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# On the influence of Mn and Mg additions on tensile properties, microstructure and quality index of the A356 aluminum foundry alloy

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**Abstract**

In Al-Si alloys, Fe is present as an inevitable impurity element, which mainly precipitates in the form of β-Fe or α-Fe crystals. While the latter usually has polyhedral or Chinese script morphology, the platelet-like shape of the β-Fe phases acts as a stress raiser and can also increase the amount of porosity. To inhibit the formation of this detrimental phase, several elements act as neutralizers of the embrittling effects of Fe and, among them, Mn is the most widely used. Mg strongly affects the mechanical properties and the formation of Fe-bearing phases. In the present work, a series of A356 aluminum foundry alloys with several combinations of Mn/Fe ratios and Mg contents were studied. To investigate the effect of Mn additions, five alloys with constant Fe and Mg content and increasing Mn/Fe ratios, from 0.37 wt. % to 1.11 wt. %, were considered. Moreover, four alloys with reduced Mg amounts up to 0.25 wt. % were evaluated. Tensile samples were machined from permanent mold castings and T6 heat-treated. The influence of the alloying elements on the mechanical properties were compared to microstructural observations. The results indicate that increasing the Mn/Fe ratios does not result in a significant increase of the tensile properties of the alloys. Conversely, the reduction of the Mg amounts leads to the decrease of yield stress, ultimate tensile strength and hardness combined with an increase in the elongation to fracture. Finally, the quality index approach was used to express the quality of the castings as a function of their ductility, yield strength and strain hardening ability.



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*Keywords:* A356 aluminum foundry alloy, Fe-rich intermetallic compounds, tensile properties, quality index

## 1. Introduction

Al-Si casting alloys are widely used in the automotive industry due to their good castability, low cost and excellent mechanical properties [Taylor (2012), Lu (2005)]. Among the commercial alloys, A356 alloy is one of the most popular alloys employed in the production of engine blocks, cylinder heads and transmission cases [Seifeddine et al. (2008)].

Chemical composition together with solidification parameters are responsible for the microstructural features, which control the mechanical properties of the alloy. Fe is considered the most detrimental impurity element in aluminum and its alloys, because it forms intermetallic compounds that are known to be harmful to the mechanical properties, such as ductility and castability [Crepeau (1995)]. A variety of Fe-rich intermetallic phases have been identified in aluminum alloys, including α-$Al_8Fe_2Si$ or α-$Al_{15}(Fe, Mn)_3Si_2$, β-$Al_5FeSi$ and π-$Al_8Mg_3FeSi_6$ and, among them β-Fe are the most harmful. In fact, the platelet-like shape of the β-Fe phases acts as a stress raiser and interferes with the flowing liquid in the interdendritic channels during solidification, increasing the amount of porosity and the brittleness of the material [Shabestari (2004), Zhang et al. (2013)].

Since Fe cannot be easily removed from the molten alloy, the formation of β-$Al_5FeSi$ can be inhibited by using different strategies to neutralize its negative effects, such as by the addition of Mn, Cr, Be and Ni [Shabestari (2004), Zhang et al. (2013)]. In particular, Mn is the most widely used and it can modify the β-Fe platelet-like morphology to more compact and harmless forms (i.e. Chinese script and/or polyhedral α-Fe phase) [Cao et al. (2004)]. It is well known that the Mn and Fe content can influence the type, the size and the ratio of different Fe intermetallic compounds [Ji et al. (2013), Timelli et al. (2011)]. Furthermore, a Mn/Fe ratio of 0.5 is recommended even though the amount of Mn needed to neutralize Fe has not been well established [Elsharkawi et al. (2010), Bäckerud et al. (1990)].

