2. PUBLISHABLE SUMMARY (2 pages)

Summary description (more information 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 prepared for MagFound with compositions AlMg5Si5Fe(0-1.0)Mn(0-1.0), AlSiFe, AlSiMn and AlSi (without Mg).
- ***Task 2: Solidification experiments,*** Around 100 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 various flow, heating and cooling rates (5,10,40 K/min) were registered and analyzed.
- ***Task 5: Microstructure determination***, The samples were evaluated with Nikon OLM and Image J software. We measured: 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-phases.
- ***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 for yield strength testing (Instron Mode 4001) were prepared by protective atmosphere and shape modification for porosity minimization.
- ***Task 8: Numerical modeling of the microstructure and flow,*** Thermo-Calc calculations were performed for Ternary Phase Diagrams, Scheil solidification and Property diagrams for mushy zone prediction. Micress simulations were done for prediction of bulk equiaxed solidification and Fluent for flow.

Description of the main results achieved so far

On the 2D micros-sections, electromagnetic stirring caused a transformation from equiaxed dendritic to rosettes, signalled by decreased Specific surface S_v. In contrary to previous studies, flow decreased secondary dendrite arm spacing λ_2 slightly for AlSi5Fe1.0 alloy, while for Mg-containing alloys λ_2 was unchanged. Forced convection decreased the length of β-Al_5FeSi (20%) and increased number density (47%) in AlSi5Fe1.0 alloy, 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, while λ_{Mg2Si} increased weakly for all alloys. In AlMg5Si5Fe1.0 alloy β starts to grow at 584 °C and Mg_2Si at 582 °C and Mg_2Si seems to diminish the flow possibilities and shortening of β intermetallics and diminished secondary arm λ_2 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. Electromagnetic stirring EMS can be used in alloys with high Fe content and limited amount of phases diminishing flow during β growth.

The effect of electromagnetic stirring on the microstructure is recorded in solidified specimens. On the DSC curves, the 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.

X-ray tomography showed 3D geometry of β-Al_5FeSi and Mn-phases, the dimension, 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 were to large for repeatable results by yield strength testing.

Mushy zone morphology in AlSiFe, 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 proposed and developed 2D maps enabled visualization of the mushy zone. 2D maps revealed liquid channel in center of the mushy zone, that can reach final solidification reaction at temperature 575 ºC, and in AlSiFe alloys presented precipitation of β-Al_5FeSi phases before the formation α-Al dendrites in the specimen center, where about 33% of all β precipitated in the liquid channel and can flow (because of magnetic stirring) into melt above mushy. The study revealed mushy zones with dense dendritic structure and liquid channels empty of Mn phases, where Mn intermetallics flow only in dendritic area. In alloys with more Si and Mn and thinner dendritic structures, the central liquid channels were filled with $Al_{15}Si_2Mn_4$, which also overwhelming precipitated above the dendrites tips. These freely flowing Mn phases seem to have the possibility to influence the fluidity, nucleation and growth of other intermetallics and dendrites. 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. Micress simulations presented thermal and solutal conditions by directional and equiaxed solidification.

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, rosette microstructure). 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 where molten metal is solidified into a product (called strand cast) shaped as "semifinished" billet, bloom, or slab. EMS might be applied in shape casting, in impermanent mold (sand mold) and in die casting (metal mold casting), by gravity or pressure casting. Another potential exploitation of the understanding of the physical mechanisms is development of numerical models for casting simulation software, that assists the design of foundry technology and optimization of casting property.

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 was the possibility of financing research studies by “iFlowFePhase” project, that assists him and lead 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.