Nano-crystalline P/M Aluminium for Automotive Applications

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Abstract. The reduction of total vehicle weight and lowering of moving masses within the engine are key elements to overcome future emission challenges of the automotive industry. Within a German BMBF funded project the melt spinning technology will be driven to a series production status. The very fast cooling condition of the melt leads to a nano-structure of the aluminium material. This results in new material properties of known alloys. The strength increases dramatically without lowered forming behaviour. With this process the freedom of designing complex alloys is very flexible. Different alloys have been investigated for several applications, where high strength at room and elevated temperatures and/or high wear resistance is required. This paper presents some results regarding the processing, microstructure and mechanical properties of a developed Al-Ni-Fe alloy. This joined research project with partners from the automotive industry as well as automotive suppliers and universities is funded by the German BMBF "NanoMobile" Program under Project number 03X3008.
1. Introduction

Rapid solidification is an effective way to get a supersaturated solid solution, thermal stable dispersoids, metastable phases or amorphous phase. The common aspect of all P/M processing routes is the rapid extraction of thermal energy from the molten alloy to the state of solid powder material. Cooling rates can rise up to $10^6$ K/s and limit the thickness of the rapidly solidified structure, which is therefore available only within fine powders, thin ribbons or flakes. Since industrial application of such discrete particles is limited, the manufacture of bulk components is required. Hot extrusion is frequently used for consolidation of these particles. High resistance to plastic deformation resulting from high strength of the rapidly solidified microstructures significantly limits the possibility to consolidate such materials at industrially acceptable and available extrusion pressures. An increasing temperature reduces this problem, but can result in undesirable and irreversible changes of the microstructures by e.g. coarsening of nano-sized matrix or dispersoids. Among the variety of developed rapidly solidified materials are preferentially interesting those, which can be produced in an industrial scale with preservation of the unique nano-/microstructure and therefore to the bulk material. The class of dispersion-strengthened Al-Fe-Ni alloys has a large potential to fulfil these requirements regarding industrial processability and technical performance [1].

2. Experimental

An industrial scale melt spinning system (200 kg batch size) has been used to produce fully alloyed ribbons of the Al-Ni-Fe based alloy. Cooling rate was in the range of $10^6$ K/s thus giving best conditions for generating unique alloy properties. Ribbons had a thickness less than 100 µm and a width of approx. 10 mm. These ribbons have been cut into flakes with a size less than 1 mm. As the hardness of the flakes is in excess of 270 HV0.02 compaction of the flakes has been done by hot isostatic pressing (HIP) using standard industrial equipment. Prior to HIP the flakes have been canned, degassed, evacuated and sealed in Al cans. After HIP the billets have been extruded (indirect extrusion mode) into round bars with an extrusion ratio of 1:17 ending up with a diameter of 26.5 mm. All test pieces have been machined from this feedstock.

X-ray diffraction (XRD) (Siemens D5000 diffractometer, CoKα radiation), scanning electron microscopy (SEM) (DSM 982 GEMINI equipment of ZEISS), transmission electron microscopy (TEM) and high-resolution Scanning-Transmission Electron Microscope (S-5500 made by Hitachi, 30kV STEM coupled with an Energy Dispersive Spectrometer) were used for structural characterization.

Tensile specimens with the gauge of ø 6 mm x 32 mm and fatigue specimens of ø 6 mm diameter, 35 mm gauge length, 22 mm screw heads and an overall length of 110 mm were machined from extruded rods. Tensile properties were measured at room and elevated temperatures up to 400°C using ZWICK 20 kN-universal testing machine with the cross-head speed of 1 mm/min. Axial fatigue tests were performed using resonance machines (100 kN-HFP 422, type Amsler/Rumul) yielding frequencies of about 120 Hz.

