Relevance of the use of the quality index concept in cast SiC_p-reinforced Al–Si–Mg composites

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The quality index, Q, defined as $Q = \text{UTS} + k\log \text{E1}$ was introduced as a means to better interpret tensile test data. However, its use in the case of composite materials is often questioned. The difficulty arises from the fact that the elongations obtained are usually close to, or less than, unity. Based on a heat-treatment study of cast Al-Si-Mg/SiC_p composites (359/SiC_p) and an analysis of the tensile properties obtained, it is shown that the concept of quality index, as it is commonly applied, is inappropriate in describing the combined effects of UTS and E1, and it is much better, instead, to use the probable yield strength (PYS) for such materials. Respective expressions for Q and PYS have been obtained for the 359, 359/SiC/10_p and 359/SiC/20_p alloys studied.

1. Introduction

In the mid 1970s, Drouzy *et al.* [1] introduced the concept of the quality index, Q, that permitted the information gathered from tensile test results to be utilized efficaciously. Rather than using ductility directly, and based on considerations of the relationships they obtained between the ultimate tensile strength, elongation and yield strength of A-S7 G alloys (Al–7Si–Mg alloys), they defined, instead, the quality index, Q, as

$$Q = \text{UTS} + k \log \text{El} \quad (1)$$

with UTS representing the ultimate tensile strength, El the elongation (El > 1%), and k a coefficient (equal to 150 MPa for the Al–7Si G06 alloy studied, equivalent in composition to A357 without beryllium). According to them, starting from a UTS–El diagram, a new system of coordinates (yield strength, YS, Q) represented by two sets of iso-lines (ISO–YS and ISO–Q) could be obtained, where YS, the probable elastic limit (or probable yield strength, PYS) was of the form

$$\text{YS}_{\text{probable}} = a\,\text{UTS} - b \log_{10} \text{El} - c \quad (2)$$

where the coefficients a, b, and c depended upon the alloy type; in the case of AS7-G, $a = 1$, $b = 60$, and $c = 13$, when YS, UTS and Q are expressed in MPa. The new variables, considered to be much better than the UTS and El variables, related directly to the properties of the alloy and the effect of various parameters could be easily monitored as well.

In order to correlate the quality index values with the tensile properties, the following empirical relationships must be established

$$\text{YS} = a_1\,\text{UTS} - a_2 \log_{10} \text{El} - a_3 \quad (3)$$

$$\text{UTS} = a + b \log_{10} \text{El} \quad (4)$$

$$Q = \text{UTS} + b \log_{10} \text{El} \quad (5)$$

where $\{a_1, a_2, a_3, a, b\}$ are empirical constants [2]. Drouzy *et al.* [1] give b as 150 MPa for elongation higher than unity.

The effect of various casting and heat-treatment variables on Q, as summarized by Gruzleski and Closset [3] is shown in Fig. 1. Some parameters change the quality index, while others do not affect it. Sounder castings generally exhibit higher quality index values. The variables that do not change Q can be manipulated to alter the UTS while maintaining the same Q level.

Although the concept of Q became widely popular, its use in the case of composite materials is often questioned. The contents of this communication are the direct result of our heat-treatment study of cast Al–Si–Mg/SiC_p composites, which investigated the effect of heat-treatment variables and concentration of SiC particulate reinforcement on the quality index, Q, and probable yield strength, PYS. Three alloys were used, 359 (Al–9.5 wt % Si–0.55 wt % Mg–0.013 wt % Sr), and 359 reinforced with either 10 vol % SiC_p (359/SiC/10_p) or 20 vol % SiC_p (359/SiC/20_p). Details of the casting, heat treatment, and tensile testing procedures for the tensile test bars obtained from permanent Stahl mould castings of these alloys are described elsewhere [4]. Each reading quoted in the tables (and figures) is the average taken from at least eight to ten test bar measurements.

