Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

USING SCRAP IN RECYCLING ALLOYS FOR STRUCTURAL APPLICATIONS IN THE AUTOMOTIVE INDUSTRY

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Keywords: recycling, scrap, die casting, light weight design, alloy optimization

Abstract

After studying CO_2 emissions caused by vehicles itself, automotive manufacturers now also consider CO_2 emission during the production of vehicles and attempt to reduce them according to a holistic approach. This is where AUDI AG as first OEM together with AMAG Casting applies this approach at the production of structural components, which have been produced by primary alloys up to now. This component segment, which is significantly growing by now, requests mainly high ductility values, in order to absorb as much energy as possible in the case of a crash. In addition to the Fe-content, recycling alloys also have further tramp elements, which occur inevitably at scrap treatment. Besides Cu and Zn there are also elements like Bi, Cr, Ni, Sb, Sn etc. which have to be considered, since they influence the requested alloy properties in a negative way. The results of the existing work show that skilled scrap input at the alloy production can reduce this negative effect close to zero.

Introduction

Within the perennial climate debate the necessity of the CO_2 reduction in road traffic, as an option to reduce the anthropogenic greenhouse gas emission, is consistently mentioned. This can be carried out during the utilization phase of the vehicle or already during production. Regarding the utilization phase, weight reduction in addition to the big trend of downsizing, resulting in efficiency increase of the engines should be alluded [1]. Smaller, more efficient engines reduce the weight significantly. A further relevant issue is light weight construction, which is for example promoted in “reversal of the weight spiral” [2] by AUDI AG. Hence the vehicle weight of the current Audi A3 2.0 TDI 110 kW could be reduced by 40 kg [3, 4], as well as the weight of the AUDI A6 3.0 TDI Quattro by 80 kg [2, 4], in comparison to the respective previous models. Weight reduction was primarily achieved by the intensified light weight construction of carriage, engine, drive chain and running gear, amongst others by the increased use of light alloys (approx. 20 % more than in former models) [2, 3], mainly aluminum. The importance of aluminum as a construction material in vehicles has also been rising. This is true, especially in Audi Space Frame® (ASF) Technology, which uses more and more aluminum cast components for structure applications. Cast parts have a big advantage: The entire component assembly and their functions can be united in one single part. Increasing requirements in crash safety request components with very high ductility. This can be achieved with vacuum aided die cast processes as well as with prevalent heat-treated primary Al-alloys. Since vehicles become more efficient and emit less CO_2, during use phase, the consideration of the energy input during the production gets more important. In the best case electric cars, working with renewable power emit just a small quantity of CO_2, although during their production more greenhouse gases are emitted, than during production of similar automobiles with combustion engines [2]. Production of primary aluminum requests a substantial energy input. Thereby, depending on the type of energy generation for the electrolysis of aluminum, an average of 8.57 kg CO_2 emission per each kg aluminum [5]. Thereof about 4.58 kg CO_2 are required for energy generation [5]. This depends on the location of the electrolysis and the resultant power source. This figure refers to the European power mix with more than 50% hydropower [5]. Therefore CO_2 emissions vary depending on the used quantity of renewable energy for the Al-electrolysis. Recycling of aluminum requires only approx. 5 % of the energy that is needed for the production of primary aluminum [6, 7]. Thus the more scrap is used in Al-alloys, the less CO_2 is emitted during its production. Therefore a recycling-alloy reduces green house gases already at the production of a component. As a further logical step at vehicle production is to produce components by recycling material, which were manufactured by primary aluminum up to now. A substantial quantity of energy and therefore CO_2 produced for its generation, would be reduced in the production process.

Recycling friendly alloys

A requirement for an increased scrap input is the development of alloys which enables Al-recycling and the use of higher input rates of different scraps. The terms scrap, recycling and recycled content are well-defined by EN ISO 14021:2001. This international norm standardizes that only scrap before and after using may be used for the calculation of the recycled content and the scrap content. Scrap produced, which can be reused in the same process, is not included in this norm [9]. This means, gates and overflows, which are re-casted within the component production, must not be calculated for the recycled content. However swarf, produced during component machining may be used for this calculation. AMAG complies strictly with the norm by calculating the scrap content of an alloy (the recycled content) individually per each batch. Also the statements of this article are conform with this norm.