On the other hand, Mg is usually and intentionally added to Al-Si alloys to improve the heat-treating capability, and hence the alloy strength (yield strength and strain hardening), through the precipitation of $Mg_2Si$ intermetallic phases during artificial aging [Elsharkawi et al. (2010)]. Besides, the formation of Fe-rich intermetallic compounds depends on the Mg amount in the alloy and, in industrial practice, the A356 alloy usually contain Mg from 0.25 wt. % to 0.4 wt. % [Wang et al. (1997)].

Quality index is an empirical parameter, derived from ultimate tensile strength (UTS) and percent elongation (% EL), through which is possible to analyze the results of tensile tests [Drouzy et al. (1980), Cáceres (2000)]. In particular, by using the UTS-% EL chart, which reports the lines of equal quality index and the lines of equal probable yield strength, the properties of the alloys can be evaluated. In fact, iso-yield stress lines depend on structural conditions of the aluminum solid solution, while iso-quality index lines depend on the compactness and finesses of the structure, i.e. solidification conditions [Drouzy et al. (1980)].

The present work summarizes the results of an experimental investigation on the mechanical properties of A356 aluminum foundry alloys with several combinations of Mn/Fe ratios and Mg contents. The results of the tensile tests were correlated to the microstructural observations, performed by optical and scanning electron microscopy. The employment of quality index charts is also proposed.

## 2. Materials and methods

The chemical compositions of the alloys investigated in the present study are given in Table 1. In order to prepare alloys with different Mg contents, the castings were poured starting from an AlSi7 alloy manufactured from commercial purity aluminum and silicon, and melted by using a crucible furnace. The melting temperature was held at 780 ± 10 °C, continuously monitored by a thermocouple inserted into the liquid metal. The reference alloy (named Ref) was prepared pouring the melt from the crucible furnace to a ladle and adding Mg in order to reach the target of 0.39 wt. %. The alloy was then grain refined by the addition of AlTi5B1 rods, and Sr was added as modifier agent. Starting from this composition, measured amounts of Mn were made to obtain five different experimental alloys with constant Fe and Mg content, but with increasing Mn/Fe ratios, from 0.37 to 1.11. Moreover, to evaluated the effects of Mg contents, four different amounts of Mg ranging from 0.27 wt. % to 0.38 %, were considered by appropriate additions to the starting AlSi7 alloy. The chemical compositions of all the prepared alloys, analyzed by Optical Emission Spectroscopy (OES) after drossing and degassing treatments, are listed in Table 1. Permanent mold castings were then performed by pouring all the prepared alloys into a L-shaped preheated steel mold. The temperature of the die was kept at 235 ± 15 °C during the casting trials. All the nine experimental conditions were investigated and three castings were made for each composition. During the casting the evolution of the temperature of the mold was continuously monitored by means of a type K thermocouple. According to UNI EN ISO 6892-1:2009 standard, tensile test specimens were machined from the castings. All the samples were subjected to the same T6 heat treatment, which comprised solution treatment at 535 °C for 4.5 h, quenching in warm water at 70 °C and artificial aging at 155 °C for 4.5 h. Tensile tests were performed at room temperature and at a constant crosshead displacement rate of 1 mm/min. Yield strength (YS), ultimate tensile strength (UTS) and percent elongation (% EL) were measured and Brinell hardness measurements (UNI EN ISO 6506-1:2015) were subsequently carried out. After the tensile tests, samples were cut perpendicular to the fracture surface, mounted in a phenolic resin and subjected to standard grinding and polishing procedures. Samples were then etched with a 0.5 % solution of HF in ethyl alcohol and microstructural investigations were performed by both Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) equipped with Energy Dispersive X-ray Spectroscopy (EDS). For each sample, 100 fields at 500X of magnification were considered and the geometrical features of the intermetallic compounds were measured by image analysis techniques. A quality index approach was also considered to evaluate how the changes in chemical composition can affect both the tensile and strain properties of the castings.

