time progresses, more of the \( \beta \) is transformed and, in doing so, the ductility increases, as does strength and hardness. This transformation process is used in many of the aerospace specifications due to its hardening effects. The hardening mechanism by the controlled precipitation of the kappa phase is also used to advantage for improving wear resistance in many bearing applications.

By viewing the structure in the unetched condition (Figure 38), the \( \kappa \) phase is more easily observed in its various forms. They have been designated by a numbering system based on the order in which they appear in the microstructure as the temperature falls on cooling. Although there are similarities between them, they can be distinguished by their morphology, location and distribution in the structure:

\[
\begin{align*}
\kappa_1 & \text{ has a rosette form} \\
\kappa_2 & \text{ is a spheroidised precipitate at the grain boundary} \\
\kappa_3 & \text{ is a lathe-shaped lamellar phase and} \\
\kappa_4 & \text{ is a fine precipitate within the grains.}
\end{align*}
\]

In terms of corrosion resistance, \( \kappa_2 \), \( \kappa_3 \) and \( \kappa_4 \) have little effect but \( \kappa_1 \) can have an influence, particularly if it forms a continuous network. Heat treatments have been developed to transform residual \( \beta \) to \( \alpha + \kappa \) and modify the \( \kappa_1 \) into a globular form and, in so doing, optimise the corrosion resistance in seawater. Heat treatment processes, including their effect on microstructure, are explained in more detail in Section 7.0.
Scanning electron microscope examination has enabled specific analysis of each phase type (Figure 39 and Table 6) \cite{10}. In general terms, \( \kappa_{\text{III}} \) differs as it is nickel-rich based on NiAl precipitates compared to the others which are relatively richer in iron and based on FeAl.
Figure 39 – Micrographic phase structure of nickel aluminium bronze - Magnification x500

Table 6 – Energy Dispersive X-Ray Spectroscopy Analysis of the Phases Present in Cast Nickel Aluminium Bronze \(^{(16)}\)

| Phase \(\) | Alloy Component (Wt %) |
| --- | --- | --- | --- | --- | --- |
| \(\alpha\) | 7.90 | 0.20 | 2.58 | 2.91 | 86.41 |
| \(\beta\) | 8.51 | 0.52 | 2.20 | 2.58 | 86.19 |
| \(\kappa_1\) | 17.35 | 1.25 | 35.69 | 18.07 | 27.64 |
| \(\kappa_2\) | 19.09 | 0.93 | 26.60 | 26.04 | 27.34 |
| \(\kappa_{II}\) | 18.87 | 0.45 | 12.86 | 26.80 | 41.03 |
| \(\kappa_{IV}\) | 8.12 | 0.84 | 42.70 | 35.32 | 13.01 |