Technical and economical produced recycling alloys generally contain trace elements, which are not contained in primary aluminum. They also show a content of alloying elements like Fe, Cu and Zn, which do not exceed the specific tolerance limits. This is one of the reasons, why primary aluminum like DIN EN 1706 2010 [10] is used for cast components with high ductility. To establish more recycling alloys in demanding aluminum components, it is necessary to achieve a comprehensive range of knowledge about the effect of these elements including their mutual reaction, in order to be able to question the necessity of the tightly put tolerance limits. An example, a small increase of the tolerable Cu-content could lead to a considerable increase of the potential scrap input – without a noticeable influence on the corrosion properties. However alloy tolerance limits can only be extended in agreement with the customer, because each part has different demands on the material.

The critical indicator of the aforementioned application, the here considered recycling alloy, is ductility. Correct heat treating of the primary alloy AlSi10MnMg (EN AC-43500 - DIN EN 1706:2010) results in excellent values in the component and reaches the values stated in the norm (provided a defect-free casting). The following values for die cast have to be fullfilled depending on the heat treating (Table 1).

Type	0,2 %-yield strength $Rp_{0,2}$ *(MPa)*	tensile strength Rm *(MPa)*	elongation at break A *(%)*
Die cast by T5	150	270	4
Die cast by T7	120	200	12

Table 1: Mechanical properties of EN AC-43500 (AlSi10MnMg) according to DIN EN 1706:2010.

Since these requirements were only achieved by primary alloys, DIN EN 1706 2010 also defines a suitable chemical composition (Table 2).

	Si	Fe	Cu	Mn	Mg	Zn	Ti	Others single	Others total
min	9.0			0.40	0.15				
	to			*to*	*to*				
max	11.5	0.20	0.03	0.80	0.60	0.07	0.15	0.05	0.15

Table 2: Alloy composition (in weight-%) of EN AC-43500 according to DIN EN 1706:2010.

Some values of the above stated tables can be found in other alloy specifications of alloy suppliers. The limitation of other elements is mostly stated with 0,05 mass percent (that equates 500 ppm), in which the sum of the tramp elements must not exceed 0,15 mass percent. This specification states furthermore, that the elements Cu and Zn are limited at 300 ppm and 700 ppm respectively. A recycling alloy with such narrow tolerance limits for both of these elements is technical and economical difficult to produce, because only a few segregated scraps can be used.

The limitation of Na, Ca and P can also be found in many alloy specifications. The limit changes depending on the customers and their experiences – though a limit of 20 ppm is an established value. This restriction leads also to a significant reduction of the potential, to produce recycling alloys according to table 2. A minor extension of the tolerance limits, for example from 20 ppm to 25 ppm, can make significant differences, regarding type and quantity of the usable input-material. In primary alloys, the limitation of further elements to 500 ppm is rather unimportant, because elements not stated in the table are not present in electrolysis material, or only in a small quantity. By using scrap it has to be considered that especially post-consumer scraps can show impurities of other materials and therefore the content of micro elements increases. Due to this, along the whole production line of AMAG, from sampling to final product, 30 elements in different range of concentrations are investigated, because of the plant, different types and origins of scrap are processed.

Elements like antimony, chrome, nickel, bismuth, tin and others can, at contents of 0.05 mass percentage, affect the mechanical properties of an alloy. Hence it is important to define the limits of these elements trough metallurgical knowledge and joint discussion with the customer, without losing the requested properties of the alloy and without unnecessary limitation of the scrap input rate. Not only the content of scrap is defined trough the amount of allowed micro elements, but also the type of input material. It is entirely possible to produce an alloy specification according to table 2 with 30% scrap content. However the inserted scraps should then be mainly clean and correctly sorted before using (e.g. chips). This has to be considered, referring to availability and price.