Table 1. Chemical compositions (wt. %) of the alloys.

| Alloy | Al | Si | Fe | Cu | Mn | Mg | Ni | Zn | Ti | Sr (ppm) |
|---|---|---|---|---|---|---|---|---|---|---|
| Ref | Bal. | 7.088 | 0.106 | 0.001 | - | 0.391 | 0.005 | 0.002 | 0.136 | 173 |
| Mn/Fe=0.37 | Bal. | 7.094 | 0.101 | 0.001 | 0.037 | 0.382 | 0.004 | 0.002 | 0.128 | 166 |
| Mn/Fe=0.50 | Bal. | 6.862 | 0.100 | 0.001 | 0.050 | 0.378 | 0.004 | 0.002 | 0.124 | 170 |
| Mn/Fe=0.79 | Bal. | 6.935 | 0.101 | 0.001 | 0.080 | 0.387 | 0.004 | 0.002 | 0.125 | 151 |
| Mn/Fe=0.95 | Bal. | 6.985 | 0.102 | 0.001 | 0.097 | 0.374 | 0.004 | 0.002 | 0.121 | 153 |
| Mn/Fe=1.11 | Bal. | 6.874 | 0.104 | 0.001 | 0.115 | 0.378 | 0.005 | 0.002 | 0.122 | 162 |
| Mg=0.25 | Bal. | 7.036 | 0.108 | 0.001 | - | 0.253 | 0.005 | 0.002 | 0.122 | 170 |
| Mg=0.30 | Bal. | 7.110 | 0.106 | 0.001 | - | 0.296 | 0.005 | 0.002 | 0.132 | 169 |
| Mg=0.34 | Bal. | 7.034 | 0.106 | 0.001 | - | 0.341 | 0.005 | 0.002 | 0.126 | 175 |

## 3. Results and discussion

### *3.1. Effect of Mn/Fe ratio*

Figure 1 shows the plots of % EL (Fig. 1a) and of UTS and YS (Fig. 1b), as a function of the Mn/Fe ratios. It is observed that the increasing of the Mn content does not significantly affect the tensile properties of the alloys. In addition, Brinell hardness tests were performed and the mean value of 101 HBW was measured for all the samples; this is consistent with the obtained results of the tensile properties.

To assess the effect of the Mn additions on the type and morphology of the intermetallic compounds, microstructural analysis was performed on all samples. Figure 2 shows the OM and SEM images of the Ref alloy, i.e. with a Mn/Fe=0, (Fig. 2a and Fig. 2b) and of the Mn/Fe=1.11 sample (Fig. 2c and Fig. 2d), respectively. Microstructural investigations revealed that, among the three Fe-rich phases which could be formed, β-Fe with a needle-like morphology were detected. These intermetallic compounds appear in light grey in the backscattered images of Fig. 2b and Fig. 2d (yellow arrows). The limited presence of α-Fe even for the highest Mn amount, is to be considered in relation to the low Fe content in the present alloy. Most of authors claimed the ability of Mn to change the Fe-rich intermetallics from β-Fe platelets to α-Fe with Chinese script morphology when Fe contents are at least of 0.2 wt. % [Seifeddine et al. (2008), Zhang et al. (2013), Abedi et al. (2010)]. Due to the little amount of Fe, it is likely that the Mn additions do not lead to the conversion of brittle β-Fe platelets into less harmful α-Fe intermetallics, whose globular or script shape could improve mechanical properties.