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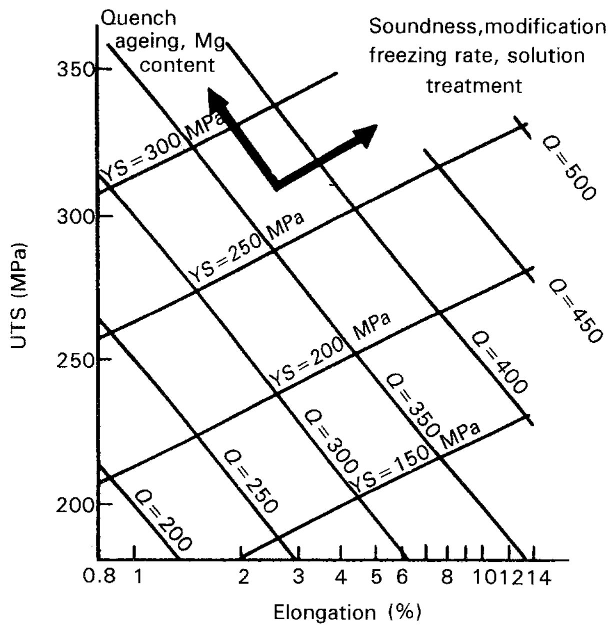

Figure 1 Relationship between UTS, El, YS and Q for an Al–7% Si–Mg alloy [3].

2. Quality index, Q

In order to establish the Q value, the plots of UTS versus $\log_{10}$ El were made to determine the best fit. Fig. 2a shows the graph of these points for the 359 alloy. Two distinct linear relationships could be established in the T6 temper (i.e. solution heat treatment + artificial ageing), one that represented ageing in the temperature range 140–180 °C, and the other for 210 °C ageing temperature. The a and b values (Equation 4) are given in Table I. In the solution heat treated (SHT) condition, the 359/SiC/10_p composite exhibited a linear relationship (Fig. 2b) for solution temperatures 520–550 °C. Solution heat treatment of this composite was studied in detail elsewhere [4]. Based on the results, for the 359/SiC/20_p composite (as well as 359 alloy), the solution heat treatment was selected to be 8 h/540 °C. Behaviour similar to that seen in Fig. 2a was observed when the 359/SiC/10_p composite was artificially aged in the temperature range 140–210 °C, Fig. 2c. For the 359/SiC/20_p composite, however, the UTS–log El plot could be expressed by means of a single relationship over the entire ageing temperature range, Fig. 2d. This observation highlights the importance of the 359/SiC/20_p composite in that it retains its resistance to softening upon ageing even at high temperatures.

Following the analysis of Purvis and Pehlke [2], the data shown in Fig. 2 and Table I can be approximately converted to obtain the quality index as follows.

In the SHT condition

$$Q = \text{UTS} + 63 \log \text{El} \qquad (6)$$

which is very close to that obtained by them for 319 alloy in the T5-temper, and shows that solution treatment improves the composite alloy quality.

