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EL TAMAÑO DE GRANO FERRÍTICO: UN FACTOR IGNORADO, DE HECHO, EN EL ANÁLISIS DEL FALLO EN EL HUNDIMIENTO DE UN FAMOSO BARCO.

FERRITIC GRAIN SIZE: AN IGNORED FACTOR, IN FACT, IN THE FAILURE ANALYSIS OF THE SINKING OF A FAMOUS SHIP.

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Abstract: In much of the literature published on the sinking of the famous ocean liner Titanic, on April 15, 1912 in the North Atlantic after hitting an iceberg, it has not been done a sufficiently rigorous analysis on the causes of it, in relation to the material behavior, given the vessel maneuver and the shock produced. The riveted steel plates, hull material, opened a huge crack of several tens of meters and there is no satisfactory explanation enough today. The steel was qualified poor for excess sulfur, giving excessive importance to the presence of manganese sulphide inclusions not globular shape, giving too much atention on the failure of the rivets. Actually the primordial cause was, in our opinion, the absence of grain refining alloyings and appropiate heat treatment of the plate, which produced excessive grain size. Under the conditions of navigation in waters below 0 ° C, the steel of the Titanic had amply exceeded the ductile-fragile transition temperature, turning the boat hull into a “crystal” container.

Keywords: Titanic, Ferritic structure, Ferritic grain size, Ductile-fragile transition temperature, Artic steels

Resumen: En la mucha literatura publicada sobre el hundimiento del famoso trasatlántico Titanic, el 15 de Abril de 1912 en las aguas del Atlántico Norte, tras chocar con un iceberg, no se ha hecho un análisis suficientemente riguroso de las causas de aquel, en relación al comportamiento de los materiales, dada la maniobra del buque y choque producidos. En las planchas de acero, material del casco, se abrió una tremenda grieta de varias decenas de metros y no existe una explicación suficientemente satisfactoria al día de hoy. El acero se calificó malo por exceso de azufre, dándole excesiva importancia a la presencia de inclusiones de sulfuro de manganeso o a su forma poco globular, habiendo también demasiada fijación en el fallo de los remaches. En realidad la causa primordial fue, en nuestra opinión, la ausencia en el acero de aleantes afinantes de grano y el correspondiente tratamiento de la chapa, que produjeron un tamaño de grano excesivo. En las condiciones de navegación, en aguas bajo 0ºC, el acero del Titanic había pasado con holgura la temperatura de transición dúctil-frágil, convirtiendo el casco en un recipiente de “cristal”.

Palabras clave: Titanic, Aceros ferríticos, Tamaño de grano ferrítico, Temperatura de transición dúctil-frágil, Aceros árticos.

INTRODUCTION

Brittle fracture was a major cause in the sinking of the Titanic. In very interesting works published on this topic, it was stated by Hillthat: “this steel was, at the time, top quality shipbuilding steel”(1), “the steel used was probably the best plain carbon ship plate available at the time of the ship’s construction”(2), but the conclusion is that it was, in fact, the low quality of the steel that caused the low toughness at low temperatures and therefore the brittle fracture when the mass of the Titanic - more than 46,000 tons at a speed of 21-22 knots - struck the iceberg.

Those papers and other news on the event, point out the relevance of the present impurities, expressed in the chemical composition, when explaining the low quality steel. The high sulphur content of the steel is also truly emphasized as the decisive reason for low toughness, mainly due to the manganese sulphide inclusions. But in our opinion, the grain size is mentioned very little as the reason for the high ITT (Impact Transition Temperature) of the Titanic steel; and no comments are made on the carbon content of the steel. In the following comments below we will try to clearly show both aspects.

EXPERIMENTAL DATA

Data published on chemical composition and grain size of the Titanic hull plate sample can be resumed as follows. Hill (1) publishes the steel composition in percentages: 0.2 C, 0.025 Si, 0.52 Mn, 0.065 S, 0.01 P, 0.0043 Cr, 0.004 N. H.P.Leighly Jr. (2) offers a similar composition, but with clear differences in phosphorus content: 0.21 C, 0.017 Si, 0.47 Mn, 0.069 S, 0.045 P, 0.024 Cu, 0.013 O, 0.035 N. Yield Strength and Tensile Strength values obtained by Leighly are 193.1 MPa and 417.1 MPa respectively. In the same work the micrographic structure of the Titanic hull plates is shown: a ferritic-pearlitic banded structure, obviously, with an average grain size of 60.40 μm longitudinally and 41.92 μm transversally; and an ITT, for 27 Joules, near to +43ºC, or to +70ºC after a Charpy impact test made on longitudinal or transversal Titanic samples, taken from a 1.875 cm thick plate sample from the hull. Hill, on the other hand**,** found a ductile-fragile transition temperature of 80-100ºF (27-38ºC).

