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Evaluation of the Effects of Variations in Chemical Composition on the Quality of Al-Si-Mg, Al-Cu, and Al-Zn-Mg Cast Aluminum Alloys

N.D. Alexopoulos and Sp.G. Pantelakis

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The effect of slight variations in chemical composition on the quality of cast aluminum alloys from three different major alloy systems was evaluated. For the evaluation of the alloy quality, an index Q_D adjusted to damage tolerance requirements that are currently involved for the design of advanced lightweight structures is used. The quality index Q_D accounts for tensile strength and ductility as well as for material failure through yielding or fracture. For this investigation, experimental results obtained for variations in chemical composition of the alloy systems Al-Si-Mg, Al-Cu, and Al-Zn-Mg were exploited. In total, castings from 37 different batches from 10 aluminum alloys, varying in chemical composition, were evaluated. Quality characterization and alloy quality ranking were made by evaluating results of 512 tensile tests using the index Q_D as well as, for comparison, the quality index Q, which is currently used by the industry. The results obtained involving the index Q_D seem to be more realistic, from the viewpoint of damage tolerance design requirements.

Keywords cast aluminum alloys, chemical composition, damage tolerance, quality evaluation, quality index

1. Introduction

Precision casting of aircraft aluminum alloys is attracting increased attention in a number of aeronautical applications, due to its potential to produce components with complex geometries cost efficiently. Yet, when compared with wrought alloys with similar chemical composition, cast alloys have inferior mechanical properties, specifically in terms of ductility. On the other hand, cast alloys present increased scatter in mechanical properties. To increase the competitiveness of cast aluminum alloys against the respective wrought materials, investigations are carried out toward improving the existing casting processes (e.g., investment casting, permanent-mold casting, etc.),[1-3] developing new casting processes (e.g., semi-solid processing, squeeze casting, Cosworth process, etc.),[4,5] and improving the existing cast aluminum alloys through modification in chemical composition and heat treatment.[6,7] Notice that, due to lack of sufficient thermochemical databases, computer-aided development of cast aluminum alloys is still not properly manageable. The approach currently used for the development of cast aluminum alloys is the trial-and-error method, which requires great experimental effort to characterize the mechanical behavior of the investigated alloy.

To reduce this experimental effort when optimizing the heat treatment of Al-7Si-Mg alloys, Drouzy et al.[8] proposed in 1980 the quality index Q. This index was derived from the observation that, as a batch of Al-7Si-Mg alloy specimens is aged for different times, a semi-logarithmic plot of tensile strength versus the tensile ductility follows a linear relationship. The quality index Q was formulated as

$$Q = R_m + d \cdot \log(A_f) \quad \text{(Eq 1)}$$

where R_m stands for the ultimate tensile strength (UTS), A_f stands for the elongation to fracture, and d is an empirically determined coefficient. For the investigated Al-Si-Mg alloy, d was experimentally derived to minus 150 MPa. The probable yield strength R_p of the alloy may be assessed using the expression:

$$R_p = a \cdot R_m - b \cdot \log(A_f) + c \quad \text{(Eq 2)}$$

where a, b, and c are alloy dependent, empirically determined coefficients. In a diagram of the UTS versus the logarithm of the elongation to fracture, Eq 1 and 2 represent sets of parallel lines called "iso-quality index" and "iso-yield strength" lines, respectively. These plots provide a very useful tool for reducing the experimental effort when developing or optimizing Al-Si-Mg cast aluminum alloys. Yet, the exploitation of the above concept to other alloy systems is not an obvious matter. Experimental results obtained in Ref. 9 for two 2xx series alloys could not be fitted by using the set of Eq 1 and 2. In Ref. 10 and 11, the iso-quality index concept has been modified such as to fit Al-Cu casting alloys whereby the calculated iso-quality index curves were no longer straight lines. Whether Q also may be applied to obtain iso-Q curves for other alloy aluminum systems is a subject for further investigation. Nevertheless, Q is very useful in its most obvious and straightforward application, namely as a tool to compare the quality of different alloys, modifications of same alloy, or even batches of the same alloy. It should be pointed out that from the engineering point of view, the definition of the term, *quality,* of a material makes

N.D. Alexopoulos and **Sp.G. Pantelakis,** Laboratory of Technology and Strength of Materials, Department of Mechanical and Aeronautical Engineering, University of Patras, 26500 Patras, Greece. Contact e-mail: pantelak@mech.upatras.gr.

Table 1 Chemical Composition of the Base Alloys[22]

Alloy	Si	Mg	Ti	Cu	Fe	Mn	Zn	Ag	Sm	La	Sr	Zr	Others	Al
A357	6.50-7.50	0.45-0.60	0.20 max	0.05 max	0.15 max	0.03 max	0.05 max	…	…	…	…	…	0.15 max	Remainder
A224	0.06 max	…	0.35	5.00	…	0.35	…	…	…	…	…	0.20	V-0.10	Remainder
7475	0.10 max	1.90-2.60	0.06 max	1.20-1.90	0.12 max	0.06 max	5.20-6.20	…	…	…	…	…	Cr-0.18-0.25	Remainder
7010	0.10 max	1.90-2.60	0.06 max	1.20-1.90	0.12 max	0.06 max	6.20-7.20	…	…	…	…	0.10	…	Remainder

sense only with reference to a specific engineering application. Modern aircraft structures are designed following damage tolerance specifications.[12] Hence, the use of cast aluminum alloys in such structures necessitates the evaluation of the quality of an alloy not only by considering the tensile strength and ductility but also the material properties characterizing the material failure through yielding or fracture.

In a previous work of the authors a new quality index Q_D, which accounts for the mentioned aircraft structure design requirements, was introduced.[13] For the convenience of the reader, a short description of the quality index Q_D will follow in Section 2. In Ref. 13, the quality index Q_D was used to evaluate the quality of different cast aluminum alloys and to compare the results against the results of the quality evaluation made by using Drouzy's quality index Q. In the present work the quality index Q_D is involved to evaluate the effects of slight variations in chemical composition on the quality of the aircraft cast aluminum alloys Al-Si-Mg, Al-Cu, and Al-Zn-Mg. The experimental results are part of an extensive experimental investigation performed in the frame of BRITE-EURAM project ADVACAST.[1] The alloy modifications are ranked with regard to their quality. The alloy ranking, which followed the present index $Q_{D,}$ was compared with the ranking made by using Drouzy's quality index Q. In many cases, ranking of the modified alloys with regard to the two different quality indices was similar. When differences were obtained, evaluation of the alloy quality with the aid of the proposed index Q_D seems, in most cases, to be more realistic with regard to aircraft structures current design requirements.

