CORRELATION BETWEEN MECHANICAL PROPERTIES AND MICROSTRUCTURE IN AN AL-7%SI ALLOY

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ABSTRACT

This paper is concerned with the sensitivity of mechanical properties to different metallurgical constituents in an Al-7%Si alloy. Secondary Dendrite Arm Spacing, silicon eutectic thickness and length, intermetallics, and volume fraction of constituents are evaluated, and its influence on both ultimate tensile strength - UTS and on strain to failure - SF is assessed. It is verified that more accurate and robust relations for UTS and SF calculation can be established if more than one metallurgical feature, for example SDAS and one eutectic geometrical parameter, are used together.
Mechanical properties of specimens, obtained by two different casting techniques and from different positions of the castings, are evaluated.

1. INTRODUCTION

Hypoeutectic Al-Si alloys combine good castability with the ability to have good ductility and toughness. In addition moderate to high strength can be achieved by applying heat treatment to the castings [1]. These properties make these alloys suitable for some applications mainly in the automotive field such as for example engine pistons.
Improvement in casting techniques has led to a decrease in casting porosities making other microstructural parameters dominant on mechanical properties. Mechanical properties are linked to microstructure and the former with solidification rate, temperature gradients, etc). In a real component it is not possible to control the previous parameters along the whole component volume. Assessing the mechanical properties along the component volume through a metallurgical inspection is an important tool to predict local mechanical properties. This paper is concerned with the obtainment of strong and accurate correlations that could be used to predict material properties.
Mechanical properties of Al-Si alloys are related to the morphology of silicon particles (size, shape, distribution) and Al dendrite parameters [2-7, 8-11, 12].
Perhaps the most convenient feature for metallographic measurement and quantification is *SDAS* It is reported [6, 7, 15, 11] that there is a good correlation between *SDAS* and *UTS* and ductility. For example on ref [6] it is discussed the relationship between the secondary dendrite arm spacing (*SDAS*) and *UTS*. Results show an increase of the ultimate tensile strength and strain to failure on both A356 and A357 (ASTM) alloys with the decrease of the secondary dendrite arm spacing (*SDAS*)[6]. Studies performed on

the sand cast A356-T6 obtained by hot isostatic pressing process revealed also an increase of ultimate tensile strength and of ductility on the A356 alloy with a decrease of secondary dendrite arm spacing (*SDAS*) [7]. Experiments performed on an Al-7%Si-Mg alloy showed also an increase of the ultimate tensile strength and the elongation with a decrease of dendrite arm spacing (*DAS*) [15]. The yield strength was found to be less influenced by the *SDAS*.

Other correlations have also been established between other constituents such as eutectic volume fraction [8] or Si and Fe intermetallics, and Si particles size and shape [1, 6-11, 13], and mechanical properties. On ref [2] there is a good correlation between the amount of dendritic α-Al phase with mechanical properties of a Sr-modified Al alloy. In another study, an increase in the strain to failure was attributed to the increase in the amount of eutectic [16, 14]. The amount of eutectic was also been mentioned to give good correlations with ultimate tensile strength and mainly with strain to rupture both in hypo and hyper eutectic alloys [8].

Notwithstanding the previous correlations few studies exist where an analysis of the accuracy and robustness between correlations with different constituents combinations and mechanical properties is made. This study will do an analysis of possible correlations between metallurgical features and mechanical properties and will show that more robust correlations may be established in different metallurgical features are considered together in order to predict mechanical properties, in particular ultimate tensile strength and strain to failure.

2. EXPERIMENTAL METHODS

A commercial Al-7%Si alloy was selected (table 1). The alloy chemical composition is presented in table 1.

Table 1: Chemical composition of the alloy as obtained by (SEM/EDS).