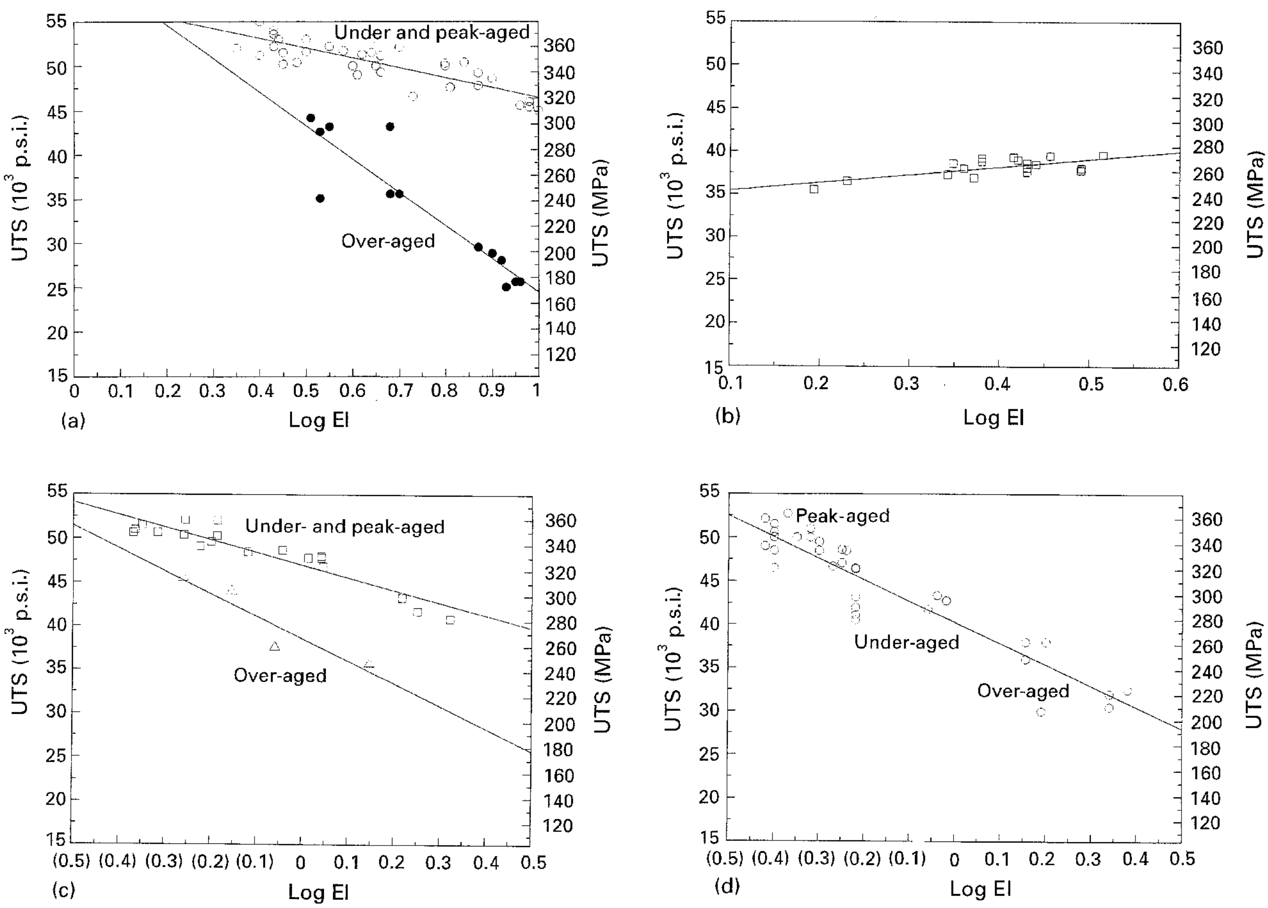

Figure 2 UTS–log El relationships for (a) 359 alloy in the aged condition, (○) 140–180 °C, (●) 210 °C; (b) 359/SiC/10_p composite in the solution heat-treated (SHT) condition, (c) 359/SiC/10_p composite in the aged condition, (□) 140–180 °C, (△) 210 °C; and (d) 359/SiC/20_p composite in the aged condition. 10^3 p.s.i. = 6.89 N mm^{-2}.

TABLE I UTS–log El relationships for the three alloys studied

Alloy/composite	Condition	a(MPa)	b(MPa)	R[b]
359	Aged(140–180 °C)	397.1	– 76.36	0.69
	Aged(210 °C)	428.9	– 260.0	0.83
359/SiC/10_p	SHT[a]	238.0	63.34	0.50
	Aged(140–180 °C)	324.3	– 114.33	0.86
	Aged(210 °C)	266.2	– 177.33	0.865
359/SiC/20_p	Aged(140–180 °C)	277.8	– 169.0	0.87

[a] SHT, solution heat treated.
[b] R, regression coefficient.