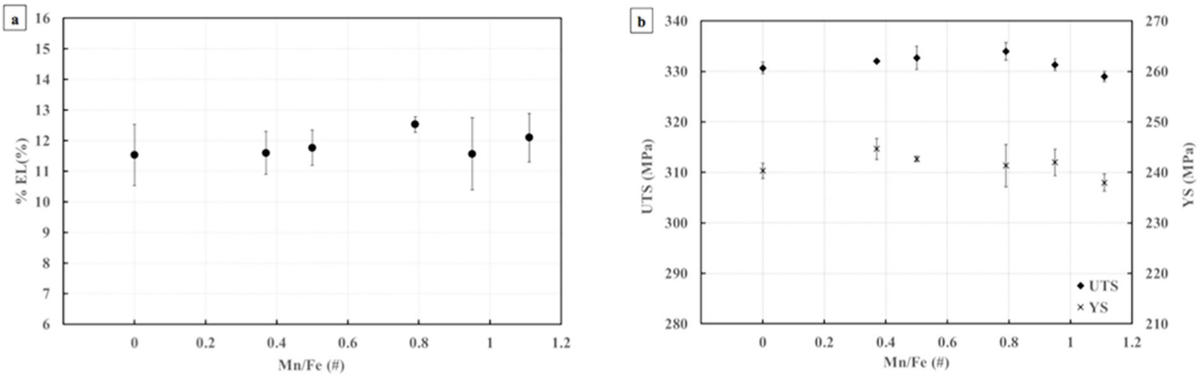


Fig. 1. Effect of Mn/Fe ratios on the tensile properties (a) % EL versus Mn/Fe ratio; (b) UTS and YS versus Mn/Fe ratio.

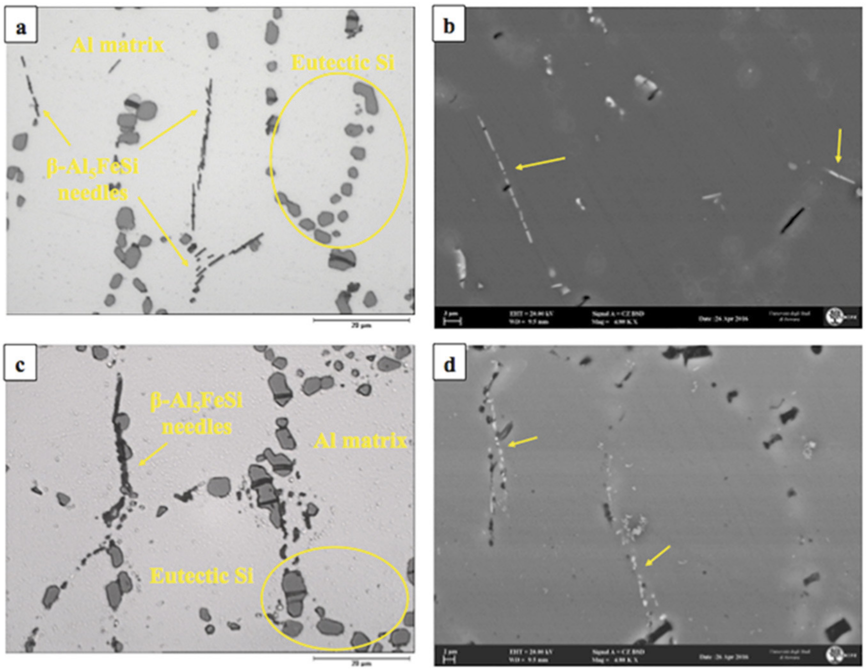


Fig. 2. (a), (b) OM and SEM images for reference sample (Mn/Fe=0); (c), (d) OM and SEM images for the Mn/Fe=1.11 sample.

Given that tensile properties are directly dependent on the microstructural features, Table 2 reports the quantitative data resulting from the microstructural analysis, in terms of number and maximum average size of the β-$Al_5FeSi$ compounds as a function of the Mn/Fe ratios. According to the number of the detected β-Fe phases, the addition of Mn causes their reduction, while the variation of their maximum average length is negligible. As shown in Fig. 2 both for the reference sample (Mn/Fe=0) and for Mn/Fe=1.11 sample, the length of the β-Fe phase appears comparable, even if their amount is remarkably reduced (Table 2). According to the experimental findings, tensile properties seem to be more dependent on the dimensions of the intermetallics rather than their amount.