	Si	Fe	Mg	Mn	Zn	Ti	Sb
Al-7%Si	6,80	0,12	0,61	0,01	0,02	0,12	0,14

The material was melt in an induction vacuum furnace at a temperature of about 100ºC above its *liquidus* temperature and then poured into a steel permanent mould. Two casting processes were used – vertical centrifugal casting and gravity casting. The permanent mould was preheated at 130 ºC for all castings. On vertical centrifugal castings the mould was rotating around the central axis of the casting machine at 450 rot/min and the molten aluminium was poured into the mould cavity by centrifugal force. For gravity castings the same induction vacuum melting equipment was used and the same melting temperatures as on centrifugal casting were used. However, in this case, the melt was manually poured into the mould.

The alloy was heat treated according to the standard industrial procedures. The imposed thermal cycle was: a solubilization at 540 ºC for 8h followed by water quenching and after an ageing at 160 ºC for 4 h.

The alloy was tested only in the final condition (after heat treatment) because it is intended to understand the correlation between material internal structure and mechanical properties on in service condition.

Three ingots for each casting technique were produced. Three specimens from each ingot, from the centrifugal castings and from the gravity castings (Figure 1) were cut in order to compare the properties of the aluminium alloy at three different distances from the surface of the ingot. Globally, 18 specimens were tested, 9 for each casting technique and three for each position in the casting.

Table 2 - Mechanical properties, constituents volume fraction and morphology, pores volume fraction and hardness of an Al-7%Si alloy

7% Si	Pos.	Mechanical properties σ (MPa)	ε (%)	E (MPa)	Hardness (HV)	Volume fraction (%) (Al) dendrites	Eutectic	Intermetalics	Macro-Pores	Morphology (μm) Eutectic Si Th	Lth	SDAS
Grav.	1	283	7,1	[illegible]4194	111±1,3	58,3	41,3	0,0	0,4	2,01	3,45	24,6
	2	267	4,7	71399	107±0,6	61,3	38,6	0,0	0,1	2,16	4,13	27,2
	3	282	3,3	71227	103±2,3	68,1	31,7	0,0	0,1	2,22	4,88	30,8
Cent.	1	321	10,2	71557	127±1,3	51,4	48,4	0,0	0,1	1,59	2,75	22,5
	2	298	8,0	74837	120±1,9	63,3	36,4	0,1	0,2	1,54	3,88	24,6
	3	285	4,0	66620	115±2,3	66,3	33,5	0,2	0,0	1,68	3,81	31,1

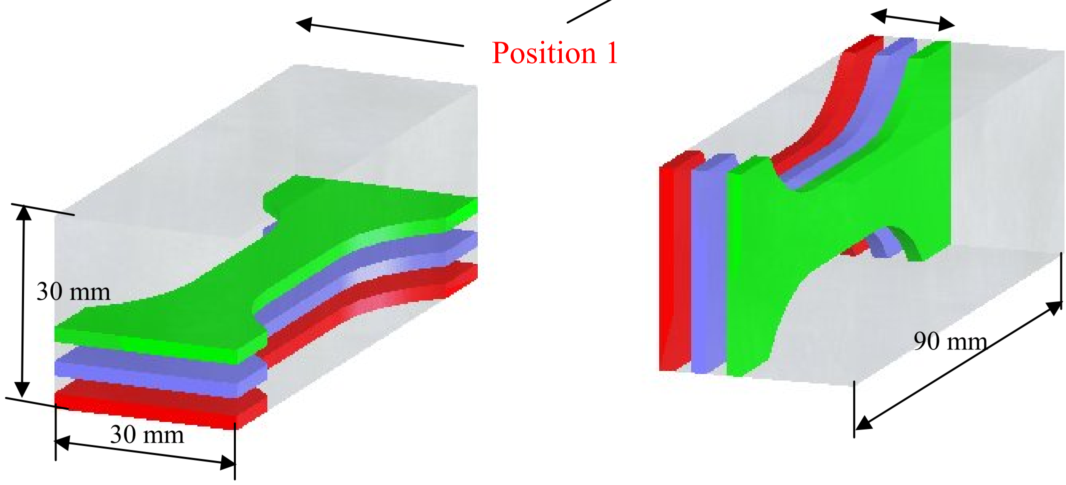


Figure 1 – Position from where tensile test specimens were taken: a) gravity castings; b) vertical centrifugal castings.