2. Quality Index Q_D

The quality index Q_D has been introduced and explicitly described in Ref. 13. The index Q_D evaluates the material quality on the basis of a balance between the material properties yield strength R_p and strain energy density W. Yield strength accounts for strength and sets the region of allowable service stresses. Energy density accounts for tensile ductility and characterizes the energy required for the material fracture. In addition, energy density may be directly related to the materials fracture toughness.[14] Hence, the quality index Q_D also involves information about the material failure through yielding or fracture and gives a direct indication for the suitability of a cast aluminum alloy for use in damage tolerance applications. For the evaluation of $Q_{D,}$ only the tensile test is required. The new quality index is determined as

$$Q_D = K_D \cdot Q_0 \qquad \text{(Eq 3)}$$

where Q_D characterizes the tensile performance of a material and K_D stands for a dimensionless factor accounting for the potential of a material to balance loss in yield strength against increase in fracture toughness and vice versa. The quantity Q_0 is formulated as

$$Q_0 = R_p + 10 \cdot W \qquad \text{(Eq 4)}$$

In Eq 4, R_p is the yield strength and W the strain energy density of the material. The strain energy density W may be evaluated from the area under the true stress-true strain curve as

$$\frac{dU}{dV} = \int_0^A \sigma \cdot d\varepsilon \qquad \text{(Eq 5)}$$

Table 2 Evaluated Tensile Test Series

Test Series	Alloy	Type of Specimen	Number of Tensile Tests Evaluated
1	A357 Sophia	Flat	30
2	A357 Sophia	Round	21
3	A357 Conv.	Flat	9
4	A357 Conv.	Round	3
5	A357 + 1% Cu Sophia	Flat	27
6	A357 + 1% Cu Sophia	Round	10
7	A357 + 1% Cu Conv.	Flat	17
8	A357 + 1% Cu Conv.	Round	21
9	A357 + 1% Cu + Ag Sophia	Flat	9
10	A357 + 1% Cu + Ag Sophia	Round	21
11	A357 + 1% Cu + Ag Conv.	Flat	9
12	A357 + 1% Cu + Ag Conv.	Round	21
13	A357 + 1% Cu + Sm Sophia	Flat	8
14	A357 + 1% Cu + Sm Sophia	Round	20
15	A357 + 1% Cu + Sm Conv.	Flat	9
16	A357 + 1% Cu + Sm Conv.	Round	3
17	A357 + 1% Cu + Ag + Sm Sophia	Flat	9
18	A357 + 1% Cu + Ag + Sm Sophia	Round	3
19	A357 + 1% Cu + La Sophia	Flat	9
20	A357 + 1% Cu + La Sophia	Round	3
21	A357 + 1% Cu + Sr Sophia	Flat	9
22	A357 + 1% Cu + Sr Sophia	Round	50
23	A357 + 1% Cu + Sr Conv.	Flat	9
24	A357 + 1% Cu + Sr Conv.	Round	15
25	A224 Var. 1 Sophia	Flat	31
26	A224 Var. 1 Sophia	Round	16
27	A224 Var. 2 Sophia	Flat	11
28	A224 Var. 2 Sophia	Round	8
29	A224 Var. 3 Sophia	Flat	8
30	A224 Var. 3 Sophia	Round	18
31	7475 Var. 1 Sophia	Flat	5
32	7475 Var. 1 Sophia	Round	14
33	7475 Var. 2 Sophia	Round	11
34	7010 Var. 1 Sophia	Flat	9
35	7010 Var. 1 Sophia	Round	12
36	7010 Var. 2 Sophia	Flat	10
37	7010 Var. 2 Sophia	Round	14

Conv., conventional; Var., variation

Table 3 Results for the Modifications of the Alloy A357

Alloy (a)	(1) A357 Flat Sophia	(2) A357 Round Sophia	(3) A357 Flat Conv. (b)	(4) A357 Round Conv.	(5) A357 + 1% Cu Flat Sophia	(6) A357 + 1% Cu Round Sophia	(7) A357 + 1% Cu Flat Conv.	(8) A357 + 1% Cu Round Conv.
R_m, MPa								
Max	381.00	373.00	358.00	324.00	418.00	393.00	375.00	351.00
Mean	372.13	362.19	339.78	319.00	402.19	386.20	349.71	329.10
St. dev.	6.60	8.72	13.61	3.74	8.59	4.19	11.53	10.28
R_p, MPa								
Max	322.00	321.00	319.00	298.00	339.00	330.00	318.00	320.00
Mean	303.23	305.24	305.67	289.33	323.41	319.40	310.00	306.05
St. dev.	9.38	13.70	11.02	6.18	8.53	6.23	4.58	7.50
A_f, %								
Max	14.90	12.10	3.50	1.90	13.20	9.80	3.80	2.30
Mean	12.19	7.92	2.16	1.37	8.72	5.46	1.92	0.53
St. dev.	1.79	2.12	0.87	0.75	2.00	2.02	1.14	0.56
W, MJ/m^3								
Max	56.59	44.68	13.05	6.57	53.50	38.91	14.28	8.32
Mean	46.04	29.36	8.08	4.87	35.94	21.82	7.47	2.36
St. dev.	6.84	7.84	3.18	2.37	8.44	7.92	4.17	1.89
Q, MPa								
Max	552.21	528.88	436.61	359.81	571.80	538.68	445.97	388.26
Mean	534.29	494.72	382.11	320.73	541.35	491.80	374.77	258.24
St. dev.	12.41	21.53	46.40	53.16	23.05	28.95	65.85	60.66
K_D, [−]								
Max	1.94	1.96	1.97	1.95	1.91	1.97	1.96	1.96
Mean	1.76	1.61	1.58	1.71	1.63	1.53	1.50	1.24
St. dev.	0.12	0.18	0.27	0.34	0.16	0.20	0.29	0.23
Q_0, MPa								
Max	865.94	755.77	438.51	351.25	843.04	710.08	449.50	390.19
Mean	763.60	598.82	386.51	338.07	682.82	537.63	384.72	329.63
St. dev.	68.54	79.55	40.29	17.54	85.73	78.92	42.39	20.94
Q_D, MPa								
Max	1672.71	1483.28	861.89	686.05	1608.98	1400.79	882.38	764.52
Mean	1348.61	977.25	620.55	585.06	1124.02	837.91	588.73	413.38
St. dev.	214.34	238.88	163.04	140.63	244.72	239.08	178.70	109.72

