2. PUBLISHABLE SUMMARY (2 pages)

Summary description (more on www.iFlowFePhase.info)

Aluminum-silicon base alloys are widely used in castings (foundry industry) due to their excellent castability and high strength-to-weight ratio. In the Al-Si alloys, the presence of small amounts of Fe and Mn brings about a complicated microstructure due to the formation of a rich variety of intermetallic phases (IMPs) during solidification, which generally have a negative effect on the mechanical and physical properties of a as cast part (porosity, cracks, hardness, lower strength). The classical methods of intermetallics treatment are: chemical processing, modification, Mn addition, alkali elements, heat treatment, solidification conditions). There only few publication about the influence of fluid flow on the microstructure and intermetallics. It was observed that Fe and Mn intermetallics in combination with flow have a different effect on microstructure and is possible to transform needle like Fe-phases to blocky ones. The application of rotating magnetic field (flow) could lead to better results in shortening Fe-phases than lowering Fe content.

The main goal of the project “iFlowFePhase” is to prepare new technology of Fe and Mn intermetallic phases treatment by fluid flow in Al-Mg-Si casting alloys. The project investigates problems of artificial fluid flow (melt stirring) influence on the growth, morphology and spatial arrangement of intermetallic phases in as-cast AlSi-base alloys containing especially Fe and Mn as alloying elements. Addition of Mg allows 3D visualization of IMPs, dendrites and eutectics. The “iFlowFePhase” studies concerns detailed tasks: solidification of casting specimens in MagFound facility by the presence of fluid flow and without it (in different solidification conditions), detailed analysis of the microstructure of the Al-Si alloys (dendritic pattern geometry, length, thickness, and density of IMPs, three dimensional morphology of IMPs, dendrites and eutectics), numerical modeling for physical understanding of the mechanisms leading to the anticipated changes in microstructure by the presence of IMPs and fluid flows. Project involves advanced unique facilities and modern scientific methods: solidification within MagFound, microstructure investigation by optical (Nikon) and SEM (Tescan) microscopes, x-ray Diffractometry (PANalytical Empyrean), metallography, quantitative image analysis (Multiscan, Image J), differential scanning calorimetry DSC (Metller Toledo), yield tensile tester (Instron), x-Ray tomography (v-tome-x s, GE).

Description of the work performed

- ***Task 1: Alloy preparation and selection,*** Alloys starting from high-purity elements have been molten, cast into a shape usable for MagFound with specified compositions AlSiFe, AlSiMn and AlSi (no Mg).
- ***Task 2: Solidification experiments,*** Around 34 solidification experiments in MagFound were performed with and without artificial fluid flow. We have applied slow bulk solidification conditions.
- ***Task 3: Local crystallographic analysis,*** Local X-ray diffractometry (Empyrean from PANalytical). The specimens were prepared, processed and data were collected.
- ***Task 4: Phase transition evaluation,*** Differential scanning calorimetry (Metller Toledo DSC-1). The DSC curves by different heating and cooling rates (5,10,40 K/min) were registered and anlysed.
- ***Task 5: Microstructure determination***, The samples were evaluated with Nikon OLM and Image J software. We measured characteristic parameters like Specific surface of dendrites S_v, Secondary Dendrite Arm Spacing λ_2, Average length L_β of the Fe-intermetallics β-Al_5FeSi, Number density n_β of β, Eutectics spacing λ_E of AlSi eutectics, Spacing λ_{Mg2Si} for Mg_2Si phases, Average length L_{Mn} and Number density n_{Mn} of Mn-intermetallics.
- ***Task 6: 3D morphology of IMPs,*** High-resolution x-ray tomography (X-Ray v-tome-x s, GE Phoenix located at PUT) was used and 3D geometries were scanned and analyzed for specified alloys specimens.
- ***Task 7: Yield strength correlations,*** The specimens require special treatment. The protective atmosphere and shape modification allowed minimization of porosity dimension and its localization for measurement.
- ***Task 8: Numerical modeling of the microstructure and flow,*** Thermo-Calc calculations performed for Binary and Ternary Phase Diagrams, Scheil-Gulliver solidification and Property diagrams. Micress simulation were done for prediction of bulk equiaxed solidification and Fluent for flow.

Description of the main results achieved so far

The effect of electromagnetic stirring on the microstructure is saved in solidified specimens. On the DSC heating and cooling curves, the visible points, picks and inflexions characterising transformations in alloys were analysed. The gained DSC curves do not differ under various flow conditions (without and with stirring). It seems that flow caused changes in microstructure are to fine for DSC measurements or the amounts of phases and characteristic temperatures stay unchanged, not influenced by stirring.