Arrows on the Figure 1 show the direction of pouring of the melt alloy.

Tensile tests were carried out on an Instron tensile testing machine. Samples were analysed by optical and Scanning Electron Microscopy/Energy Dispersion Spectroscopy (*SEM/EDS*) Metallurgical features were quantified by image analysis.

3. RESULTS AND DISCUSSION

Obtained results for the studied alloy, concerning mechanical properties namely ultimate tensile strength and strain to failure, and constituents volume fraction and morphology, are presented in Table 2 and Figures 2 to 8. Figures 2 to 5 present different types of correlations between one internal microstructure feature and mechanical properties (Ultimate Tensile Strength -*UTS* and Strain to failure - *SF*).

Figures 6 to 8 present different types of correlations between mechanical properties and a parameter that includes two or more internal microstructure features.

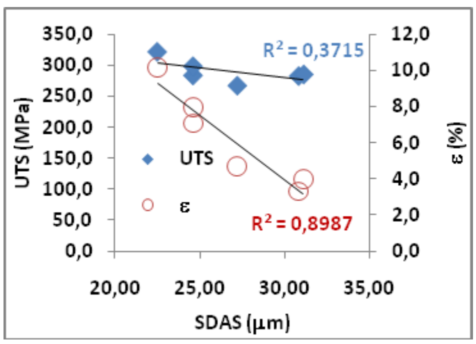


Fig. 2 – Correlation between *UTS* and *ε* and *SDAS*

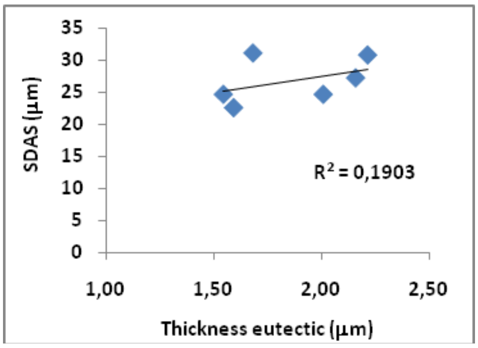


Fig. 3 – Correlation between *SDAS* and Thickness of eutectic

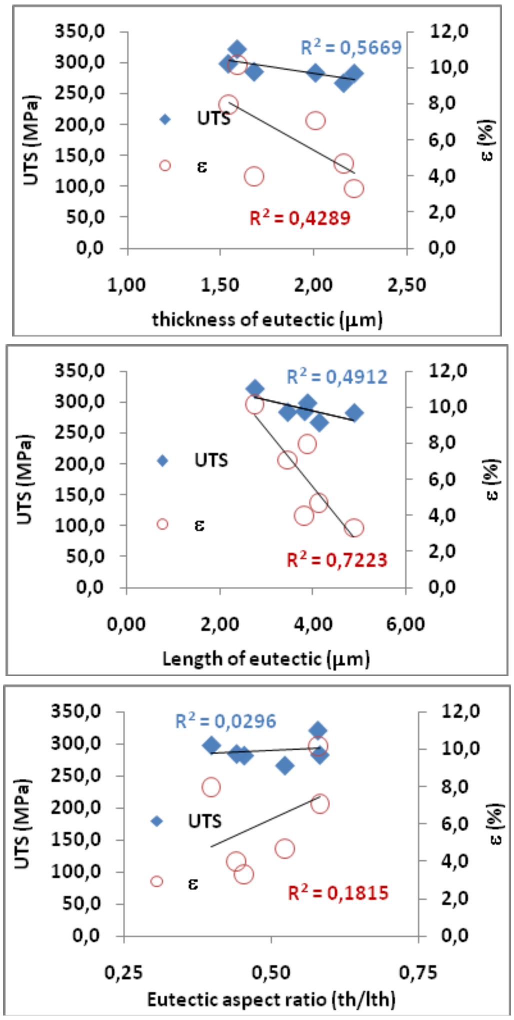
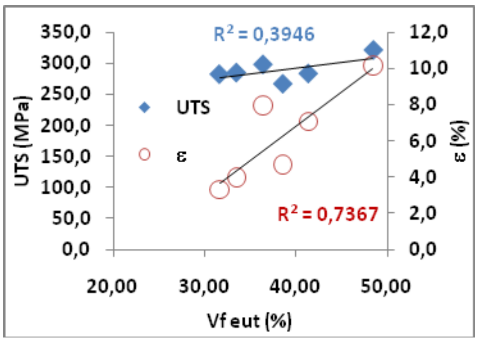