GRAIN SIZE

We estimate that the grain size of the Titanic steel is too coarse: 60.40 μm longitudinal, 41.92 μm transversal. This fact alone should be enough to justify, in our opinion, the fragile behaviour of the hull at low temperatures, the cause (reason) of the sinking. Micrographies Figs.1,2,3,4 show the structure of plain carbon steel with carbon content very similar to the Titanic hull plate, 0.2%C, with different grain sizes. Titanic plate microstructure - average grain size between 60.40 and 41.92 μm - should be between 1 and 2 samples. All the micrographies show banded structure with ferrite and pearlite as in the Titanic, as well as manganese sulphide inclusions, located in the ferritic banded structure (outside the pearlite). The alphagenous character of phosphorus and silicon in solid solution inside the plain carbon steel is decisive in this situation (3) either in our steel or in that of the Titanic.

Without taking into account the inclusions, above mentioned and using F.B. Pickering (6) equations, the ITT values for different grain sizes were calculated, see Fig. 5, as a function of the carbon percentage of Titanic steel (0.2%),. 5). The theoretical values of the elastic limit of that steel, for different grain sizes, are indicated in Fig. 6. The agreement between UTS theoretical values, and, above all, the YS ones, with the experimental results obtained by Leighly (for grain sizes between 60.40 and 41.92 μm) makes the validity of the theoretical curve shown in Fig. 5 reasonable.

In such a curve it is pointed out that only grain size over ASTM 7.5 (less than 23.3 μm) produces a ductile-fragile transition below 0ºC, and in that case, the Titanic steel would behave right, without brittle fracture, referring only at this factor. But for grain sizes similar to the Titanic hull plate (4.5-6 ASTM, in Figure 5), ITT theoretical temperature becomes around +40ºC, a temperature very close to the experimental ductile-brittle transition temperature referred by Hill (1) and also to the ITT values measured by Leighly (2), as mentioned in the previous paragraph.

Everything seems to indicate, without looking at inclusions as the reason for the brittleness of the Titanic's hull, that *a quite high grain size (60.40-41.92μm) would be enough to explain the fragility of the steel:* its impact energy would became lower than 27 Joules at temperatures below +40ºC.

We also assume that the Titanic disaster would have happened even though the plate used in its building had been treated by normalizing heat treatment in order to avoid any Widmanstätten possible structure, as well as for grain refining: from curve 5 it follows, that normal grain sizes, after normalizing (in the range of 7 ASTM, about 28 μm) the ITT for a 0.2%C steel is always above 0ºC. Anyway the Titanic steel would have been brittle at- 2ºC, sea water temperature at the time of the collision.

Only a thermomechanical grain refinement (using Ti or Nb as gamma grain refiners, or as inhibitors of the gamma recrystallization for controlled rolling, followed by allotropic transformation of the deformed gamma grains to alpha phase (7), would have made possible "Arctic" grain sizes in the range of ASTM 10 to 12(9-5 µm), just enough for very low transition temperatures and good toughness. But from the time of the Titanic's construction half a century would have to pass until those techniques and developments could be used in a widespread manner allowing the construction of icebreaking ships, off-shore platforms, Arctic oil pipes and so on (8), with fair toughness up to – 80ºC (Arctic quality).

CHEMICAL COMPOSITION

It is far from our aim to reduce the importance of other factors in the ductile-brittle transition temperature such as: the amount of pearlitic cementite (directly associated with the steel carbon content) and the amount of non-metallic inclusions of the manganese sulphide type, for example.

The steel of the Titanic is a semikilled one with high oxygen and low silicon levels. The high sulphur and phosphorus contents indicates that the steel was produced in an acid furnace, and the low level in nitrogen makes the use of the open hearth process very probable, not in a Bessemer converter.

The Titanic sample used by some of the researchers is a piece of the hull obtained from the ocean bottom used as representative of thousands of tons. To justify the deviations between head and tail of each casting, as well as for those existing, between the different castings, it seems appropriate to put forward to the hypothesis of the use in its construction of a steel with lower carbon content to avoid the brittle fracture (the carbon partition ratio k for δ iron is $k=C_S/C_l= 0.13$).