Electromagnetic stirring caused a transformation in microstructure from equiaxed dendritic to rosettes with minor dendrites as an effect of rotation of dendrite tips and ripening arms of deformed dendrites. In contrary to previous studies, flow decreased secondary dendrite arm spacing λ_2 for AlSi5Fe1.0 alloy, while for Mg-containing alloys spacing λ_2 was almost unchanged. Specific surface S_v decreased under flow and signalled the modification of microstructure. Forced convection decreased the length of β-Al_5FeSi (20%) and increased number density (47%) in AlSi5Fe1.0 alloy in equiaxed solidification, in accordance with directional solidification. Stirring decreased length of Mn-rich phases (9%) and increased number density (35%) in AlMg5Si5Mn1.0 alloy. Melt flow changed eutectic spacing λ_E depending on alloy composition, while λ_{Mg2Si} increased weakly for all alloys. Mg_2Si phases reduced fluid flow and consequentially reduced shortening of β-Al_5FeSi phases, diminished secondary arm ripening caused by forced convection and supported diffusive ripening. Mg_2Si do not disturb transformation from dendrites to rosettes under flow. Shortening of β phases caused by stirring occurred in equiaxed solidification without remelting, probably by mechanical fragmentation, modified solute distribution and additional nucleation sites. Stirring application depends on chemical composition, precipitating phases (e.g., Mg_2Si) and growth sequence of phases.

X-ray tomography showed 3D geometry of β-Al_5FeSi and Mn-phases, the dimension and, morphology and localization in the specimens. The measured volume fraction, surface and specific surface of phases presented no connection to melt stirring. The results of X-ray diffractometry has not presented any effect of melt flow on microstructure phases quantity analysis, crystallographic texture. The final quality of casting is influenced by the presence of materials discontinuity, shrinkage defects and gas porosity. The protective atmosphere and shape modification allowed for minimization of porosity dimension and its localization in studied specimens, but still porosities are to large for repeatable results by yield strength testing.

Mushy zone morphology in AlSiMn and AlSiFeMn alloys was studied using directional solidification and the CALPHAD technique. Property diagrams and solidification paths presented the segregation effect on the characteristic temperatures, mushy zone length and the sequence of occurring phases whilst 2D maps enabled visualization of the mushy zone during directional solidification. The study revealed mushy zones with dense dendritic structure and liquid channels empty of Mn phases, where Mn intermetallics may not flow in the liquid, but only between dendrite arms. In other samples (those with more Si and Mn), thinner dendritic structures were found, where the central liquid channels were filled with $Al_{15}Si_2Mn_4$, which also formed above the dendrites. These freely flowing Mn regions seem to have the possibility to influence the fluidity of liquid above the dendrites, as well as the nucleation and growth of other intermetallics and dendrites. The melt flow may lead to a mainly dendritic mushy zone or to a mushy with dendrites reaching only the lower half of mushy and Mn intermetallics forming in upper half. The $Al_{15}Si_2Mn_4$-rich liquid channel that was elucidated high flow possibility of melt only and melt with Mn precipitates. Different flow possibilities in the dendritic and eutectic areas indicate complex interactions between phases and complicated fluid flow effects on the microstructure, which vary by alloy composition.

Potential exploitation of results

Turbulent flow during mold pouring is the negative effect because of oxides and air entrapment into casting. But the flow after complete pouring and fully filled mold improves the microstructure of solidified castings trough modification of dendritic structure (e.g. lower secondary dendrite arm spacing SDAS). The potential exploitation relies on designed stirring and controlled fluid flow (in solidifying castings) generated through located in mold electromagnetic stirrers EMS. Such technology might be applied in continuous casting, impermanent mold (sand mold) and die casting (metal mould casting). In continuous casting the molten metal is solidified into a product (called strand cast) shaped as "semifinished" billet, bloom, or slab for subsequent rolling in the finishing mills. Similar technology EMS might be applied in gravity die casting and pressure die casting for shape casting. Another potential exploitation of the understanding of the physical mechanisms is creation of numerical models including them into casting simulation software.

Prospects of the research career development and re-integration

The aim of the Fellow is to develop his scientific research at the Poznan University of Technology PUT and extend his research on the microstructure, physical processes occurring during solidification of alloys and numerical simulation in casting technology. The Fellow owns the degree of Doctor Engineer (PhD Eng.) and position called "adiunkt" (Assistant Professor) till February 2019. For the researcher Piotr Mikolajczak, the very important is the possibility of financing studies by "iFlowFePhase" project, that lead him to professor thesis preparation. The Fellow is strongly determined to prepare the professor thesis and achieve the level of an independent expert (doctor habilitus) till February 2019. The level of an independent expert (doctor habilitus) assures long term position at the PUT.