Fig. 4 – Eutectic: a) thickness; b) length; c) aspect ratio



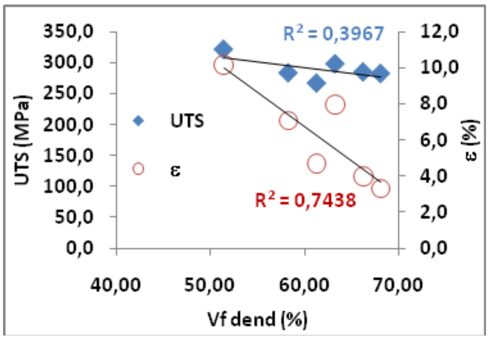


Fig. 5 – Volume fraction: a) eutectic; b) dendrites

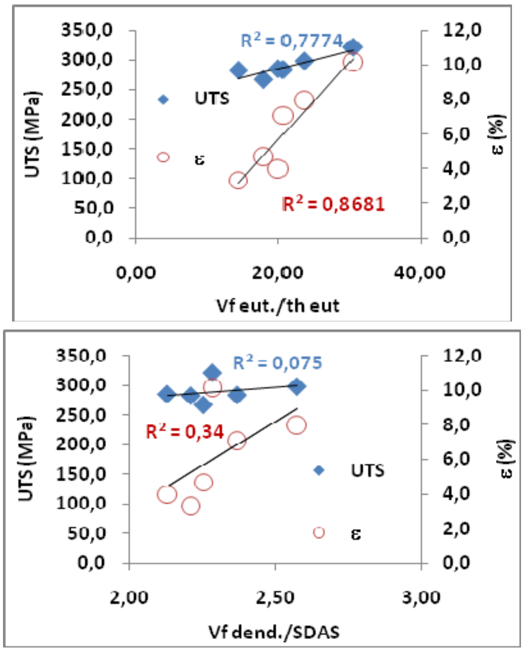


Fig. 6 – Volume fraction/geometrical feature: a) Vf_{eut}/th_{eut}; b) $Vf_{dend}/SDAS$

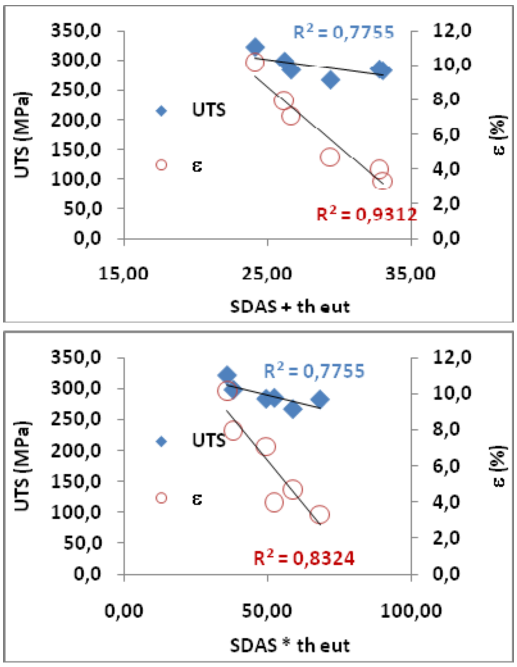
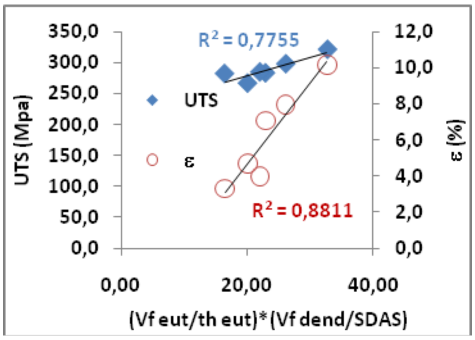