Table 2. Measurements of average dimensions of β-$Al_5FeSi$ needles for the different Mn/Fe ratios.

| Alloy | Number of particles (#) | Average maximum length (μm) | Standard Deviation (μm) |
|---|---|---|---|
| Ref (Mn/Fe=0) | 167 | 12.08 | 6.01 |
| Mn/Fe=0.37 | 80 | 10.97 | 5.44 |
| Mn/Fe=0.50 | 37 | 11.08 | 6.76 |
| Mn/Fe=0.79 | 40 | 8.31 | 2.83 |
| Mn/Fe=0.95 | 49 | 10.29 | 5.16 |
| Mn/Fe=1.11 | 25 | 10.49 | 3.45 |

### *3.2. Effect of Mg content*

With regard to the effects of the Mg contents on the tensile properties, Fig. 3 reports the variation of the % EL (Fig. 3a) and of UTS and YS (Fig. 3b) as a function of the Mg amounts. Experimental values indicate that the reduction of the Mg content with respect to the Ref alloy (Mg=0.39 wt. %) leads to an increase of % EL (Fig. 3a) but, at the same time, to a significant reduction of UTS and YS (Fig. 3b). These results are consistent with the literature since it is well known that the tensile properties are dependent on the Mg amount, which is available for precipitation during artificial aging [Taylor et al. (2000)]. As a practical rule, Mg is usually added to A356 alloy in the range from 0.25 wt. % to 0.4 wt. % [Wang et al. (1997)], allowing to improve YS and UTS but reducing the ductility [Cáceres et al. (1999)].

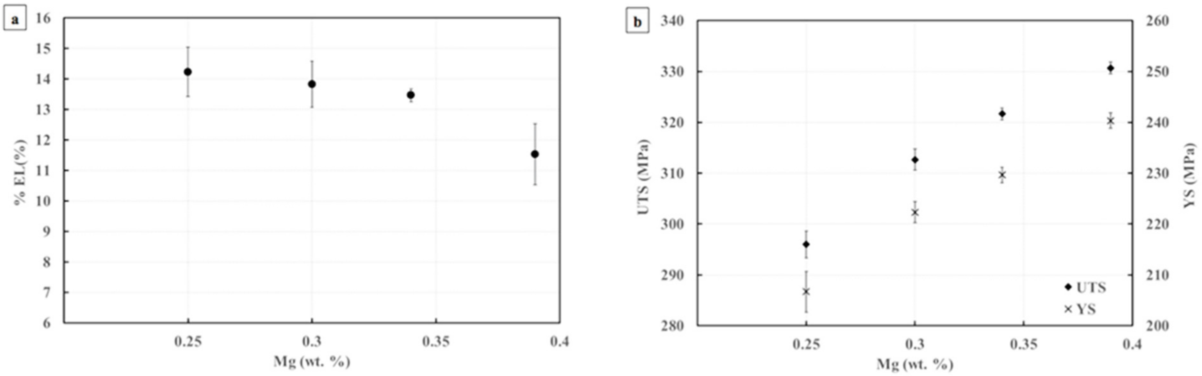


Fig. 3. Effect of Mg contents on the tensile properties (a) % EL versus Mg amount; (b) UTS and YS versus Mg amount.

With regard to the hardness of the alloys, experimental results show that an increment of the Mg content leads to an increase of the hardness values, from 92 HBW (Mg=0.25 wt. %) to 101 HBW (Ref alloy, Mg=0.39 wt. %), associated with the reduced ductility (Fig. 3a). One possible explanation for the reduced ductility associated with the highest Mg content might be due to the stronger Al matrix which is likely to increase the loading on the Si particles and thus increasing the probability of their cracking [Wang et al. (1997)]. Figure 4 shows the comparison between the OM micrographs of Ref alloy (Fig. 4a) and the Mg=0.25 wt. % alloy (Fig. 4b), evaluated in the region near to the fracture surface. It can be noted that the reference alloy shows a higher content of cracked Si particles.