ITT temperatures are shown in Figs. 7 and 8, as a function of grain size, for low carbon ferrite-pearlite steels. Therefore, for a 0.11 %C steel with 41.92 µm grain size, similar to the lowest value experimented by Leighly, in the transversal direction, the obtained ITT temperature -without taking into account the inclusions that because of the damage would increase that temperature- would be, in the best case, 27ºC. Therefore a steel of 0.11 used in the Titanic would also have been fragile at –2ºC, (because lowering the carbon content the A_3 temperature would increase and, after hot rolling, the grain size would have been even greater than 60.40 µm T. and 41.92 µm L.).

Currently, 0.11 %C steels, normally ductile because of their low grain size and carbon content, are nevertheless fragile due to the existence of impurities (inclusions). That is the case, for instance, of a 16.3 µm grain size diameter ferritic steel (8.5 ASTM equivalent showed in Figure 7) with the following composition in percentages: 0.11 C, 0.51 Mn, 0.13 Si, 0.046 P, 0.015 S, 0.45 Cu, 0.21 Ni, 0.18 Cr, 0.0117 Al, 0.023 Sn, 0.002 Ti, 0.0007 Zn, 0.017 As, 0.05 Mo, 0.034 Pb, 0.013 V, 0.0120 N. This steel has 0.04% inclusions by weight. These plates, with recrystallized structure, have been aged for 3 hours at 75ºC to favour the precipitation of intermetallic compounds.

The volumetric pearlitic fraction measured by quantitative Metallography (9) is 10.3 +/-0.36 (the theoretical value is 11.78% for carbon steel without any alpha or gamma promoting elements in solid solution). The calculated ITT, as a function of the pearlitic fraction, grain size, silicon and nitrogen contents, is – 4ºC.

In fact, the ITT for this steel is OºC. Fig. 9 shows the brittle appearance of the fracture of the steel after a tensile test conducted at 0ºC (taking into account that brittle fracture, when produced by impact, always happens at higher temperatures than when produced by tensile test). The ITT would be a little bigger than +35ºC if one accepts that, according to some researchers (6), with 0.04% MnS by weight, the biggest change is produced in the ITT: +25ºC T. and +35ºC L. Figs. 10 and 11 show steel fracture, after tensile tests, fully ductile at +75ºC and 50% ductile at +35ºC.

For a 0.05% C Steel and a grain size similar to that of the Titanic plates, the ITT obtained would be –22ºC for 41.92 µm and –12ºC for 60.40 µm grain size. But if the percentage of inclusions were 0.04% MnS the ITT would also be above 0ºC and therefore would have been inappropriate steel for the Titanic.

Regarding the Titanic's steel, with 0.2% C, its MnS inclusions content is too high: 0.18% by weight i.e. ten times higher than that recommended for normal constructional steels and very much higher than for Arctic quality (0.005%).

The influence of manganese sulphide inclusions on the ITT depends not only on the volume fraction but on the distribution and morphology (elongation) as well. So, for thick plates, when the inclusions remain globular after hot rolling, the sites for fracture initiation are minimized and the toughness is maintained.

The differences between the ITT theoretically calculated values for the Titanic's steel near +40'C without taking into consideration the inclusions and the experimental ones obtained by Leighly (2) would quantify a little adverse effect of the MnS inclusions (from impact curves and an impact energy of 27 Joules, +47ºCL and 70ºC T. could be deduced). The differences between Hill's ITT value (80-100ºF) and +40ºC theoretical is also very small. This seems to advise suggest that the inclusions had little effect on the ITT, in comparison with the coarse grain size of Titanic steel.

CONCLUSIONS

From the above considerations the excessive grain size: too big (60.40-41.92μm) could be enough to explain the brittleness of the Titanic's steel: without taking into account the non-metallic inclusions, its impact energy would be lower than 27 Jules at –2ºC. We think that the Titanic disaster could not have been avoided just by heat treatment of the plates: by grain size refinement after the steel normalizing. Only a thermomechanical ferritic grain refinement (using Ti or Nb as gamma grain refiners or as recrystallization temperature raisers, after the subsequent controlled rolling followed by allotropic gamma to alpha transformation) would have produced favourable grains for toughness at low temperature or Arctic qualities (5 μm grain size). But unfortunately half a century would be needed, from the Titanic's construction, until the appropriate technology would be widely available, allowing the construction of today's icebreaking ships, off-shore platforms, arctic oil pipes, etc.