Fig. 7 – Geometrical features of both eutectic and dendrites: a) th_{eut}+ *SDAS*; b) th_{eut}*SDAS*



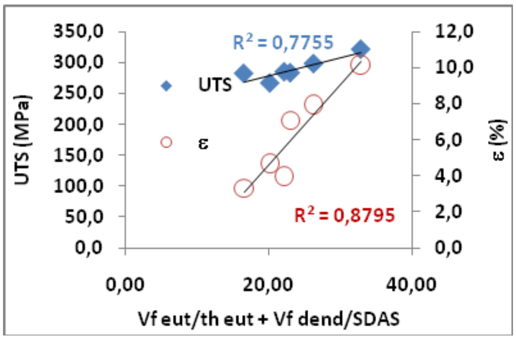


Fig. 8 – Volume fraction/geometrical feature: a) Vf_{eut}/th_{eut}; b) $Vf_{dend}/SDAS$

The *first aspect* on this study is related to different correlations between mechanical properties and metallurgical features.

Secondary dendrite arm spacing (*SDAS*) is the most used metallurgical parameter to predict mechanical properties [2, 6-7, 11, 15]. On fig. 2 it can be seen that there exists a correlation between ultimate tensile strength and strain to failure with *SDAS*. This parameter is used because it is the most convenient feature for metallographic measurement and quantification. The previous assumption (good correlation between *SDAS* and mechanical properties) is based on the fact that during solidification there is a good interconnection between the dimensions of the different constituents. Thus, the assessment of only one feature could give a good overview of all constituents. Although this reasoning is true it may not be so linear. As a fact, for example during thermal treatment (ageing or other) while eutectic substantially changes its shape the *SDAS* remains almost with the same geometry. On fig. 3 it is shown that eutectic shape have a poor correlation with *SDAS* (high scattering) for different processing techniques and positions in the casting (different cooling rates). Thus, when accuracy of predictions is important the use of *SDAS* is not adequate to predict the *UTS*. Examples of equations as those based on *SDAS* can be found in literature [2, 6, 7, 15]. An example is given in eq. 1.

$$UTS = -1{,}4399 \cdot SDAS + 340 \text{ [MPa]}$$

where: *UTS* is ultimate tensile strength and *SDAS* is secondary dendrite arm spacing.

As the eutectic constituent is the dominant constituent controlling *UTS*, correlations between geometrical features of the eutectic and mechanical properties can also be established [8], as can be seen on fig. 4. It is observed that improved correlations (as compared with *SDAS*) exist between eutectic thickness and length and *UTS*. Predictions with the eutectic silicon aspect ratio (another variable also tried for correlations with mechanical properties [17]) do not seem also to be very accurate. Fig. 5 show correlations of *UTS* with isolate volume fraction of both dendrites and eutectic and again the correlations are not very accurate.

Up to now it seems that correlations with only one geometrical feature are not very accurate. It seems obvious that better correlations could be obtained if they would also take into account other constituents. The relations would be more robust and accurate because they would go deeper into the overall material. It is also a fact that nowadays due to image software developments it is equally easy to quantify other metallurgical constituents or even different metallurgical constituents at the same time as it was some years ago to manually quantify *SDAS* by using optical analysis.