Table 3 shows the material input at the production of the specified alloy, according to DIN EN 1706:201, those with loosening of the tolerance limit of iron, copper and zinc (but with similar low contents of micro elements, like in primary alloys), and those with an additional defined tolerance for micro elements, which have no negative effects on the performance of the alloy. No micro element exceeds the 500 ppm limit and also the total content of them remains under the specified 0.15 mass percent in the specification. Though it is important these limits are defined, to ensure the requested properties of the alloy, nevertheless some micro elements are clearly less than 500 ppm due to technical reasons.

Extension / Tolerance specification	EN1706	Cu, Fe, Zn	Cu, Fe, Zn +trace elements
Ingots use	> 60	< 30	< 10
Alloy elements	10	10	10
Scrap	< 30	> 60	> 80

Table 3: Input rates of ingots, alloy elements and scraps according to the specifications. Values at a defined input quantity (scrap availability) rounded to 5 %. (Status September 2013)

The values in table 3 are standard values, which can vary according to the scrap availability and the scrap purity, but show which effects little variations in tolerance of the chemical composition have on the scrap input rate.

As already mentioned the quantity and quality of the input material could be raised by extending the tolerance limits (as shown in figure 1)

Hence not only clean, exactly defined kinds of scrap can be used as alloy inputs (2a), but also waste metal and swarf – which can be partially oily – and others.

To ensure the requested scrap input rate and their quality, an estimation of the potential production quantity and the production time line is important. To ensure type, quantity and availability of the input material, these factors have to be known.

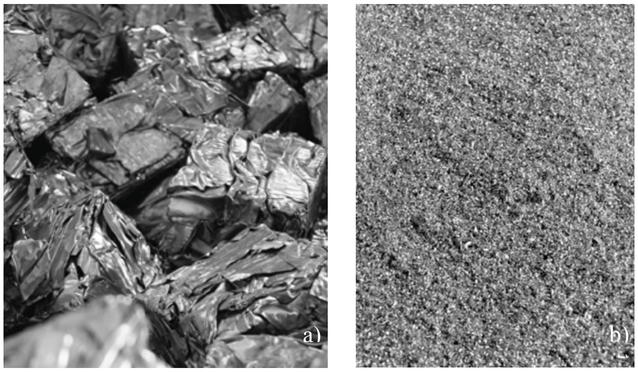

Figure 1: Examples for scrap input for recycling alloys; a) Clean, homogeneous sheets or plate packages with defined composition; b) Oil and emulsion coated aluminum chips, from machined processing (partially mixed with other materials)

Course of action for optimization of alloys

In the present project the critical parameter of the recycling alloy is the ductility of the component. To get optimized results, a matrix of elements which occur in recycling alloys, was created (Table 4). Hence, the influence of the particular materials on this parameter could be investigated.

Moreover, variations of the alloy additives were chosen, to investigate the influence of the elements on the cast ability of the alloy, the ability for joining processes like welding and riveting and the corrosion properties. Their negative effect had to be as small as possible.

Alloy elements compared to primary alloys				
Cu	none	minor	average	
Fe		minor	average	high
Zn	none	minor	average	high
Trace elements	none	minor	average	

Table 4: Experimental matrix to optimize the recycling alloy for the intended use, especially the up-keeping of the ductility in comparison to the primary alloy.

As this experimental matrix provides a high quantity of permutations, the first sequence had to be achieved through chill cast tests. Therefore, smaller quantities of material were melted in a crucible furnace, alloyed according to the requirements and a tensile test bar was cast. This procedure was also used in previous projects and dissertations at AMAG to determine the optimum mechanical values of alloys (Figure 2) [11, 12].