(a) The alloy numbers refer to the test series in Table 2.
(b) Abbreviations for Tables 3-8: Max, maximum value evaluated; Mean, average value; St. dev., standard deviation; Conv., conventional

where U is the strain energy, V the material volume, and A the elongation just before fracture. In Eq 4 the strain energy density W is multiplied by the empirical factor 10. The value 10 represents a typical value of the ratio R_p/W for property optimized advanced aluminum alloys, which are currently used in aircraft applications (e.g., aluminum alloys 6013, 2091, 8090).[15] The factor K_D in Eq 3 is determined as:

$$K_D = \left(\frac{R_{pi}}{R_{p\,max}} + \frac{W_i}{W_{max}}\right) \quad \text{(Eq 6)}$$

In Eq (6), i stands for a specific alloy modification of a base alloy. R_{pmax} and W_{max} stand for the maximum values of yield strength and energy density that could be achieved by varying chemical composition and/or heat treatment of the base alloy within defined ranges. For a specific alloy batch, K_D characterizes the scatter in properties by evaluating the different specimens. In the latter case, i in Eq 6 stands for a specific specimen. Hence, the average quality index of an alloy modification, derived out of n specimens is formulated as

$$Q_D = \sum_{i=1}^{n} \frac{Q_{Di}}{n} \quad \text{(Eq 7)}$$

K_D is always smaller than 2. The value 2 represents the ideal alloy modification, which would converge maximum yield strength and maximum energy density, or the ideal alloy batch with no scatter in properties. Using Eq 3, 4, and 6, the proposed quality index can be written as

$$Q_D = \left(\frac{R_{pi}}{R_{p\,max}} + \frac{W_i}{W_{max}}\right) \cdot (R_{pi} + 10\,W_i) \quad \text{(Eq 8)}$$

3. Experimental Procedure

The investigation was performed for the aluminum alloy systems Al-Si-Mg, Al-Cu, and Al-Zn-Mg. The base alloys selected were the alloy A357 for the system Al-Si-Mg, the alloy A224 for the system Al-Cu, and the alloys 7475 and 7010 for the system Al-Zn-Mg. Around these base alloys a number of modifications were made. In total, 10 different alloys were produced. The chemical compositions of the base alloys may be found in Table 1. The essential modification for the Alloy A357 is the addition of 1% copper to increase the strength. Further modifications by using, in addition to copper, a further alloying element (namely Ag or Sm or Ag and Sm or La or Sr) have also been made. For the alloy A224, two modifications were investigated; they included addition of Mg and Sm and a small increase in the Fe content. For the 7475 alloy, two varia-

Table 4 Results for the Modifications of the Alloy A357 + 1% Cu

Alloy (a)	(9) A357 + 1% Cu + Ag Flat Sophia	(10) A357 + 1% Cu + Ag Round Sophia	(11) A357 + 1% Cu + Ag Flat Conv.	(12) A357 + 1% Cu + Ag Round Conv.	(13) A357 + 1% Cu + Sm Flat Sophia	(14) A357 + 1% Cu + Sm Round Sophia	(15) A357 + 1% Cu + Sm Flat Conv.	(16) A357 + 1% Cu + Sm Round Conv.
R_m, MPa								
Max	374.00	386.00	374.00	360.00	368.00	370.00	370.00	350.00
Mean	368.00	373.14	368.00	336.71	365.38	344.65	354.67	348.67
St. dev.	5.40	6.05	5.40	11.34	2.00	10.99	9.25	1.25
R_p, MPa								
Max	321.00	329.00	321.00	327.00	313.00	319.00	325.00	314.00
Mean	310.78	314.57	310.78	321.14	308.75	304.65	309.33	311.67
St. dev.	9.95	7.87	9.95	4.13	3.60	6.27	8.14	2.95
A_f %								
Max	4.00	6.20	4.00	1.80	5.10	4.90	4.00	0.50
Mean	3.38	3.41	3.38	0.45	3.58	2.32	2.57	0.40
St. dev.	0.42	1.38	0.42	0.51	1.01	1.00	1.00	0.14
W, MJ/m^3								
Max	15.20	24.08	15.20	6.72	19.02	18.80	15.26	2.43
Mean	12.96	13.44	12.96	2.20	13.55	8.66	9.82	2.03
St. dev.	1.61	5.28	1.61	1.69	3.71	3.69	3.73	0.51
Q MPa								
Max	462.31	497.86	426.31	374.29	472.14	473.53	455.23	304.85
Mean	466.78	447.70	446.78	255.20	445.77	392.95	409.97	283.62
St. dev.	12.47	30.51	12.47	58.18	18.56	37.28	34.79	29.32
K_D, [−]								
Max	1.97	1.94	1.97	1.99	1.99	1.99	1.95	2.00
Mean	1.82	1.51	1.82	1.31	1.70	1.42	1.60	1.83
St. dev.	0.10	0.22	0.10	0.25	0.19	0.21	0.26	0.21
Q_0, MPa								
Max	464.21	549.80	464.21	392.08	501.24	505.00	469.67	338.25
Mean	440.42	448.98	440.42	343.10	444.26	391.28	407.53	332.00
St. dev.	15.99	53.78	15.99	18.20	36.94	40.53	41.53	5.39
Q_0, MPa								
Max	914.95	1066.18	914.95	780.92	999.28	1006.83	914.88	676.51
Mean	803.60	691.81	803.60	453.54	761.48	562.38	660.72	608.96
St. dev.	72.43	186.69	72.43	118.97	151.34	147.53	171.22	78.66

(continued)

tions were considered: one contained a small addition of Zr while the second contained a small addition of Cr, but no Zr. Finally, for the 7010 alloy two modifications varying in the Zn content were investigated.