Based on the previous reasoning that isolate metallurgical features may not provide as accurate results as correlations with more constituents at the same time, fig. 6 provides correlations with the volume fraction of one constituent divided by one of its geometrical features. Fig. 7 provides relations: 7a) sum; and 7b) multiplication, with geometrical features of two constituents simultaneously. Finally

Fig. 8 provides relations with: a) a sum and b) a multiplication of the ratios Vf_{eut}/th_{eut} and $Vf_{dend}/SDAS$, respectively.

It is clear on fig. 6a that correlations for UTS are globally more accurate when both the eutectic volume fraction and its thickness are used together. The same does not happen for the ratio with dendrites. Correlations are improved if both the eutectic and SDAS are taken into consideration through its geometrical features, as presented in Fig. 7. When both ratios are taken into consideration at the same time (Fig. 8) it is clear that the correlations are also consistent for UTS. R^2 is always superior to 0,77.

These last correlations are more robust because they do not depend on one single metallurgical feature. It is also clear that the last correlations are mainly dependent on the ratio of eutectic (*Vf/Th*) because the geometrical feature (thickness of eutectic) is much smaller than the geometrical feature *SDAS* (see table 1). The ratios are quantified as the amount (volume fraction) of the constituent divided by one of its geometrical features. As the amount of the constituent increases more influent it is on the material. As the geometrical feature reduces its value improved *UTS* values are obtained (geometrical feature in denominator). It is observed that although the volume fraction of eutectic is smaller than the one of dendrites the ratio *Vf/th* is much bigger. Thus, for this material, it is the eutectic that provides the material mechanical resistance [8]. When Si is in the form of eutectic, as it increases the *UTS* of the material also increase. For example, for the same Si content [8], as the volume fraction of eutectic increases *UTS* also increase. It is not the Si itself that promotes the resistance but the α phase of the eutectic that is constrained by the Si lamellas and thus restrains the onset of the eutectic α slip process [18]. Thus the volume fraction of eutectic and also its geometrical features are the main controlling parameter of *UTS* [8].

Regarding *SF* - strain to failure, it is mainly dependent on the α phase of the eutectic but also on the α phase of the dendrites. The dendrites are the last constituent to break in a tensile test. It is interesting to observe that for *SF* there is also a good correlation with an isolate metallurgical feature namely with the *SDAS* (Fig. 2). Correlations are poor with isolate eutectic geometrical features. The best predictions for *SF*, with the exception of the correlation with *SDAS* (Fig. 2), are obtained again when both constituents are taken into consideration at the same time through their geometrical features (Fig. 7) or through their ratios ((*Vf/Th* and $Vf_{dend}/SDAS$)(Fig. 8). R^2 is always superior to 0,87 in the last case.

Existing relationships in literature [1] between ultimate tensile strength and secondary dendrite arm spacing and the size of silicon lamellas in interdendritic eutectic regions [1](eq. 2) seem to be adequate because it sums geometrical features of both dendrites and eutectic giving a similar correlation as the one on Fig. 7a.

$$\sigma = k + k_2 \cdot \gamma^{-\frac{1}{2}} + k_3 \cdot \lambda^{-\frac{1}{2}}$$

where: σ is the ultimate tensile strength, k, k_2 and k_3 are empirical constants, γ is the size of silicon lamellas in interdendritic eutectic regions and λ is the secondary dendrite arm spacing.

Another equation (eq. 3) as proposed by Ceschini *et al.* [17] also includes geometrical features of both eutectic and *SDAS* features by multiplying them. It should give results similar to the ones in fig. 7b.

$$IM = SDAS.d.AR.(150-HV).10^{-3}$$

where: *IM*- is a parameter that takes into consideration *SDAS*, *d* – grain size, *AR* – aspect ratio of eutectic Si particles, and *HV*-hardness of the material.