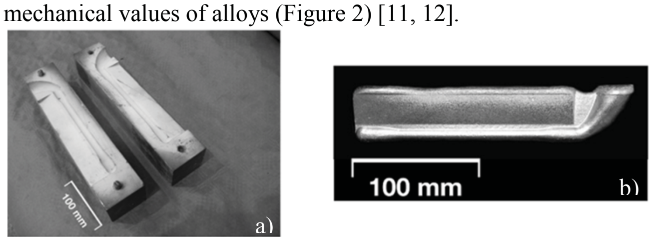

Figure 2: Tensile bar test mold and test bar; a) Hot work steel strip mold (1.2343); b) test bar with gate and overflow

M10 tensile test bars were produced according to DIN 60125:2004 (test length 48 mm, thickness 8 mm) [13]. The bars were heat treated according to the requirements of DIN EN 1706:2010; appropriate to the industry standards. The below mentioned values (tested according to DIN EN 10002-1:2001 [14]) demonstrate the average out of at least three cast tensile bars (figures 3 and 4). It is worthwhile noting, that the slower cooling of the tested chill casts (amongst other through a testing thickness of 8 mm and an on top resting high-mass sink head) influences the mechanical properties appropriately in comparison to the fast casting die cast parts.

Gravity die casting results

Figure 3 shows values of 18 different variants, although it shows that the heat treatment T7 (overaging) results in a leveling of the mechanical values ($Rp_{0,2}$ und Rm) trough coarsening of the secondary dispersoids (Ostwald ripening), but the ductility changes in accordance to the composition. That means, that testing via chill casting is suitable to conduct a primary alloy selection from a test matrix according to their properties.

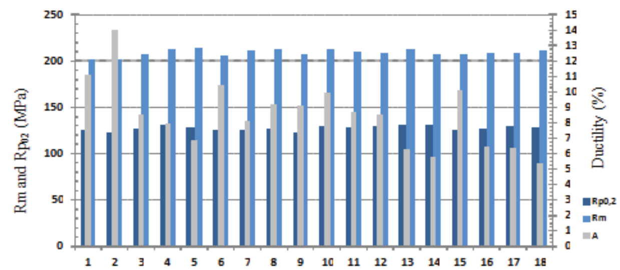

Figure 3: Mechanical properties of chill cast specimen from eighteen different alloys similar to the EN AC-43500 DIN EN 1706:2010. Ductility values corresponding to 5-14 % of the alloy composition can be achieved. From the test matrix, an initial selection of favorable alloy compositions is possible.

Similarly, characteristics for maximum strength (peak-aged) of the above mentioned alloy compositions were determined. The results are shown in figure 4. In addition to the ductility values, also the strength of the different alloy compositions changes because of the saturated mixed crystal and the maximum obstacle effect on the dislocation motion due to secondary phase precipitates is reached. Even here, the values of chill cast specimen enable promising tolerance limits for a recycling-friendly alloy.

The combination of the results of the different alloy compositions with different heat treatments allows a more precise restriction of tolerance limits for individual elements. Also the determination of suitable alloy variants which are then cast series production conditions is enabled. In this case, differences in the process have to be considered.

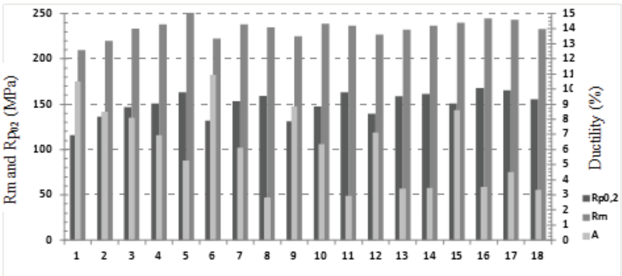

Figure 4: Mechanical properties of chill cast specimen from eighteen different alloys similar to the EN AC-43500 according to DIN EN 1706:2010. Ductility values corresponding from 3 to 11 % of the alloy composition can be achieved. Strengths vary for $Rp_{0,2}$ from 115 to 155 MPa and for Rm from 210 to 250 MPa. An initial selection of a favorable alloy composition is possible.