TABLE II Calculated values of Q for 359/SiC/10_p composite in the solution heat-treated (SHT) condition[a]

Solution temperature (°C)	Solution time (h)	Q (MPa)	
		from Eq. 1	from Eq. 6
520	2	271.17	256.8
	4	327.75	285.0
	8	308.0	279.1
	16	334.0	293.25
	24	341.55	292.14
538	1	279.45	259.44
	2	317.40	285.0
	4	327.75	294.7
	8	329.82	293.25
	12	327.75	290.49
	16	339.48	303.86
	24	332.0	295.73
550	1	326.7	285.0
	2	336.72	297.3
	4	333.3	296.7
	8	345.0	301.53
	16	324.3	294.0
	24	322.3	288.4

[a] El > 1%.

TABLE III Calculated values of Q for the 359 alloy in the aged condition[a]

Ageing temperature (°C)	Ageing time (h)	Q (MPa)		
		from Eq. 1	from Eq. 7	from Eq. 10
140	5	458.0	235.0	385.0
	12	468.6	274.8	405.1
	24	462.5	290.0	406.0
155	5	431.3	295	386.7
	12	449.6	326.6	409.3
	24	432.7	335.2	401.0
180	5	430.5	322.7	395.2
	12	441.7	321.6	402.4
	24	432.0	301.0	389.0

[a] El > 1 %.

In the aged condition:
(a) for 359 alloy

$$Q = \text{UTS} - 76 \log \text{El} \quad (7)$$

(b) for the 359/SiC/10_p composite alloy

$$Q = \text{UTS} - 114 \log \text{El} \quad (8)$$

(c) for the 359/SiC/20_p composite alloy

$$Q = \text{UTS} - 169 \log \text{El} \quad (9)$$

TABLE IV Calculated values of Q for the 359/SiC/10_p composite in the aged condition[a]

Ageing temperature (°C)	Ageing time (h)	Q (MPa)			
		from Eq. 1	from Eq. 8	from Eq. 11	from Eq. 13
140	5	313.2	272.1	307.5	463.1
	12	330.5	319.6	329.0	480.5
	24	315.8	349.0	320.4	466.0
155	2	329.6	275.5	322.0	479.4
	5	337.4	326.5	335.9	487.4
	12	314.6	367.9	322.1	465.0
	24	293.4	396.0	307.7	443.8
180	5	269.2	390.0	286.1	420.0
	12	280.6	378.0	294.2	431.0
	24	285.7	365.5	297.0	436.0

[a] El > 1 %, $Q_1 > Q_8$; El < 1 %, $Q_1 < Q_8$; El ~ 1 %, $Q_1 \sim Q_8$.

TABLE V Calculated values of Q for the 359/SiC/20_p composite in the aged condition[a]

Ageing temperature (°C)	Ageing time (h)	Q (MPa)			
		from Eq. 1	from Eq. 9	from Eq. 12	from Eq. 13
140	5	275.0	305.4	272.6	424.4
	12	295.0	365.5	290.5	444.7
	24	309.8	405.6	304.1	460.0
155	5	301.0	383.8	296.1	451.0
	12	323.0	433.6	316.4	473.0
	24	311.6	457.0	303.0	461.6
180	5	297.6	443.0	389.0	447.6
	12	313.3	440.0	305.7	463.3
	24	300.0	382.9	295.1	450.0

[a] El < 1 %.

These equations show that the numerical value of b increases continuously with increasing concentration of SiC_p reinforcement.

The calculated values of Q, using either Equation 1 (with $b = 150$ MPa) or Equation 6, are shown in Table II, while those using Equation 1 and Equations 7–9 are shown in Tables III–V for the three alloys in the aged condition. As can be seen, except in the solution heat-treated condition, using Equations 7–9 to describe the combined effect of UTS and El in the aged condition is misleading. The difficulty of employing the quality index concept in cast composites arises from the fact that the elongations

TABLE VI Measured (YS) and calculated (PYS) values of yield strength for the three alloys studied