The *second aspect* on metallurgical based mechanical properties predictions is the sensitivity of the mechanical properties to the metallurgical features changes. It is important to use a metallurgical feature that is able to properly predict mechanical properties but at the same time it is also relevant that that feature is not so sensitive to changes in metallurgical features in a way that an eventual error on observation, errors due to few measurements or with high dispersion (R^2) values, may introduce substantial errors on predictions. Otherwise a substantial number of readings of that feature would be necessary to obtain accurate predictions.

Figs. 9 and 10 show the sensitivity of both *UTS* and *SF* to the previous different metallurgical features and different combinations.

It is clear that both *UTS* and *SF* are more sensitive to isolate metallurgical features either volume fraction or a geometrical feature such as thickness of eutectic. This was expected and can be an advantage regarding the simplicity of measurement. However although the combined relations are less sensitive (an exception occurs for *SDAS* and $SDAS+th_{eut}$ correlated with *SF*) they are more robust because they provide more accurate results (higher R^2 values) and thus give an improved level of confidence.

Accurate results for mechanical properties (*UTS* and *SF*) could then be correlated with the constituents based on the equations that incorporate the higher R^2 values:

For UTS they should incorporate:

- Vf_{eut}/th_{eut}; or
- $Vf_{eut}/Th_{eut} * Vf_{dend}/SDAS$; or
- $Vf_{eut}/Th_{eut} + Vf_{dend}/SDAS$; or
- $SDAS+th_{eut}$; or even
- $SDAS*th_{eut}$.

For SF – Strain to Failure they should incorporate:

- Vf_{eut}/th_{eut}; or
- $Vf_{eut}/Th_{eut} * Vf_{dend}/SDAS$; or
- $Vf_{eut}/Th_{eut} + Vf_{dend}/SDAS$; or
- $SDAS+th_{eut}$; or even
- $SDAS*th_{eut}$.

Relations with only SDAS seem to give also good predictions although only for *SF*.

As usually both UTS and SF predictions are required simultaneously, expressions should give good predictions in both cases. Thus the correlations should include:

- Vf_{eut}/th_{eut}; or
- $Vf_{eut}/Th_{eut} * Vf_{dend}/SDAS$; or
- $Vf_{eut}/Th_{eut} + Vf_{dend}/SDAS$; or
- $SDAS+th_{eut}$, or even $SDAS*th_{eut}$.