3. Results and Discussion

3.1 Microstructure of the extruded alloy

XRD revealed that the microstructure of the extruded alloy contained only α-Al and τ-Al₉FeNi. The volume fraction of this intermetallic phase is estimated to be about 20 vol% by the comparison of the experimental and theoretical X-ray patterns of the corresponding phase mixture. The size of the intermetallics strongly varies within bands up to a value of about 0.8 µm for coarser regions and 0.1-0.2 µm within the finer microstructures can be estimated. Rapidly solidified Al-Fe-Ni alloys derive their attractive ambient and elevated temperature properties from this monoclinic τ-Al₉FeNi which is isomorphous with Al₉Co₂ [2, 3]. The τ phase is thermally stable, shear resistant and forms a defined orientation relationship with α-Al [4].
In the Al areas the grains were revealed by tilting the specimen in the microscope to obtain the image of grain boundaries. In Figure 1 the sequence of images is shown in which the grains appear or disappear depending on the specimen inclination with regard to the incident electron beam. The BF transmission mode images were used to manually trace the image of Al grain boundaries in the investigated material. The average size value of the Al matrix is about 280 nm with a standard deviation of 90 nm. There was no significant change in the microstructure of the extruded alloy as a result of thermal exposure up to about 400 °C. Conformation of this thermal stability of the microstructure is provided by the room-temperature hardness levels following isothermal elevated temperature treatments. After heat treatment at 450 °C the coarsening of the intermetallic phase became evident.

3.2 Mechanical properties of the extruded material
To characterize the suitability of the new material for load bearing applications, tensile and fatigue tests were made over a wide temperature range. The room temperature yield strength of about 530 MPa does not significantly drop up to 150 °C. This temperature increase is associated by a remarkable improvement in ductility of some 200 %. Noticeable softening commences above 150 °C which makes the ductility grow further. At 200 °C, the yield strength exceeds still the 400 MPa level which is a remarkable value for an aluminium alloy.

In Fig. 2 the temperature dependence of the tensile strength is compared with that of the conventional Cu-Mg-Fe-Ni alloyed grade AA 2618 after T6 heat treatment. At 180 °C the new alloy has about 150 MPa more tensile strength or, if the tensile strength is to be maintained at 310 MPa, allows 50 °C higher service temperatures.
Fatigue properties were determined at room temperature, 150 and 250 °C. If the stress ratio R is defined as $R = \sigma_{\text{min}}/\sigma_{\text{max}}$ during a load cycle, stress ratios of $-2.3$, $-1$ and $0$ were applied at room temperature and 250 °C. At 150 °C only $R = -1$ and $R = 0$ were tested. For each S-N curve about 15 specimens were available. The tests were discontinued at $10^7$ cycles for time reasons; well knowing that at this cycle number a so-called endurance limit has not yet been reached. The fatigue amplitudes at $10^7$ cycles are shown as a Haigh diagram in Fig. 3. There is virtually no curvature in the stress amplitude versus mean stress within $-2.3 \leq R \leq 0$. The test results at room temperature are in good consideration with the linear relation by Goodman. At 250 °C the slope is less inclined than at room temperature which signifies the high ductility at elevated temperatures. Most striking is, however, the unusually high fatigue strength level at 250 °C with mean stresses. The alloy is obviously rather resistant to creep deformation up to this temperature.

**Figure 2:** Effect of temperature on the ultimate tensile strength of the extruded Al-Fe-Ni alloy compared to the conventional aluminium alloy AA2618.

**Figure 3:** Influence of temperature to fatigue strength in the Haigh diagram.
4. Summary and conclusions

A new high performance Al-Ni-Fe based alloy has successfully been developed by applying melt spinning technology and downstream processing via HIP and hot extrusion. The alloy exhibits excellent static strength properties in excess of 600 MPa at room temperature and more than 400 MPa at 200 °C. Compared to those properties for the standard wrought alloy AA2618 this is an overall improvement of at least 30 – 40 % for the whole temperature range from -196 up to 250 °C. Dynamic properties have been evaluated at room temperature, 150 °C and 250 °C and again this alloy shows superior properties compared to those ones of conventional counterparts. As an additional benefit the alloy doesn’t need any heat treatment to show up with these properties.

The material has a nano-crystalline microstructure and it exhibits an excellent thermal stability. Up to an annealing temperature of 400 °C the microstructure still stays nano-crystalline. This makes it a preferred alloy for elevated temperature application such like valve train components or compressor wheels where a high fatigue strength and good ductility are basis requirements. It is expected that this type of alloys will contribute significantly to solve today’s challenges in automotive in terms of lowering fuel consumption, reducing emissions and downsizing of engines.

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