Considering the relationship between the Mg contents and the Fe-rich intermetallic phases it should be noted that in alloys with low levels of Mg (0.3–0.4 wt. %), in place of the π-Fe phase, only cluster of small β-Fe needle-like intermetallics are observed [Taylor et al. (2000)]. According to the literature, the Fe-rich intermetallic phases observed in the present study, were mainly fine and fibrous β-Fe platelets, whose measurements are listed in Table 3. In particular, experimental measurements of the intermetallics highlighted that a decrease of the Mg content does not significantly affect both the amount and the size of the β-Fe phase (Table 3), which are roughly the same for the Ref alloy (Mg=0.39 wt. %) and for the minimum Mg amount considered (Mg=0.25 wt. %).

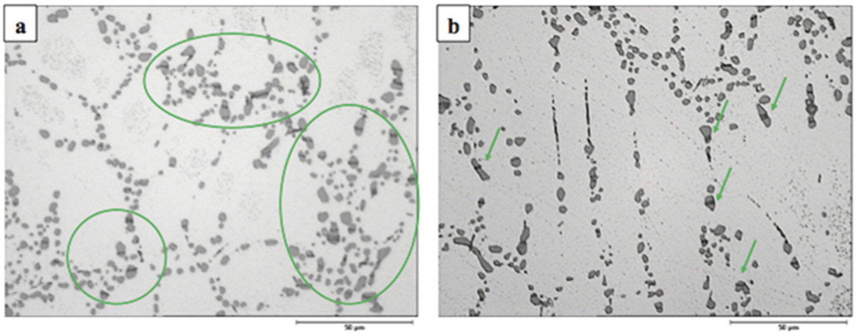


Fig. 4. Optical micrographs of the cracked Si particles for (a) Ref alloy (Mg= 0.39 wt. %) sample; (b) Mg=0.25 sample.

As a result, no variation of both amount and size of the intermetallics indicate that the tensile properties are mainly affected by the precipitation hardening due to the $Mg_2Si$ particles.

From the comparison among the measurements of the β-$Al_5FeSi$ needles performed in alloys with different Mn/Fe ratios (Table 2) and Mg amounts (Table 3), no significant variations of the average maximum length were detected. This experimental finding suggests that, for all the investigated alloys, the observed β-$Al_5FeSi$ phases result from the decomposition of the π-$Al_8Mg_3FeSi_6$ during the solution treatment.

Table 3. Measurements of average dimensions of β-$Al_5FeSi$ needles for the different Mg amounts.

| Alloy | Number of particles (#) | Average maximum length (μm) | Standard Deviation (μm) |
|---|---|---|---|
| Ref (Mg=0.39) | 167 | 12.08 | 6.01 |
| Mg=0.25 | 121 | 13.96 | 6.32 |
| Mg=0.30 | 110 | 13.72 | 6.57 |
| Mg=0.34 | 167 | 11.45 | 4.76 |

### 3.3. Quality index charts

In addition to tensile testing and microstructural characterization, the quality index approach [Drouzy et al. (1980)] was applied to study the effects of varying the Mn/Fe ratio and the Mg content on the quality of the A356 aluminum alloy. The quality value (Q) proposed by Drouzy is defined by equation (1), which relates the UTS and the % EL:

$$Q = UTS + k \cdot \log(\%\ EL) \qquad \text{(MPa)} \tag{1}$$

where, for the A356 alloy $k$ is equal to 150 MPa [Drouzy et al. (1980)]. The authors introduced also an empirical equation (2), which relates UTS and % EL with respect to the probable yield strength ($YS_{PROB}$):

$$YS_{PROB} = a \cdot UTS - b \cdot \log(\%\ EL) - c \qquad \text{(MPa)} \tag{2}$$

where the parameters *a, b, c* are empirical constants whose values depend on the alloy system and, for the A356 alloy *a*= 1, *b*=60 and *c*=13. In a UTS-% EL diagram, i.e. a quality index chart, it is possible to identify two privileged directions: the so-called iso-quality lines, calculated by equation (1) and the so-called iso-probable YS lines, calculated by equation (2). Therefore, each point of the plot is characteristic for a specific alloy, according to its process variables, heat treatment, chemical composition.