All castings were performed by the companies, Ciral (Chantilly, France) and Thyssen (Soest, Germany), in the framework of the BRITE-EURAM project ADVACAST.[1] The alloys were produced using the SOPHIA process,[2] which is a patented casting process that allows higher cooling rates and a close control of the progressing solidification rate for producing casting aluminum alloys with improved mechanical properties and lower scatter in data. For comparison, some alloys have been also produced using the conventional investment casting process. In the following tables, "Conv." and "Sophia" will refer to conventional and Sophia casting processes, respectively, and the produced alloys will be evaluated separately.

The alloys were cast in the form of plates with different thicknesses, namely 10, 20 and 30 mm. The produced cast alloys were solution heat treated, then quenched, and finally artificially aged. The heat treatment of the investigated alloys can be found in Ref. 1. For the evaluation of the quality of the produced alloys, tensile tests were carried out. Flat and round specimens were machined from blocks of the material according to the standard DIN 50125. Flat and round specimens of the same material were considered separately. The investigation included 37 tensile test series, which are summarized in Table 2. In total, results of 512 tensile tests have been considered; all tests are taken from Ref. 1.

In the present work, the tensile test results were evaluated to characterize the alloys by means of the quality indices Q_D and Q, respectively. Hence, with respect to Eq 1 and 8, the considered properties were: tensile strength R_m, yield strength $R_{p0.2\%}$, elongation to fracture A_f, and energy density W. As the elongation to fracture of the produced alloys was low and the specimens do not show appreciable tensile necking, the energy density W was calculated using engineering stress-engineering strain curves.

4. Results and Discussion

The results for the influence of the effects of slight variations in the chemical composition on the quality of the considered Al-Si-Mg, Al-Cu, and Al-Zn-Mg base alloys are summarized in Tables 3-6. Each table includes the values derived for

Table 4 Results for the Modifications of the Alloy A357 + 1% Cu (continued)

Alloy (a)	(17) A357 + 1% Cu + Ag + Sm Flat Sophia	(18) A357 + 1% Cu + Ag + Sm Round Sophia	(19) A357 + 1% Cu + La Flat Sophia	(20) A357 + 1% Cu + La Round Sophia	(21) A357 + 1% Cu + Sr Flat Sophia	(22) A357 + 1% Cu + Sr Round Sophia	(23) A357 + 1% Cu + Sr Flat Conv.	(24) A357 + 1% Cu + Sr Round Conv.
R_m, MPa								
Max	373.00	373.00	386.00	381.00	405.00	381.00	366.00	350.00
Mean	365.44	368.00	372.89	379.33	377.00	366.82	344.22	303.07
St. dev.	5.52	3.74	6.74	1.25	26.86	9.14	19.52	15.70
R_p, MPa								
Max	333.00	324.00	337.00	330.00	349.00	330.00	323.00	323.00
Mean	314.78	314.00	325.11	327.33	332.11	313.88	305.44	290.60
St. dev.	7.90	7.12	6.01	2.05	18.19	10.96	11.70	17.08
A_f, %								
Max	4.20	1.90	4.20	3.30	11.60	8.60	2.70	2.10
Mean	3.04	1.80	2.79	2.60	7.52	5.24	1.72	0.69
St. dev.	0.71	0.08	0.94	0.50	2.57	1.78	0.56	0.54
W, MJ/m^3								
Max	16.26	7.61	16.67	13.19	47.71	32.55	10.08	7.32
Mean	11.69	7.30	10.99	10.56	29.06	20.00	6.59	2.69
St. dev.	2.70	0.22	3.68	1.87	10.29	6.67	2.12	1.68
Q_0, MPa								
Max	466.49	408.81	479.49	456.78	564.67	516.46	418.70	372.33
Mean	435.96	406.22	435.04	440.47	505.00	468.57	376.04	255.59
St. dev.	21.08	2.83	32.13	11.78	34.04	37.01	39.31	65.77
K_D, [−]								
Max	2.00	1.95	2.00	1.98	1.97	1.95	1.91	1.91
Mean	1.66	1.93	1.62	1.79	1.56	1.57	1.60	1.27
St. dev.	0.18	0.02	0.23	0.14	0.22	0.21	0.22	0.22
Q_0, MPa								
Max	495.62	394.80	503.70	456.93	815.12	638.53	402.03	368.16
Mean	431.69	387.02	435.06	432.91	622.70	513.91	371.39	317.52
St. dev.	30.55	5.56	39.89	17.26	104.85	67.07	25.38	20.27
Q_D, MPa								
Max	991.24	762.34	1007.40	906.93	1605.84	1244.17	757.33	704.40
Mean	723.74	746.65	715.79	778.23	995.15	818.40	599.40	405.91
St. dev.	128.47	13.94	164.94	91.91	330.44	202.50	117.40	97.54

(a) The alloy numbers refer to the test series in Table 2.

the tensile properties, UTS, yield strength, elongation to fracture, and energy density for all test series of the different modifications in the chemical composition of a base alloy. As an increase in strength is "redeemed" by a decrease in tensile ductility and vice versa, it is difficult in many cases to judge whether the modification has improved the material quality. Referring, for example, to Table 3, it is very subjective to decide whether the alloy 5, which is the alloy A357 modified by the addition of 1% Cu, with 30 MPa higher strength and 20 MPa higher yield strength, but 3.5% less elongation to fracture, has better quality than the basic alloy A357 referred to as alloy 1 in Table 3. The quality indices Q_D and Q of Eq 8 and 1 provide a very useful tool for a more objective quality assessment. The derived values for the indices of Q_D and Q for the investigated variations in the material's chemical compositions are also given in Tables 3-6. In the following, the values for Q_D and Q will be exploited as a means to assess the effect of a specific modification in chemical composition on the material's quality. For each quantity in the Tables, the mean values, the maximum values obtained through the series of performed tests, and the standard deviation are given.