Perhaps if the Titanic's steel had lower carbon content, brittle fracture could have been avoided. Nevertheless, to achieve this, the carbon content should have been lower than 0.05% for the grain size of the Titanic steel (although when carbon content is lower A_3 temperature rises and the ferritic grain size is coarser and therefore toughness decreases).

In fact, *the steel used was probably the best plain, carbon steel available at the time of the ship construction.*

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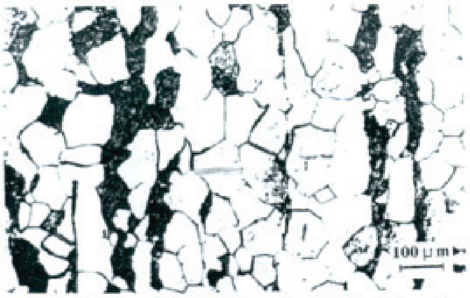

Fig.1

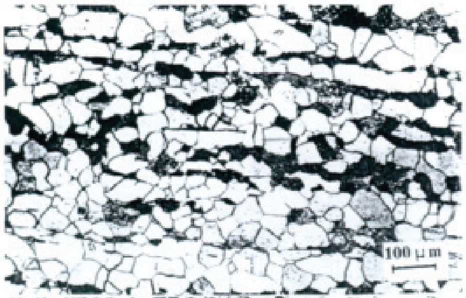

Fig.2

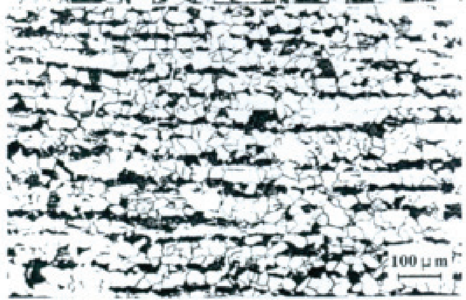

Fig.3

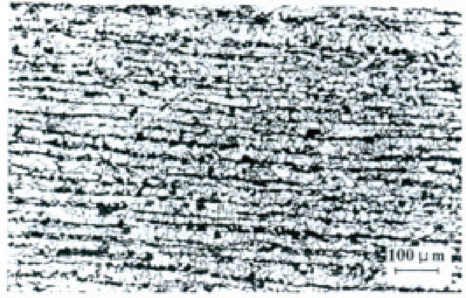

Fig.4

Fig. 1 – 4. Banding structure ferrite-pearlite plain carbon 0.2% steel. Different grain sizes, MnS inclusions are localized in the ferrite bands (Fig. 1 and 2).

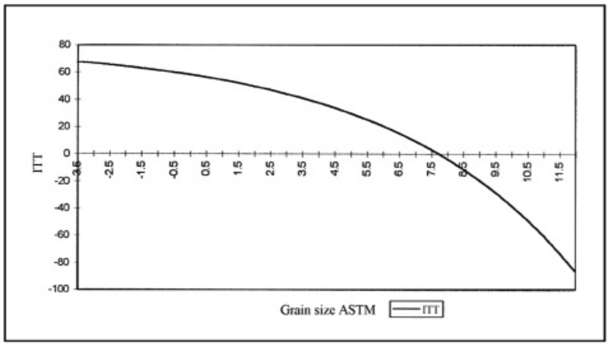

Fig. 5. Plain carbon steel 0.2%C. Grain size and Impact Transition Temperature en ºC (ITT).

