Arch. Metall. Mater. **63** (2018), 2, 667-672

DOI: 10.24425/122392

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ANALYSIS OF PRODUCT QUALITY IN THE PROCESS OF PLASTIC CONSOLIDATION OF FRAGMENTED FRACTIONS OF THE AK11 ALLOY

The aim of this publication is to present practical application of the R. Kolman's quality rating method used in the evaluation of aluminium alloys. The results of studies of the mechanical and physical properties of the three selected test materials are discussed. To find the best material, the quality level of each of the tested materials was assessed using quality ratings proposed by R. Kolman. The results of the conducted analysis have proved that the best material was an AKII MM alloy, i.e. a casting AK11 aluminium alloy from the 4XXX series.

Keywords: aluminium alloys, ingots, mechanical properties, quality of the material, the Kolman's method

1. Introduction

Aluminium and its alloys belong to the group of materials widely used in the manufacture of objects that surround us in practically all our everyday activities. Sometimes these are the packages for food and beverages, on other occasions - the finishing building elements like gutters, or – finally - parts of vehicles [1-8]. An additional advantage of this material is practically 100% recoverability of the large pieces of scrap from secondary production. Compared to the primary production of aluminium, recyclable aluminium and its alloys can significantly (up to 95%) reduce the cost of obtaining one tonne of this material, reducing also the consumption of natural resources [9,10].

Nowadays over 90% of the cast products are made from aluminium alloys included in the 4XXX series (Al-Si) [11]. This publication discloses the results of mechanical tests carried out on the three selected materials subjected to plastic consolidation, all of them being variants of one starting material. The aim of the studies was to determine the quality of each material based on the results of mechanical tests. To determine the total quality rating for each of the materials tested, the method of quality assessment proposed by R. Kolman was used.

2. Theoretical introduction

Currently the metal used most widely next to the steel is aluminium and its alloys. Based on a report prepared at the request of the European Commission, it has been estimated that in 2010 the world production of primary aluminium totaled ~40 Mt and of the secondary aluminium ~50 Mt. [12] Most commonly, aluminium and its alloys are used in the production of electrical cables, beverage and food cans, and packaging for foodstuff. This material is also used in the automotive industry, among others, for parts of the car body and for structural components, such as engine blocks.

Introducing alloying elements to aluminium significantly increases the mechanical properties of this material. Compared to steel, aluminium alloys have a much lower density. This translates into a much more favourable strength-to-weight ratio. The most commonly used division of aluminium alloys is into wrought alloys and casting alloys.

Studies covered by this publication have been carried out on the casting AK11 aluminium alloy with silicon as a main alloying element. The content of silicon ranges from 10 to 13wt%. The alloy features a very high castability, low casting shrinkage, high thermal and electrical conductivity, and good machinability [13]. Unfortunately, its structure is characterized by the presence of coarse silicon precipitates embedded in the alloy eutectic and adversely affecting the alloy mechanical properties [14-16]. The refinement of the eutectic is possible, among others, by the addition of modifiers, such as Na, Sr, Sb and P introduced during melting process [17]. A similar effect of structure refinement, combined with accumulation of plastic deformation, occurs during machining, which is one of the basic finishing operations carried out on cast products [18]. In chips

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and dust produced during machining, Si precipitates undergo mechanical disintegration by both physical cutting of material into smaller pieces and large deformation which occurs in the deformation zone. The fine fractions formed in this manner require consolidation to a solid form [19].

Highly developed surface and the affinity for oxygen of aluminium particulate make the conventional recycling through remelting ineffective in this case [20]. Losses can reach even 40% of the scrap metal weight [21-24]. Additionally, during recrystallization after the remelting process, coarse silicon phases tend to re-appear in the structure of the product. An alternative for recycling of fine fractions with preservation of high mechanical properties as a result of the fragmentation of brittle Si phases can be the process of plastic consolidation. This process involves the mechanical integration of particles by one of the plastic forming methods which is direct extrusion [25,26]. The process runs at temperatures much lower than the remelting temperatures used in conventional recycling, which prevents intensive oxidation of the surface of disintegrated aluminium scrap. This method can significantly reduce the waste material volume and energy consumption [27,28]. The essence of the process consists in the formation of cohesive bonds between the surfaces of particles as a result of plastic deformation without the involvement of diffusion phenomena taking place in powder metallurgy [29,30].