As shown in Table 2, the essential modification for the alloy A357 was the addition of 1% Cu to increase the strength, whereby the effect of further alloying elements on the material's quality was also investigated. In addition, these test series aimed to quantify the improvement of the material's quality when using the Sophia casting process as compared with the conventional investment casting process. As shown in Table 2, the investigation for the alloy A357 included, in total, 24 test series. The mechanical properties and the quality indices derived for the A357 base alloy and modifications are summarized in Tables 3 and 4. The quality indices Q_D of the A357 aluminum alloy series are presented in Fig. 1. A general remark is that the Sophia alloys have appreciably higher mechanical properties and quality indices than the conventional alloys. It is worth mentioning that for the A357 base alloy, the quality index Q_D for the Sophia castings has more than twice the value of the respective conventional investment castings. The same order of magnitude of improvement has been also confirmed for the A357 + 1% Cu as well as for the A357 + 1% Cu + Sr modifications. This is due to the dramatic improvement of ductility (up to 6 times) when using Sophia (Tables 3 and 4). The modifications A357 + 1% Cu + Ag and A357 + 1% Cu + Ag + Sm cast using Sophia are still appreciably better than

Table 5 Results for the Modifications of the Alloy A224

Alloy (a)	(25) A224 Var. 1 Flat Sophia	(26) A224 Var. 1 Round Sophia	(27) A224 Var. 2 Flat Sophia	(28) A224 Var. 2 Round Sophia	(29) A224 Var. 3 Flat Sophia	(30) A224 Var. 3 Round Sophia
R_m, MPa						
Max	424.00	378.00	301.00	258.00	395.00	378.00
Mean	386.84	368.75	274.73	201.00	358.25	363.00
St. dev.	17.54	5.71	16.86	34.96	18.22	8.77
R_p, MPa						
Max	297.00	252.00	222.00	253.00	255.00	247.00
Mean	257.00	236.06	216.73	183.75	220.38	229.67
St. dev.	18.43	7.70	3.05	36.12	18.19	7.73
A_f, %						
Max	9.96	10.00	8.45	4.00	8.53	11.60
Mean	7.85	8.96	6.32	1.58	7.12	8.44
St. dev.	1.11	0.53	1.50	0.97	1.44	1.05
W, MJ/m^3						
Max	35.87	36.89	24.38	10.89	29.81	11.60
Mean	30.71	33.41	17.69	3.61	25.84	8.44
St. dev.	3.71	1.75	4.43	2.86	5.17	1.05
Q_0, MPa						
Max	549.95	521.34	430.85	348.31	515.52	523.27
Mean	520.36	511.45	392.35	220.81	484.36	501.52
St. dev.	16.27	4.92	27.80	58.63	25.80	10.13
K_D, [−]						
Max	1.92	1.93	1.99	2.00	1.87	1.94
Mean	1.72	1.84	1.70	1.06	1.73	1.67
St. dev.	0.10	0.05	0.19	0.39	0.18	0.09
Q_0, MPa						
Max	631.42	603.89	462.76	361.93	520.06	647.78
Mean	564.06	570.13	393.60	219.89	478.73	539.71
St. dev.	34.26	17.55	45.04	61.66	52.59	37.20
Q_0, MPa						
Max	1213.92	1167.05	919.27	723.85	974.29	1253.59
Mean	974.29	1051.24	678.18	256.36	838.09	906.73
St. dev.	109.74	61.11	144.92	188.58	160.65	116.50

(a) The alloy numbers refer to the test series in Table 2.

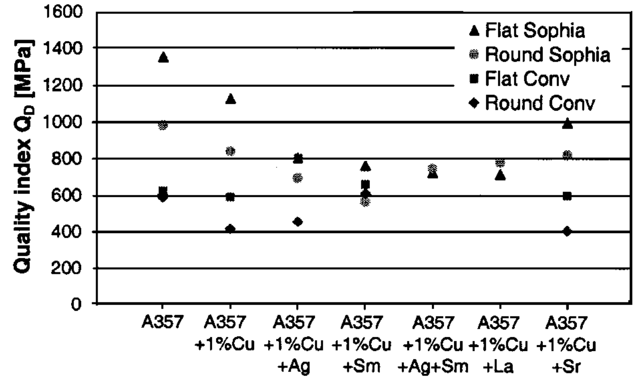

Fig. 1 Quality indices of 3xx aluminum-alloy series

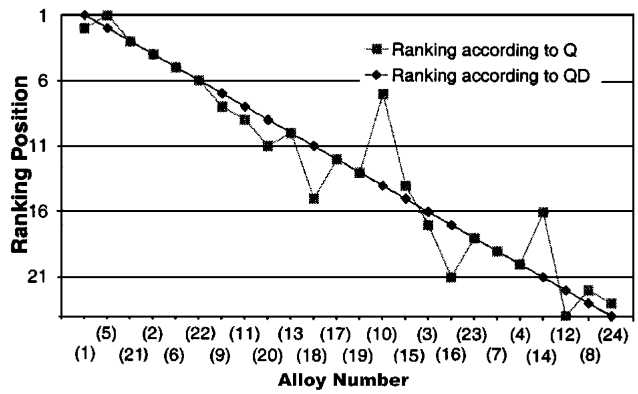

Fig. 2 Ranking of the 3xx aluminum alloys using the quality indices Q_D and Q; the alloy numbers refer to the test series in Table 2

those cast by conventional investment casting techniques, with the exception of the round specimens for the latter alloy.

The addition of copper in this alloy series leads to a better response to heat treatment and influences the strength of the alloy due to formation of nonequilibrium precipitates θ (Al_2Cu) resulting from the artificial aging heat treatment. However, the higher strength achieved is accomplished with some reduction in ductility.[16,17] When comparing alloy 1 (A357 Flat Sophia) to alloy 5 (A357 + 1% Cu Flat Sophia), the copper addition increases the properties R_p and R_m by 20 and 30 MPa, respectively. Nevertheless, the elongation to fracture decreases from 12.19-8.72%, which corresponds to more than 25% reduction. As follows from the comparison of test series 3 and 7 for Flat conventional, and 4 and 8 for Round conventional, the same trend has been observed for the conventional A357 alloys without and with 1% Cu, i.e., a small increase in strength redeemed by an essential drop on ductility. This was mainly attributed to the negative influence of the addition of Cu to the eutectic structure. The influence of copper on the silicon structure is not so evident at low solidification (cooling) rates.[1,18] The quality index Q_D better ranks the alloy A357 without copper for both Sophia and conventional castings (Fig. 1 and 2, Table 3). The quality index Q better ranks A357 without Cu for conventional castings but not for the Sophia Flat specimens (test series 1 and 5 in Fig. 2 and Table 3). In the authors' opinion, although an increase of 20 MPa yield strength and 30 MPa tensile strength is appreciable, the sacrifice of 25% elongation to fracture for an increase of about 7% in tensile and yield strength should not be interpreted as a quality improvement.

