Challenges in aluminum alloys for elevated temperature applications

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Al-Si-based alloys are the most widely used among aluminum casting alloys because of their good castability, high corrosion resistance, and good weldability. However, their mechanical properties rapidly decrease when they are exposed to high temperature. Two main reasons causing the alloys to lose their mechanical properties are the coarsening of precipitates because of high diffusivity of Cu and Mg in aluminum and the dissolution of the eutectic silicon phase due to its low eutectic temperature. Many studies have attempted to find new aluminum-based alloys having a eutectic temperature higher than Al-Si (577 °C), which are more suitable for high-temperature applications. It was reported that eutectic aluminum-nickel alloys (Al-Ni) can fulfill these requirements. The Al-Ni alloy contains very fine rod-like Al3Ni eutectic structure, which has good chemical stability and excellent thermal properties up to 500 °C. In spite of these, the mechanical properties of Al-Ni are not good enough to apply to high-temperature engineering structures. The matrix of eutectic Al-Ni is relatively weak because the solubility limit of Ni in Al is low. Therefore, alloying addition to Al-Ni plays an essential role not only in improving the mechanical properties of the alloys by the precipitation mechanism but also in preserving the thermal stability and structure of eutectic Al_3Ni. Moreover, precipitates that result from the alloying elements should have high thermal stability to improve the high-temperature properties of the Al-Ni alloy as well.

Scandium (Sc) is one of the alloying elements having high thermal stability. Eutectic Al-Ni alloys with Sc additions were studied through the microstructure, resultant hardness after elevated temperature exposure, high-temperature tensile properties, fracture behavior, and TEM micrographs. We found that the hardness increases with increasing amount of Sc and remains high when the temperature reaches 300 °C, which is a result of precipitation hardening of Al3Sc precipitates. The hardness then decreases because of coarsening of the precipitates. The tensile properties at high temperature of Al-6Ni alloys with Sc additions are better than those of Al-6Ni alloy without Sc addition. This can also be explained by the occurrence of Al3Sc precipitates. The fracture behavior of the alloys has the same trend as the tensile properties. Therefore, Al-6Ni-0.4Sc is a new candidate for high-temperature engineering applications.

We furthered our study on the simultaneous addition of zirconium (Zr) and scandium (Sc) in Al. Dilute, binary Al–Sc and Al–Zr alloys form, upon aging, a high number density of coherent, stable Al_3Sc and metastable Al_3Zr L12-nanoprecipitates, respectively, providing a sizeable precipitation strengthening effect at ambient and elevated temperatures. Although the volume fraction of these nanoprecipitates is below 1 vol.% (based on the equilibrium phase diagram), they have high thermal stability and excellent coarsening resistance up to 300 ◦C for Al_3Sc and 450 ◦C for Al_3Zr. This is because of the slow diffusivity of Sc and Zr in Al. We found that simultaneous Zr and Sc addition provides a combination of rapid L12-precipitation from Sc and slow L12-coarsening from Zr, achieving better coarsening- and creep resistance than if equivalent amounts of Sc and Zr are added separately. Partial replacement of Sc with Zr also reduces the cost of the alloy, while maintaining good mechanical properties at both room and elevated temperature. We will briefly discuss the mechanism of simultaneous addition of Zr and Sc in Al that will lead to the potential of new aluminum alloy with increased creep resistance for the new challenging applications.