As a result of plastic consolidation, the dispersed pieces of scrap are transformed into an integral solid body in the shape of rod, pipe, or section. Often the resulting semi-finished or finished product is further processed by plastic forming or surface treatment. A major problem of recycling without the involvement of liquid phase is the need for scrap segregation, cleaning from oily substances used during machining and removal of metallic inclusions. This is particularly important during manufacture of products, which should be characterized by the mechanical properties and chemical composition strictly corresponding to the requirements of relevant standards. Recycling of fine fractions by plastic consolidation is today a good alternative to conventional methods, mainly due to the significant reduction in energy consumption, the possibility of processing fractions of aluminium and its alloys practically non-recyclable by conventional techniques (dust, foils, small chips) and reduced emissions to the environment.

3. Description of tests and test results

Tests described in this publication were carried out to determine the mechanical properties of the three selected materials, which were three variants of one starting material. It was decided to use at the beginning two variants of the starting material and compare them with a reference material. As a next step, the mechanical properties of these materials were tested and based on the results obtained, the quality function was calculated.

The main tested material was a casting AK11 aluminium alloy from the 4XXX series. Using an ingot made of this material, fine chips of 0.16-0.4 mm fraction (AK11 MM) were produced in a milling machine designed by Łukasz Wzorek [25]. The machine is controlled by a PC which, via a Mach 3 program, is converted into a CNC (Computerized Numerical Control) controller. Based on the G-codes, it allows a biaxial control of the machine operation. During this operation, the tool penetrates the material to a depth of 0.5 mm, making a spiral movement and running from the centre of the workpiece at a spindle speed equal to 28 000 rpm.

The second tested material was composed of chips made by turning (AK11 TM). The process proceeded at a spindle rotating speed equal to 315 rpm and a feed rate of 0.2 mm/s, which produced chips with an average size equal to 22 × 4 × 1 mm. Both operations were carried out without the use of coolant.

As a reference material, solid ingot cast from the same batch of materials from which the AK11 MM and AK11 TM chips were manufactured was used. In a next step, loose chips of AK11 MM and AK11 TM were pre-compressed in a vertical hydraulic press at a pressing force of 100 T. For this purpose, a sample of about 25 g was placed in a specially designed die and pressed with a pressing force equal to 30 T. As a result of this operation, a compact of 40 mm diameter and 10 mm height was obtained. In the next stage of studies, seven of such compacts served as a feedstock for the extrusion process using an 8 mm diameter die operating in a horizontal hydraulic press at a temperature of 400°C and a feed of 3 mm/s. As a reference material, a solid ingot was extruded under the same conditions. From the obtained rods, test pieces were prepared for mechanical tests.

To determine the mechanical and physical properties, the following tests were performed on the three tested materials:

- tensile test (ultimate tensile strength and yield stress),
- measurement of Vickers hardness,
- density measurement.

The tensile test was carried out in accordance with the European Standard PN-EN ISO 6892-1:2010 [31] at room temperature on fivefold samples with a base length of 25 mm and a diameter of 5 mm using a Zwick/Roell Z050 testing machine. The stretching speed was $8 * 10^{-3}$ s^{-1}. The obtained results are summarized in Table 1.

Additionally, Vickers hardness was measured using a Shimadzu HMV-2T hardness tester operating under a load of 9,807 N in accordance with the European Standard EN ISO 6507-1: 2007 [32]. The results are shown in Table 2.

The density of the extruded rods was measured by the method of Archimedes on a RADWAG WPA 60/K device. This test involved weighing the sample in air and in a liquid of known density. In the case under discussion, it was demineralised water at a temperature of 20°C with a density of 0.9965137 g/cm^3. The results are summarized in Table 3.

In tables and figures, the following designations were used:

- UTS – ultimate tensile strength,
- YS – yield stress,
- E – elongation,
- IM – Ingot Material,
- MM – Milling Material,
- TM – Turning Material,

- CM – Cast Material,
- PN-EN 1706: 2011 [33], AC-44000 – European Standard for aluminium and aluminium alloys – Castings – Chemical composition and mechanical properties.

The values of mechanical properties obtained on individual samples are shown in Fig. 1.