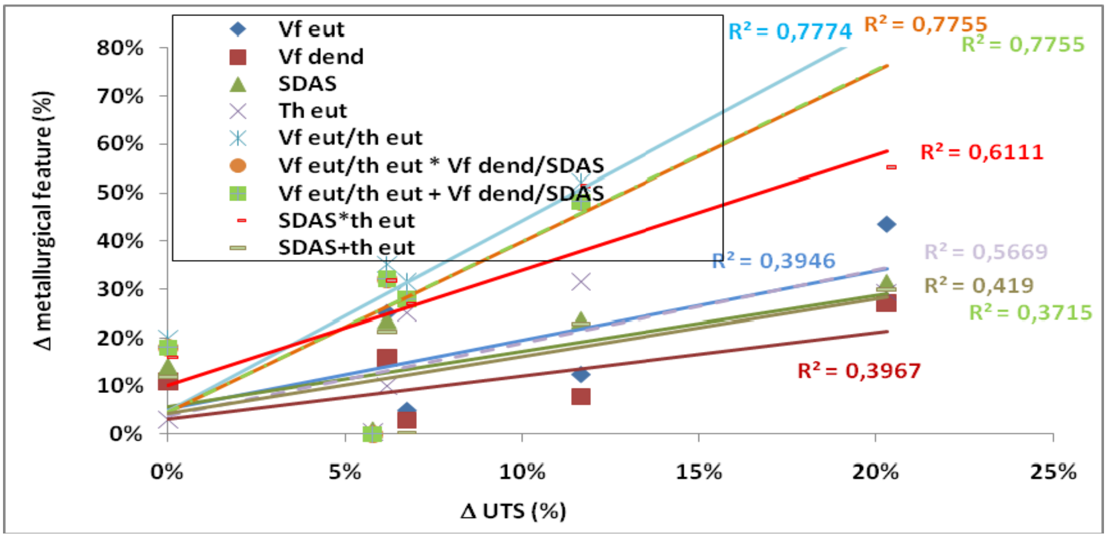


Fig. 8 Normalized values of UTS (normalized to the minimum value) and different metallurgical features (normalized to each minimum value).

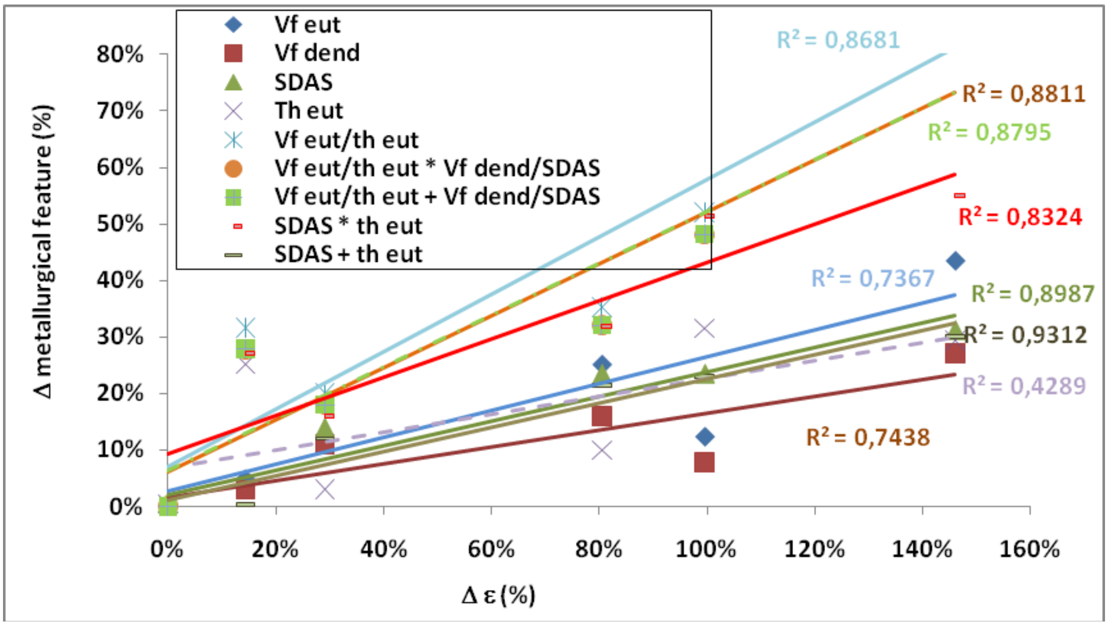


Fig. 9 Normalized values of Strain to Failure (normalized to the minimum value) and different metallurgical features (normalized to each minimum value).

It must be highlighted that porosity was not taken into consideration on the previous analyses because, as observed in table 2, the porosity level is very low.

Not withstand good predictions obtained by previous researches [1, 15, 17] the authors of this paper suggest that the equations that should be used are the ones that include more metallurgical parameters such as volume fraction of constituents and their geometrical features. They are the ones that would give the more reliable predictions with higher level of confidence and that could be used for more aluminium alloys, e.g. are more universal.

5. CONCLUSIONS

The main conclusions of this work are:

- Correlations between isolated and combined microstructural features and mechanical properties, namely *UTS* and *SF*, can be established;
- An improved level of confidence is obtained with correlations that include at least two geometrical parameters of both dendrites and eutectic;
- An increased reliability is obtained using correlations that includes the constituents volume fraction and their geometrical parameters.

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