Research Programs

Solution Heat Treatment Of Aluminum Alloys: Effect On Microstructure And Service Properties

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Goal

The overall goal has been to predict and control the response to solution treatment of cast Al-Si-Cu-Mg alloys whose initial microstructure, chemistry, and energetic state are determined by previous processing.

Approach

We surveyed the knowledge base that exists in industry and the metallurgical literature, characterized the range of commercial practice, and performed controlled experimentation to develop databases, understanding, and quantitative models for predicting response to solution treatment of cast aluminum alloys. The primary focus of the project has been to characterize and quantitatively model response to solution heat treatment of the microstructure and properties of cast 319 aluminum alloys for automotive applications. The results of six major tasks - a literature survey, industry surveys, characterization of vendor castings, controlled experiments, quantitative modeling, and database development - have been integrated and reported in terms of process-microstructure and process-property diagrams.

Outcome

The specific objective has been to develop a quantitative, predictive system to evaluate the evolution of microstructure and attainment of properties in critical locations of heat treatable aluminum alloy castings. Data and diagrams that may be used to predict and understand microstructure and property development as a result of solution heat treatment in relation to as-cast microstructure are highlighted in the body of this CHTE report and are discussed in detail in the appendices. To obtain the full report, please contact CHTE (dapelian@wpi.edu, or mpi@wpi.edu).

The underlying vision is to enable process engineers to utilize quantitative process models to design the total fabrication process for components made from complex aluminum alloys in order to obtain required properties in critical areas, in a way that is energy efficient and most economical. The underlying vision is a goal of a Department of Energy sponsored program at UConn and WPI, in collaboration with industry partners, that builds upon the results and concepts developed under the CHTE program.

Specific Objectives

- Expand and extend the knowledge base and the current understanding of how solution heat treatment affects the structure and properties of cast Al-Si-Cu-Mg alloys.
- Survey the current spectrum of industrial practice and the range of resulting microstructures and properties.
- Prepare computational models for predicting both solutionizing kinetics and the effect of solutionizing on microstructure.
- Develop a database of diffusivity and phase equilibria parameters directly pertinent to the solution heat treatment of Al-Si-Cu-Mg alloys.
- Design, perform, and analyze experiments to develop and validate the models.
- Compile and present the results of industrial surveys, quantitative models, and controlled experiments in a series of process diagrams that relate heat treatment to microstructure and properties.

Strategy and Major Tasks

A Literature Review — Prepare a literature review, specific to the 319 family of aluminum-silicon-copper casting alloys, that deals specifically with availability of data and understanding for constructing process - microstructure and process - property diagrams for solution heat treatment; availability of process diagrams; and experience with the application of process diagrams to the design of heat treatment operations within integrated manufacturing processes.

Survey of the Industry Knowledge Base — Contact CHTE member companies to survey current industry practices and developments that impact or are impacted by heat treating practices for aluminum alloys

Characterization of Vendor Castings — Characterize microstructures and properties achieved by two or more vendors using distinctly different processes.

Quantitative Process Model Development — Quantitatively model the thermal conditions and kinetics of microstructure development during casting and heat treatment.

Database Development — Compile and experimentally determine, where necessary, the data on diffusivity, phase equilibria, and kinetics of cast Al-Si-Cu-Mg alloys to understand and quantitatively model microstructure evolution during solution heat treatment.

Experimental Validation of Process Diagrams — Design and carry out an experimental program to develop process diagrams for the solution treatment of complex aluminum alloys that can be used for quantitative process design. Focus on the solution heat treatment of cast 319 alloy to map the interdependence of solution treatment and the previous casting process (melt chemistry and quality, casting process, and solidification parameters, such as thermal gradient and cooling rate).

Process Diagram Reports — Integrate the results of industry surveys, experiments, and modeling into quantitative process diagrams.

Summary

The body of the final report (available for CHTE members) is meant to summarize and integrate the important results of the CHTE program. Details of the procedures, results, and concepts of the program are found in the extensive appendices. Where one process-microstructure or process-property diagram is presented in the body of the report, similar diagrams for other compositions or melt treatments are included in the appendices.

Fundamentally important are the results of diffusion studies. D_{CuCu} and D_{SiSi} in the primary α-phase of the Al-Si-Cu ternary alloy are comparable to the tracer diffusion coefficients. The cross coefficients D_{CuSi} and D_{SiCu} for the α-phase of the ternary alloy are negligible. The addition of a small amount of Mg to the α-phase increases the diffusivity of Cu and Si significantly. The diffusivity of Cu through a two-phase region of α-phase and silicon-phase is substantially greater than through single-phase α-solid solution.

A computer model has been developed for predicting phase appearance, phase disappearance, and solute redistribution during solidification and solution heat treatment of binary and ternary alloys. The program has been applied to Al-Si-Cu alloys to show the parametric dependence of microstructure evolution during solution heat treatment. The extension of this computer model to quaternary and higher order alloys is the basis of a DOE sponsored program. The software developed under the DOE program will be distributed commercially. CHTE members who have an application for the software are encouraged to contact us.

Dendrite spacing and volume percent porosity are the two key microstructural parameters selected to characterize as-cast structure. Dendrite arm spacing is more difficult to measure but is a fundamental parameter for computer models. Dendrite cell spacing is easier to measure, but measurements are less consistent than for dendrite arm spacing.

The process-microstructure maps we developed characterize the range of as-cast microstructure in 319 aluminum alloy automotive castings made by three processes: permanent mold, lost foam, and composite (sand/Cu-chill) molds. Fine dendrite spacing and low volume percent porosity are sought in those regions of an automotive casting where good tensile and fatigue properties are specified.

The process-microstructure diagrams document the evolution of microstructure for the alloy of nominal composition. Of particular importance is the representation of the relative rate of dissolution of the θ-phase, $CuAl_2$, as a function of a parameter t/das^2 that is directly proportional to the relative diffusion time. The time at the solution treatment temperature, t, is used to characterize the solution treatment process and the dendrite spacing to characterize the as-cast microstructure and the casting process. Condensation of the data to a single curve makes the diagram a useful predictive tool.

The use of process-microstructure maps that plot relative amount of undissolved θ-phase vs. t/das^2 have been used to compare the influence of changes in chemistry on the rate of evolution of microstructure during solution treatment.

Process-property diagrams, the relation among as-cast microstructure, characterized by dendrite spacing, solution treatment (characterized by time at temperature), and tensile properties, are presented in four formats: two-dimensional curves, three-dimensional contour plots, tensile properties versus the parameter t/das^2, and Drouzy/Caceras quality charts.

Importantly, the data indicate that for all dendrite spacing, two hours of solution treatment at 505 C is sufficient to produce significant increases in tensile and yield strength. Where size and volume fraction of porosity increase with increasing dendrite spacing, as in the casting design used in this CHTE program, extended solution treatment will improve tensile strength, relative ductility, and overall quality only in locations with relatively fine dendrite spacing and volume fraction porosity.

We will build upon the results of the CHTE program in the program funded by the Department of Energy to develop an integrated model of the heat treatment process for cast aluminum alloys. We will extend the databases, understanding, and computer models developed under the CHTE program to develop commercially available software. The DOE program combines the talents of UConn and WPI researchers and builds on a complementary program on thermal analysis sponsored by CHTE at WPI. The continued involvement of CHTE members in guiding and collaborating in the DOE program is strongly encouraged. In particular, we invite CHTE members to bring to our attention challenges in the heat treating and metals processing industries where the software initiated under the CHTE program and being developed further under the DOE program can be applied.