TABLE 1

Mechanical properties of as-extruded rods

	UTS [MPa]	YS [MPa]	E [%]
AK11 IM	193	85	12
AK11 MM	222	98	14
AK11 TM	171	80	16
AK11 CM, EN AC-44000	≥170	≥80	≥7

TABLE 2

Hardness values obtained in individual tested samples

	AKII IM	AKII MM	AKII TM
	Hardness		
	HV 0.1		
	66,27	62,97	51,07
	62,38	65,00	51,65
	61,60	64,79	50,63
	59,36	64,80	49,65
	59,00	63,57	51,07
	59,18	63,77	51,21
	60,84	65,21	51,21
	61,80	65,21	50,91
	61,03	64,38	50,64
	59,52	63,31	50,34
Average	61,10	64,30	50,84
Standard deviation	2,18	0,83	0,56

TABLE 3

Hardness of the tested samples

	Hardness
	HV 0.1
AK11 IM	61
AK11 MM	64
AK11 TM	51

TABLE 4

The density of as-extruded rods

	Density
	g/cm^3
AK11 IM	2,6548
AK11 MM	2,6694
AK11 TM	2,6570
AK11 CM, EN AC-44000	2,65

4. Assessment of the test material quality

Quality of the tested materials was assessed by the R. Kolman's method. Using this method, quality classes (grades) were determined for each parameter and then, based on the obtained results, relevant ratings were assigned and quality of each parameter was established. Summing up sequentially the ratings obtained for individual parameters, the total material quality was assessed.

To evaluate the quality classes, a 10-tier quality rating scale generally outlined in Table 5 has been used. The assumption was that only levels above 0.7 could be considered satisfactory, while high quality of the material starts with the values above 0.8.

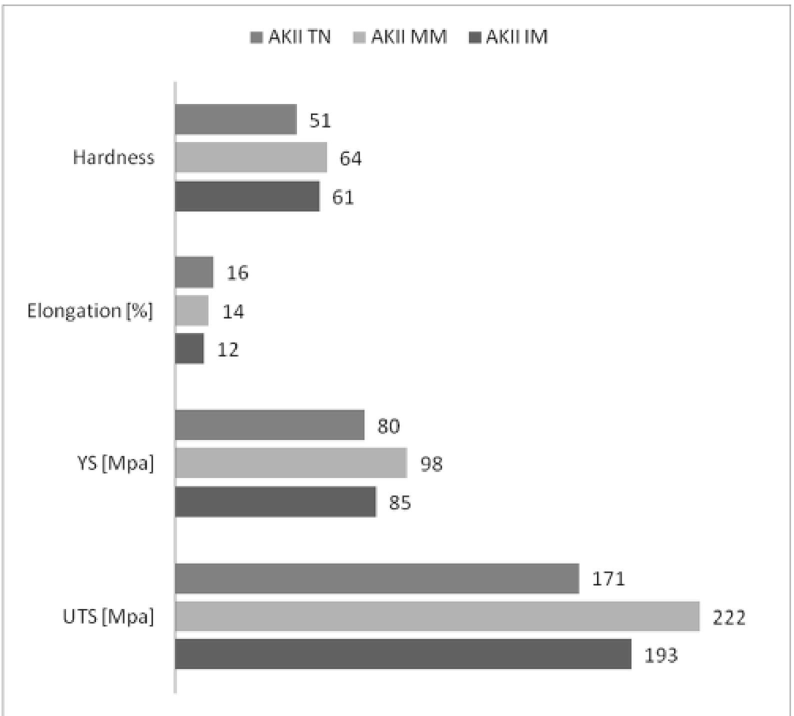

Fig. 1. Mechanical properties of the tested alloys

TABLE 5

Quality ratings

Rating	Quality coefficient	Description
9	0,95	Excellent
8	0,9	Outstanding
7	0,8	Good
6	0,7	Satisfactory
5	0,6	Moderate
4	0,5	Average
3	0,4	Unsatisfactory
2	0,3	Poor
1	0,2	Critical
0	0,1	Bad

Source: Own study

Then, using the PN-EN 1706:2011 Standard and the determined optimal min-max values, the quality ratings were calculated for each tested parameter. Table 6 compares ratings obtained for the tested parameters (the quality ratings for density were not determined):

- ultimate tensile strength,
- yield stress,
- elongation,
- hardness.

Based on the criteria set out in Table 6, the point values were determined and quality ratings were assigned to each of the three tested materials, calculating next the average values. Each specific rating denotes the specific quality level of a specific mechanical property of the tested material. Based on the obtained results, for each material, an average from the four tested parameters was calculated and final quality of the tested materials was set. The results of calculations are compared in Table 7 and plotted in Figure 2.