The small addition of Ag on the copper modified A357 alloy downgrades the quality of the Sophia alloys (Table 4). On the contrary, the conventional A357 + 1% Cu + Ag alloys have higher quality than the conventional A357 + 1% Cu alloys. This effect, which is reflected in both indices Q_D and Q (Fig. 1 and Table 4), was justified by metallographic investigations. Silver addition influences the eutectic microstructure at low solidification rates (Conventional). The lamellar, plate-like Si phases, which can be seen at the alloy A357 + 1% Cu for this solidification rate, coarsen due to the silver addition. For higher solidification rates no difference in eutectic structure can be detected.[1,4]

The small addition of Sm on the alloy A357 + 1% Cu downgrades the quality of the Sophia alloys, as well. Nevertheless, a significant increase of the quality is observed for the conventional alloys. This result has been supported by metallographic investigations. The Sm addition influences the eutectic Si-structure. For lower solidification rates, which are the conventional alloys, the creation of plate-like silicon structures

Table 6 Results for the Modifications of the Alloys 7475 and 7010

Alloy (a)	(31) 7475 Var. 1 Flat Sophia	(32) 7475 Var. 1 Round Sophia	(33) 7475 Var. 2 Round Sophia	(34) 7010 Var. 1 Flat Sophia	(35) 7010 Var. 1 Round Sophia	(36) 7010 Var. 2 Flat Sophia	(37) 7010 Var. 2 Round Sophia
R_m, MPa							
Max	545.00	511.00	496.00	527.00	505.00	536.00	497.00
Mean	506.00	491.21	462.91	501.00	489.00	514.40	466.00
St. dev.	24.59	11.53	26.81	19.10	11.02	14.89	26.26
R_p, MPa							
Max	493.00	480.00	476.00	495.00	487.00	512.00	490.00
Mean	479.00	464.64	422.73	472.22	470.92	485.60	447.57
St. dev.	12.28	10.83	55.41	16.29	19.68	14.70	26.56
A_f, %							
Max	10.70	4.30	4.00	7.40	4.00	5.77	2.40
Mean	4.92	2.61	1.89	3.76	2.49	4.04	1.35
St. dev.	3.87	0.79	0.82	2.09	0.93	1.27	0.56
W, MJ/m							
Max	61.24	23.66	21.10	40.40	21.84	32.68	13.63
Mean	27.99	14.43	11.02	20.71	13.77	22.47	7.86
St. dev.	21.99	3.94	4.64	11.22	4.84	7.04	2.67
Q, MPa							
Max	683.64	606.02	584.31	657.38	592.31	645.18	551.03
Mean	586.87	550.11	499.02	576.41	543.17	601.71	476.53
St. dev.	78.54	28.36	39.97	53.14	32.35	30.52	51.95
K_D, [−]							
Max	1.99	1.99	1.97	1.95	2.00	1.98	1.99
Mean	1.43	1.58	1.41	1.47	1.60	1.64	1.49
St. dev.	0.38	0.17	0.26	0.27	0.24	0.23	0.23
Q_0, MPa							
Max	1101.41	712.59	673.02	873.04	705.45	826.81	623.29
Mean	758.86	608.93	532.96	679.32	608.61	710.33	526.17
St. dev.	229.77	41.65	77.31	108.71	59.81	76.12	48.24
Q_D, MPa							
Max	2193.89	1419.24	1326.25	1700.23	1410.89	1634.25	1242.76
Mean	1171.21	967.83	770.95	1025.63	986.47	1179.31	795.00
St. dev.	658.32	172.15	252.74	358.86	243.18	288.18	199.03

(a) The alloy numbers refer to the test series in Table 2.

for copper modified alloy can be canceled by Sm-addition. For higher solidification rates a refining of the eutectic structure could not be observed.[1]

Addition of both alloying elements Ag and Sm on the copper modified A357 alloy was made only for Sophia alloys. Just as when alloying with Ag or Sm separately, the Ag + Sm modified alloys show lower quality, when compared with the A357 + 1% Cu alloys. As can be seen in Table 4, both indices Q_D and Q reflect the fact that all modifications of the chemical composition by alloying the A357 + 1% Cu Sophia alloy with Ag, Sm, or both (namely alloys 9, 10, 13, 14, 17, 18 in Table 4), result in a decrease of the quality. The quality of the above alloys is expressed by quality indices of the same order of magnitude.

Although the addition of a small amount of La to the material A357 is expected to improve tensile strength and ductility,[16,19] such an effect could not be observed in the present investigation. As shown in Table 4, the addition of La causes a decrease of the tensile properties as compared with the A357 + 1% Cu Sophia alloy. This can also be seen in the values of the quality index Q_D in Fig. 1. Metallographic investigations made in Ref. 1 showed that La did not change the lamellar, plate-like Si-structure for low solidification rates. For the higher solidification rates (i.e., Sophia process) a refining effect caused by the La addition could not be observed. Yet, even at low solidification rates (i.e., conventional alloys) the addition of La did not change the lamellar, plate-like Si structure.

Strontium is expected to slightly improve the ductility of the material, due to the formation of the "globular" eutectic structure.[20] In the present investigation, the small addition of Sr to the alloy A357 + 1% Cu did not have an appreciable influence on the quality (Fig. 1 and Table 4).

The difference in quality evaluation by involving Q_D or Q is reflected by the ranking of the alloys using the above indices (Fig. 2). As can be seen, ranking is similar, with the essential exception of the first two positions. This difference in ranking leads to two different answers to the question of whether the addition of Cu increases the quality of A357 or not. As already discussed, it is difficult to judge whether the alloy A357 without copper (373 MPa tensile strength and 12.2% elongation to fracture) is better, as evaluated using Q_D, than the alloy A357 + 1% Cu (402 MPa tensile strength and 8.7% elongation to fracture by some increased property scatter), or worse, as evaluated.