To estimate both the effect of the Mn/Fe ratios and the Mg contents by the quality index approach, from tensile test data quality index charts were derived by equation (1) and equation (2) and the results are reported in Fig. 5.

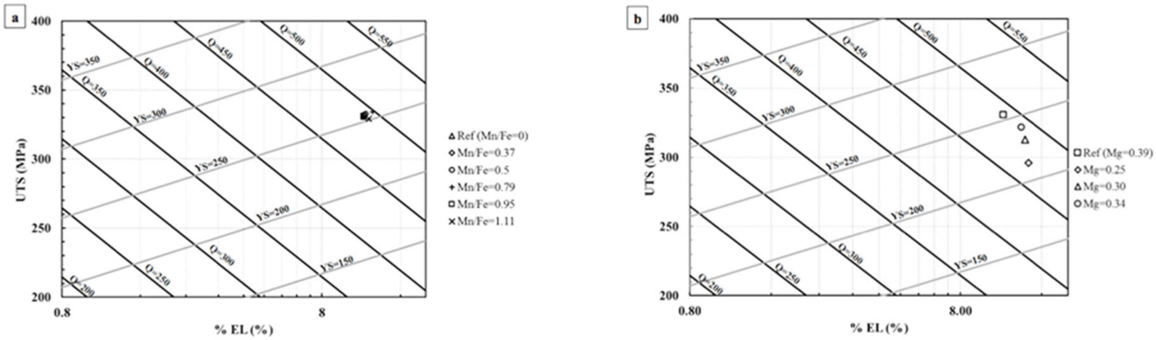


Fig. 5. Quality index chart (a) Mn/Fe ratios samples; (b) Mg samples.

Taking into account the six alloys differing in their Mn/Fe ratio (Fig. 5a), the quality index chart shows that points are grouped around the Q value of 490 MPa and $YS_{PROB}$ value of 254 MPa. These results shows that the variation of the Mn/Fe ratios does not modify the Q and $YS_{PROB}$ values, according to the previously experimental findings (Fig. 1).

Conversely, concerning the four alloys differing in the Mg content (Fig. 5b), a decrease in Mg content from 0.39 wt. % to 0.34 wt. % does not significantly modify the quality of the alloy because the corresponding points are approximately on a 490 MPa iso-Q line. Moreover, further decreasing of Mg from 0.34 wt. % to 0.25 wt. % contents seems to determine a slight worsening of the quality index from about 490 MPa to 469 MPa, with just a slightly improvement of the ductility of the alloy.

## 4. Conclusions

According to the experimental findings the following conclusions can be drawn:

- The increasing of the Mn/Fe ratio does not significantly affect tensile properties and hardness values. The Mn additions do not lead to the conversion of brittle β-Fe platelets into less harmful α-Fe phases due to the little amount of Fe. However, the addition of Mn causes the reduction of the number of β-$Al_5FeSi$ phases, while the variation of their maximum average length is negligible. Therefore, tensile properties seem to be more dependent on the dimensions of the intermetallics rather than their amount.
- The reduction of the Mg content, with respect to the Ref alloy (Mg=0.39 wt. %), leads to an improved percent elongation but also reduce the ultimate tensile strength, yield strength and hardness values. As a matter of fact, the reduction of percent elongation with the increasing of Mg content might be due to the stronger Al matrix, which is likely to enhance the probability of Si particle cracking, as suggested by microstructural observations. Moreover, the observed Fe-rich intermetallic phases are mainly fine and fibrous β-Fe platelets. The decrease of the Mg content does not significantly affect both the amount and the size of these phases.
- Quality index charts proposed by Drouzy et al. were used to evaluate if different Mn/Fe ratios and Mg amounts would significantly affect the quality of the A356 alloy. From this approach seems that the best compromise between the quality and the ductility of the alloy could be obtained with a Mg content of 0.34 wt. %. Surely, further investigations should be performed and a larger number of sample and condition should be considered in order to confirm these preliminary results.