TABLE 6

Values of quality ratings obtained for the mechanical properties of test materials

UTS [MPa]	YS [MPa]	Elongation [%]	Hardness	Rating	Description
230-224	110-107	18-17,15	70-68,5	9	Excellent
223-218	106-104	17,14-16,3	68,49-67	8	Outstanding
217-206	103-98	16,29-14,6	66,99-64	7	Good
205-194	97-92	14,59-12,9	63,99-61	6	Satisfactory
193-182	91-86	12,89-11,2	60,99-58	5	Moderate
181-170	85-80	11,19-9,5	57,99-55	4	Average
169-158	79-75	9,49-7,8	54,99-52	3	Unsatisfactory
157-146	74-69	7,79-6,1	51,99-49	2	Poor
145-134	68-62	6,09-4,4	48,99-46	1	Critical
>134	>62	>4,4	>46	0	Bad

TABLE 7

Description of the tested parameters quality

Parameter tested		Sample tested		
		AKII IM	AKII MM	AKII TM
UTS	Rating	5	8	4
	Description	moderate	outstanding	average
YS	Rating	4	7	4
	Description	average	good	average
Elongation	Rating	5	6	7
	Description	moderate	satisfactory	good
Hardness	Rating	6	7	2
	Description	satisfactory	good	critical
Average	Rating	5	7	4,25
	Description	moderate	good	average

From the above it follows that the highest level of quality was achieved by the sample of AKIIMM. The average quality rating for this material was 7 points (in a 1-9 point scale), and

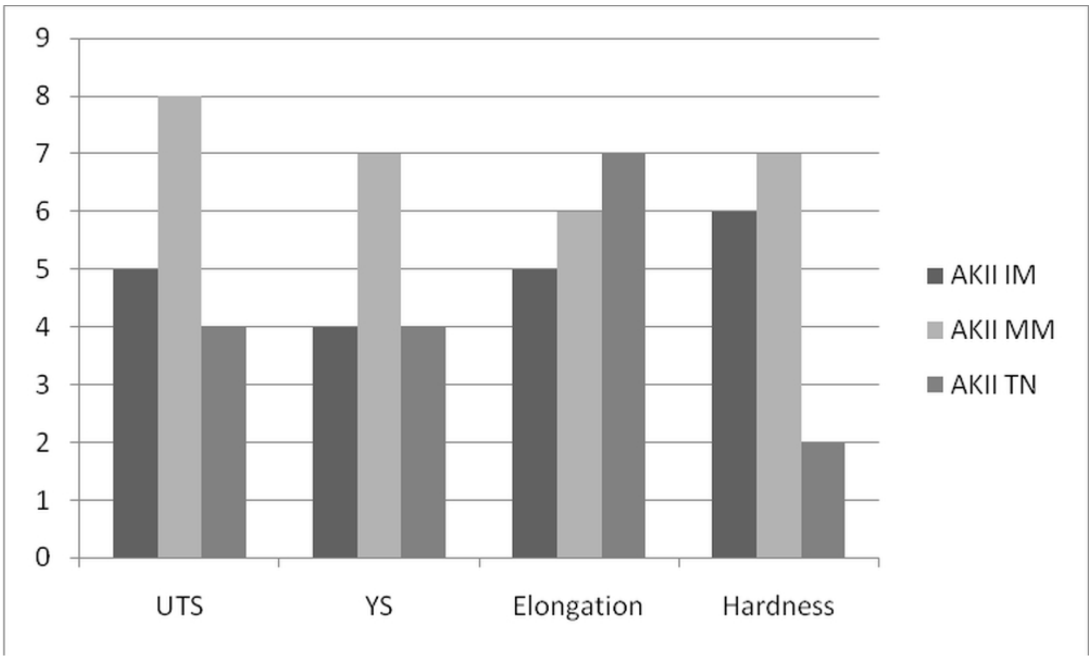

Fig. 2. Quality ratings for the mechanical properties tested on subsequent samples

the overall quality was assessed as good. In particular, the material showed a very high tensile strength and good properties in terms of the yield stress and hardness. Only for deformation the rating was less satisfactory, but even then 6 points were achieved.

The other two samples were characterized by a clearly inferior level of material quality. In the case of AK11 IM, the resulting quality level was 5, which means that the material properties were obviously inferior to AKII MM in each test category. Particularly low values were obtained for the yield stress.

The worst results gave the sample of reference material. The rating it received was 4.25. In this case, the parameter responsible for the rating so low was hardness.

5. Summary

From the test results obtained in this study, analysed by the method of quality assessment proposed by Professor Kolman, it follows that the best material is the AKII MM alloy. This is a casting AK11 aluminium alloy from the 4XXX series. For its machining, a CNC milling machine controlled by Mach 3 has been used. The material is characterized by a very high tensile strength and has obtained the total quality rating of 7 (in a 0-9 point scale). This shows that for the manufacture of this material the optimum technology yielding the best mechanical properties has been selected.

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