The modifications in the chemical composition of the alloy A224 included (1) the addition of Mg and Sm and (2) the

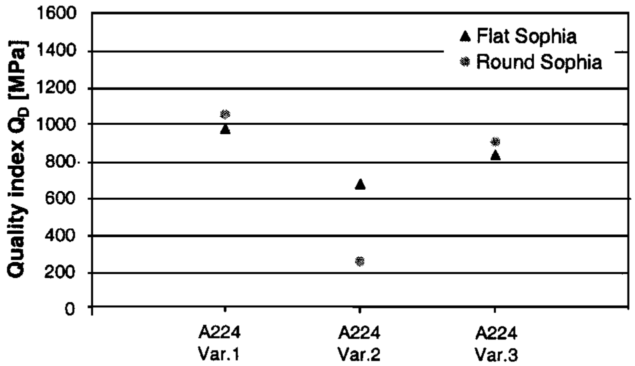

Fig. 3 Quality indices of 2xx aluminum-alloy series

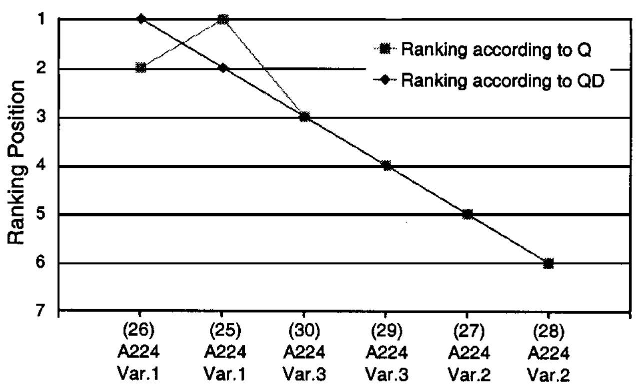

Fig. 4 Ranking of the 2xx aluminum alloys using the quality indices Q_D and Q; the alloy numbers refer to the test series in Table 2

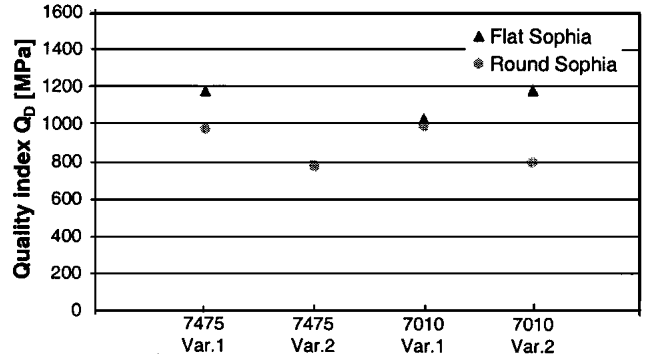

Fig. 5 Quality indices of 7xxx aluminum-alloy series

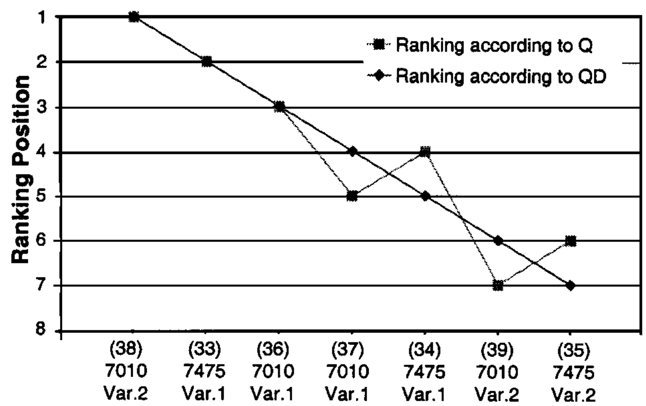

Fig. 6 Ranking of the 7xxx aluminum alloys using the quality indices Q_D and Q; the alloy numbers refer to the test series in Table 2

increase of the Fe content (<0.10%). All modifications in chemical composition of alloy A224 result in lower quality (Table 5). The decrease in mechanical properties is reflected by a drop of the quality indices Q_D and Q. The quality indices Q_D derived for the investigated variations of the A224 alloy are displayed in Fig. 3. When comparing alloys A224 Variation (Var.) 1 and Var. 3, their difference is the percentage of impurities Si and Fe on alloy composition. The higher the percentage of these elements, the lower the quality (Fig. 3 and 4). Iron has a low solubility (≈0.04%) in solid aluminum, and most of the iron present in aluminum over this amount appears as an intermetallic second phase in combinations with aluminum and often other elements.[16] It is well known that the presence of these phases downgrades the mechanical properties.[21,22]

Alloy A224 Var. 2 involves Mg and Sm in its chemical composition. A minor addition of Be is also present, while the percentage of the impurity Si is higher. The quality of the alloys is significantly decreased, as compared with the A224 Var. 1 and A224 Var. 3 variations. The cause for the obtained quality decrease should be further investigated.

Ranking of the alloys 2xx according to their quality evaluated using Q_D and Q is given in Fig. 4, and with the exception of the inverse alloy ranking at the first two positions when using Q_D and Q, the results do not differ. Q_D favors the higher ductility of the A224 Var. 1 Round Sophia specimens and the very low scatter in properties reflected by a high K_D value of 1.84. On the contrary, Q favors the appreciable higher strength of the A224 Var. 1 Flat Sophia specimens.

As expected, the tensile strength properties of the investigated alloys 7475 and 7010 are appreciably higher as compared with the alloys of the 3xx and 2xx aluminum alloy series. This gives high quality indices Q, although the elongation to fracture of said alloys is relatively low, ranging from 2-5% (Table 6). The quality indices Q_D for the 7xxx alloys are given in Fig. 5. The difference in the chemical composition between alloys 7475 Var. 2 and alloys 7475 Var. 1 is the use of Cr instead of Zr. The tensile properties increase and this results in a higher quality index Q_D. Chromium is used to refine the grains in Al-Mg-Zn alloys and to cancel the negative effect of the presence of iron in these alloys.[1,21]

The investigated 7010 alloys vary on the Zn content. On the basis of the performed investigation, no secure assessment can be made about the influence of the Zn content on the materials quality (Fig. 5).

Ranking of the alloys using Q_D and Q is shown in Fig. 6. As can be seen in Fig. 6 and Table 6, the quality index Q_D seems to penalize the low ductility of the alloys more than the index Q.