Ageing temperature (°C)	Ageing time (h)	359		$359/SiC/10_p$		$359/SiC/20_p$	
		YS (MPa)	PYS (MPa)	YS (MPa)	PYS (MPa)	YS (MPa)	PYS (MPa)
140	5	182.6	184.6	232.7	243.4	257.0	256.6
	12	238.0	231.0	273.5	289.2	304.0	322.0
	24	265.6	271.0	306.0	305.4	331.0	341.1
155	2	–	–	268.0	257.2	–	–
	5	260.8	264.5	299.0	293.6	323.0	331.0
	12	303.6	303.0	315.0	316.0	360.0	354.8
	24	312.0	307.6	331.0	331.2	361.0	361.9
180	5	297.0	293.3	328.4	317.2	348.0	353.5
	12	314.0	298.1	325.0	321.5	340.0	357.6
	24	293.0	271.0	310.0	306.6	324.0	330.0

obtained are usually close to, or less than, unity. This results in a negative log El value which, combined with a negative slope direction, renders an increase in the obtained Q value with decreasing elongation, unless the absolute value of the slope is used, regardless of its sign, in which case, Equations 7–9 will be rewritten as

$$Q = \text{UTS} + 76 \log \text{El} \quad (10)$$

$$Q = \text{UTS} + 114 \log \text{El} \quad (11)$$

$$Q = \text{UTS} + 169 \log \text{El} \quad (12)$$

In their investigations on the influence of defects on the reliability of the mechanical properties of Duralcan F3S.20S composite (same as the present $359/SiC/20_p$ composite), Asselin *et al.* [5] used the following equation for determining the Q values of their composite samples

$$Q = \text{UTS} + 150 \log (10\ \text{El}) \quad (13)$$

The Q values calculated from their equation for the present $359/SiC/10_p$ and $359/SiC/20_p$ composites are given in Tables IV and V, respectively. As can be seen, these Q values lie in the range of those obtained for 359 alloy (Table III, applying Equation 1). However, while such a calculation apparently provides attractively similar Q values for both base alloy and composite, no reasoning for using 10 El rather than the actual elongation values (El < 1%) was provided by Asselin *et al.* [5].

In order to overcome this difficulty, the concept of "ISO–Q" may be considered, Fig. 1. Assumption of a "constant Q" for each alloy/composite in the aged condition (140–180 °C, with respect to the plots shown in Fig. 2) leads to the development of the following expressions.

For 359 alloy

$$Q = \text{UTS} + 147 \log \text{El} \quad (14)$$

For the $359/SiC/10_p$ composite alloy

$$Q = \text{UTS} + 148 \log \text{El} \quad (15)$$

For the $359/SiC/20_p$ composite alloy

$$Q = \text{UTS} + 160 \log \text{El} \quad (16)$$

TABLE VII Empirical constants for Equation 3 with their respective signs

Alloy	Condition	a_1	a_2	a_3
359	Aged	1.5	– 0.20	270
$359/SiC/10_p$	SHT	0.8	21.4	28
	Aged	1.1	38	67.8
$359/SiC/20_p$	Aged	0.6	37	– 117.3

which are comparable with the original relationship established by Drouzy *et al.* [1].

3. Probable yield strength (PYS)

As shown in Fig. 1, the contributions of quenching, ageing and magnesium content are reflected more in the yield strength than in the other properties. The analyses of Drouzy *et al.* [1] and McLellan [6] show that the a_1 constant is essentially unity. Purvis and Pehlke [2] have shown that a_1 could be as low as 0.39 and that a_3 is negative (with respect to the signs in Equation 3). The measured (YS) and predicted (PYS) values of yield strength obtained from the present study are listed in Table VI, the empirical values of a_1, a_2, a_3 being listed in Table VII.

The above analysis shows that in composite materials with elongations inferior to unity (cast composites, aged condition), the concept of quality index, as it is commonly applied, appears to be inappropriate in describing the combined effects of UTS and elongation. It is much better, instead, to use the probable yield strength (PYS) for such materials.

Acknowledgements

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