Verification using die casting

For the experiments with a die casting machine, the determined alloy compositions were produced with the corresponding tolerance limits and were cast to plates with a die casting machine (Bühler Evolution 120, 1200 t clamping force) under condition comparable to serial production.

Looking at the results of the optimization of alloys as well as the adapted process parameters, recyclable structural cast alloys seem to be feasible for series production. Besides the secondary phases, also the primary phases have to be considered, as these have particular negative influence on the ductility values, as soon as they reach a certain size. Regarding to ductility and crash performance, it could be shown in a previous paper [8] that the accurate Fe/Mn ratio as well as the process parameters are crucial for the performance of the alloy. Figures 5 and 6 of this paper are illustrating this. In Figure 5 an inappropriate ratio of Fe/Mn and unadjusted machine parameters result in larger, primary Al-Fe-Mn phases. With almost the same Fe-content, but under optimized conditions, these phases are significantly smaller and therefore have little negative impact on the ductility values of the cast component (Figure 6).

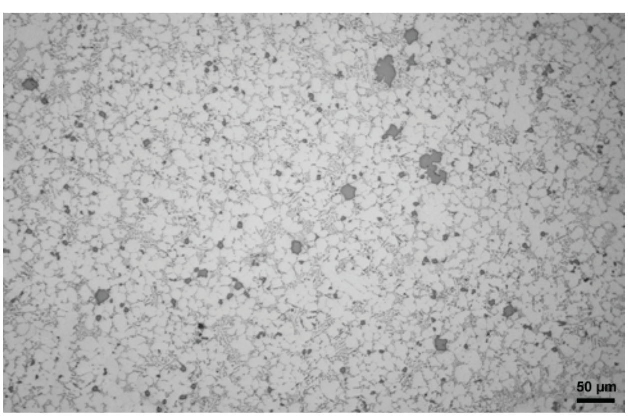

Figure 5: Specimen of a die casting plate with large primary Al-Fe-Mn phases. This - via chill casting determined - promising alloy was not cast with process parameters suitable for series production of crash relevant, because it exhibits suboptimal Fe/Mn results.

It should be pointed out that several combinations recycling-friendly alloys with appropriate tolerance limits and optimized process parameters exist. Further research will reveal the best possible version out of these alloy parameter combinations.

Figure 6: Specimen of a die casting plate with fine, evenly distributed primary Al-Fe-Mn phases. This - through chill casting determined - promising alloy shows optimal Fe/Mn results and was cast with process parameters suitable for series production of crash relevant parts.

Future Work

After the encouraging results at the die cast cell, producing and testing a real component out of the series under industrial conditions will be the next step. Mechanical properties, as well as the influence of the co- and trace elements on alloy properties such as cast ability, corrosion resistance, joining abilities as in welding and riveting and of course crash performance, will be tested.

Summary

The use of lightweight materials is an important factor to reduce CO_2 emissions of vehicles. Not only CO_2 emissions of a running vehicle have to be considered, but also during the manufacturing process of the components. One contribution to this is the substitution of a primary alloy (from electrolysis) by a recycling friendly alloy, which can be mainly produced using scrap. In the framework of an AMAG and AUDI project the possibility to expand the tolerance levels - which are stated in the technical delivery specifications - has been evaluated. Without compromising the required alloy properties, the use of scrap has been enabled. Besides the common impurities of scrap, such as iron, copper and zinc, also the contents of trace elements have to be considered. Production of test pieces via gravity casting in a mold turned out to be a practical way to examine the wide experimental matrix of alloys and to narrow down to the most promising versions, in order to die-cast them under industrial conditions. Doing so, differences among the casting processes have to be considered. It appears that the ranking of the alloy compositions, which achieve good mechanical properties in gravity mold casting, corresponds to the sequence in the high pressure die casting process. Following up to the first promising results, component tests will help to assess the suitability for series production of the optimized recycling-friendly alloy.

Acknowledgements

The authors would like to thank AIT Leichtmetallkompenzzentrum Ranshofen GmbH for the casting and the tensile tests.

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