As an increase in strength is always redeemed by a decrease in tensile ductility (Tables 3-6), it is usually hard to judge without appreciably subjectivity, which alloy modification has a higher quality. A more objective decision can be made by involving the quality indices Q_D and Q. However, it should be stated that the use of the quality indices Q_D and Q as tools to support a decision on material selection should be limited to alloys of the same alloy series. The different aluminum alloy

Table 7 Ranking of the Best Four Among the 37 Investigated Alloys

Ranking of Alloys Based on Quality Index Q			Ranking of Alloys Based on Quality Index Q_D		
Ranking Position	Alloy	Q	Ranking Position	Alloy	Q_D
1	(36)-7010 Var. 2 Flat Sophia	601.71	1	(01)-A357 Flat Sophia	1348.61
2	(31)-7475 Var. 1 Flat Sophia	586.87	2	(36)-7010 Var. 2 Flat Sophia	1179.31
3	(34)-7010 Var. 1 Flat Sophia	576.41	3	(31)-7475 Var. 1 Flat Sophia	1171.21
4	(32)-7475 Var. 1 Round Sophia	550.11	4	(05)-A357 + 1% Cu Flat Sophia	1124.02

Table 8 Tensile Mechanical Properties of the Best Four Alloys Among the 37 Investigated Alloys

Property	(01) A357 Flat Sophia	(05) A357 + 1% Cu Flat Sophia	(31) 7475 Var. 1 Flat Sophia	(32) 7475 Var. 1 Round Sophia	(34) 7010 Var. 1 Flat Sophia	(36) 7010 Var. 2 Flat Sophia
R_m, MPa						
Mean	372.13	402.19	506.00	491.21	501.00	514.40
St. dev.	6.60	8.59	24.59	11.53	19.10	14.89
R_p, MPa						
Mean	303.23	323.41	479.00	464.64	472.22	485.60
St. dev.	9.38	8.53	12.28	10.83	16.29	14.70
A_f, %						
Mean	12.19	8.72	4.92	2.61	3.76	4.04
St. dev.	1.79	2.00	3.87	0.79	2.09	1.27
W, MJ/m^3						
Mean	46.04	35.94	27.99	14.43	20.71	22.47
St. dev.	6.84	8.44	21.99	3.94	11.22	7.04
Q, MPa						
Mean	534.29	541.35	586.87	550.11	576.41	601.71
St. dev.	12.41	23.05	78.54	28.36	53.14	30.52
Q_D, MPa						
Mean	1348.61	1124.02	1171.21	967.83	1025.63	1179.31
St. dev.	214.34	244.72	658.32	172.15	358.86	288.18

series have been developed such as to have different microstructural and technological features, with the aim to involve them in different applications. Ranking of the investigated 3xx, 2xx and 7xxx aluminum alloy modifications by using the quality indices Q_D and Q has been made in Fig. 2, 4, and 6. As can be seen, the use of the two indices leads to similar quality assessments and, hence, similar ranking positions for the different alloys. The differences obtained in ranking by using Q_D and Q reflect the different sensitivity of the two indices on variations in strength and ductility. To have a better understanding about the sensitivity of the involved quality indices on the variations of the tensile properties, a ranking of all 37 investigated alloys was also made, and the properties of the alloys ranked at the first four positions by using Q_D and Q were discussed. The best four alloys by ranking all 37 alloys according to Q_D and Q are given in Table 7. The respective properties are given in Table 8.

Index Q_D ranks the specimens of the A357 Flat Sophia alloy at the first position among the 37 investigated alloys. This ranking position reflects the good balance between yield strength (303 MPa) and tensile ductility (A_f = 12.2%) for this alloy. The energy density of 46 MJ/m^3 is the highest of all alloys investigated; this is essential for use in damage tolerance applications, as the alloy is expected to have good fracture toughness. The quality index Q ranks the flat specimens of alloy 7010 Var. 2 Sophia (36) at the first position. As can be seen in Table 8, ranking of this alloy at the first position reflects the very high tensile strength of 514 MPa; yet, the achieved elongation to fracture of 4% is relatively low. The evaluated energy density of 22 MJ/m^3 indicates the potential for an improvement of the tensile ductility with the proper heat treatment. Quality of 7010 Var. 2 Sophia flat specimens is ranked according to Q_D at position 2.

The index Q ranks at position 2 the 7475 Var. 1 Sophia flat specimens. This quality ranking is mainly due to the high tensile strength R_m and to the relatively high A_f for a “brittle” high strength alloy of the 7xxx series. Notice that this alloy has the greatest potential for improvement, due to its high energy density of 28 MJ/m^3. This alloy is ranked at position 3 according to the Q_D index. The Q index ranks at position 3 the flat specimens of 7010 Var. 1 Sophia. This alloy has a high tensile strength value (501 MPa) but low elongation to fracture. At position 4, the same index ranks the high strength but brittle alloy 7475 Var. 1 Sophia Round, with a 2.6% elongation to fracture. The quality index Q_D ranks at position 4 another well “balanced” alloy, A357 + 1% Cu Flat Sophia. This ranking position reflects the mediocre values of yield strength and energy density.

It should be noticed that according to index Q, the best four alloys have high strengths, but low elongations to fracture, which do not exceed 3-4%. It seems that Q might underestimate low ductility in quality evaluation when the strengths are high. The quality of the alloys that are more balanced between yield strength and tensile ductility seems to be better assessed when using the quality index Q_D. On the other hand, the quality index Q_D might overestimate high ductility and toughness values in the overall quality evaluation.

5. Conclusions

- The effect of slight variations in chemical composition on the quality of the cast aluminum alloys Al-Si-Mg, Al-Cu and Al-Zn-Mg was evaluated.
- As an increase in strength is always redeemed by a decrease in tensile ductility and vice versa, evaluation of the quality of an alloy has been made by involving quality indices such that a more objective judgment can be made.
- The quality index Q_D, proposed by the authors, can account for the influence of slight variations in chemical composition of the same alloy on the quality. For comparison, quality assessment was also made by using the quality index Q applied by the industry. The two indices result in similar quality assessment.
- In many cases, both indices Q_D and Q ranked the alloys in similar positions. When the ranking position was different, the index Q_D provided a more realistic ranking of the alloys from the viewpoint of the requirements for the design of aircraft structures.

Acknowledgments

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