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## References

Abedi K., Emamy M., 2010. The effect of Fe, Mn and Sr on the microstructure and tensile properties of A356-10% SiC composite. Materials Science & Engineering A 527, 3733–3740.

Bäckerud S.L., Chai G., Tamminen J., 1990. Solidification characteristics of aluminum alloys, Oslo, Norway.

Cáceres C.H., 2000. A phenomenological approach to the quality index of Al-Si-Mg casting alloys. International Journal of Cast Metals Research 12, 367–375.

Cáceres C.H., Davidson C.J., Griffiths J.R., Wang Q.G., 1999. The effect of Mg on the microstructure and mechanical behaviour of Al-Si-Mg casting alloys. Metallurgical and materials transactions A 30A, 2611–2618.

Cao X., Campbell J., 2004. The solidification characteristics of Fe-rich intermetallics in Al-11.5Si-0.4Mg cast alloys. Metallurgical and Materials Transactions A 35A, 1425–1435.

Crepeau P.N., 1995. Effect of iron in AI-Si casting alloys: a critical review. AFS Transactions 103, 361–366.

Drouzy M., Jacob S., Richard M., 1980. Interpretation of tensile results by means of quality index and probable yield strength. AFS International Cast Metals Journal 5, 43–50.

Elsharkawi E.A., Samuel E., Samuel A.M., Samuel F.H., 2010. Effects of Mg, Fe, Be additions and solution heat treatment on the π-AlMgFeSi iron intermetallic phase in Al-7Si-Mg alloys. Journal of Materials Science 45, 1528–1539.

Ji S., Yang W., Gao F., Watson D., Fan Z., 2013. Effect of iron on the microstructure and mechanical property of Al-Mg-Si-Mn and Al-Mg-Si diecast alloys. Materials Science & Engineering A 564, 130–139.

Lu L., Dahle A.K., 2005. Iron-rich intermetallic phases and their role in casting defects formation in hypoeutectic Al-Si alloys. Metallurgical and Materials Transactions A 36A, 819–835.

Seifeddine S., Johansson S., Svensson I.L., 2008. The influence of cooling rate and manganese content on the β-$Al_5FeSi$ phase formation and mechanical properties of Al-Si based alloys. Materials Science and Engineering A 490, 385–390.

Shabestari S.G., 2004. The effect of iron and manganese on the formation of intermetallic compounds in aluminium-silicon alloys. Materials Science and Engineering A 383, 289–298.

Taylor J.A., 2012. Iron-containing intermetallic phases in Al-Si based casting alloys. Procedia Materials Science 1, 19–33.

Taylor J.A., St John D.H., Barresi J., Couper M.J., 2000. Influence of Mg content on the microstructure and solid solution chemistry of Al-7%Si-Mg casting alloys during solution treatment. Materials Science Forum 331–337, 277–282.

Timelli G., Fiorese E., 2011. Metodi di neutralizzazione del Fe in leghe Al-Si da fonderia. La Metallurgia Italiana 2, 9–23.

Wang Q.G., Cáceres C.H., 1997. Mg effects on the eutectic structure and tensile properties of Al-Si-Mg alloys. Materials Science Forum 242, 159–164.

Zhang Z., Tezuka H., Kobayashi E., Sato T., 2013. Effects of the Mn/Fe ratio and cooling rate on the modification of Fe intermetallic compounds in cast A356 based alloy with different Fe contents. Materials Transactions 54 (8), 1484–1490.