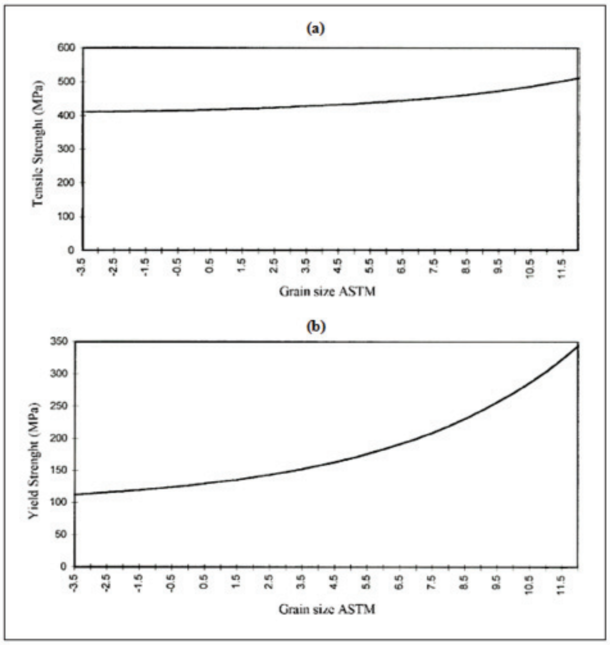

Fig. 6. Plain carbon steel 0.2 %C. Grain size and: a)Tensile Strenght - b)Yield Strenght

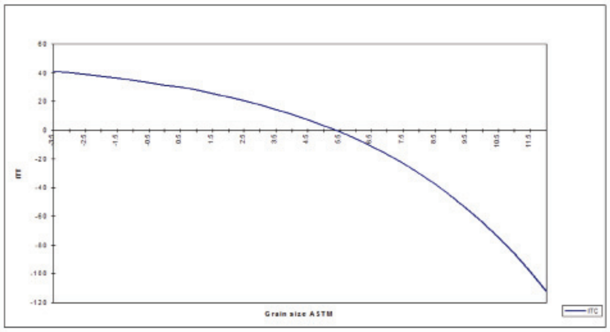

Fig. 7. Plain carbon steel 0.11%C. ITT (ºC) versus ferrite grain size (ASTM).

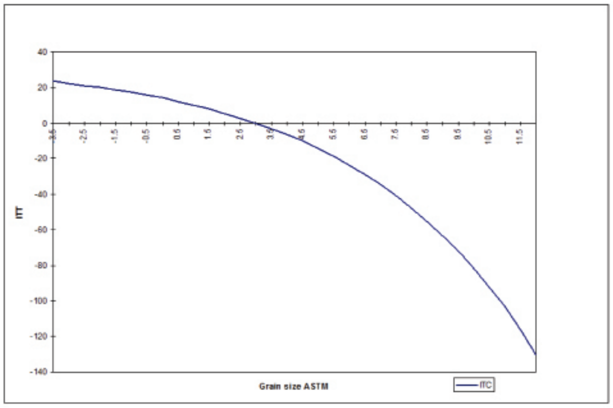

Fig. 8. Plain carbon steel 0.05%C. ITT (ºC) versus ferrite grain size (ASTM).

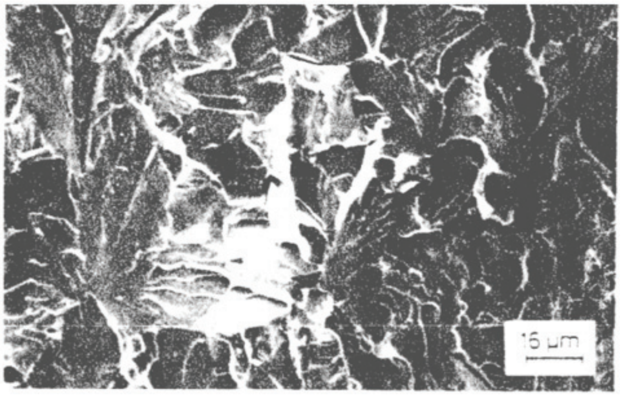

Fig. 9. Brittle fracture by tension at 0º C (SEM)

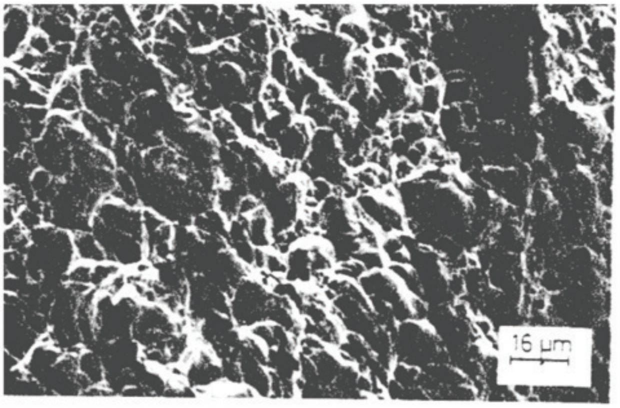

Fig. 10. Ductile fracture by tension at +75º C (SEM)

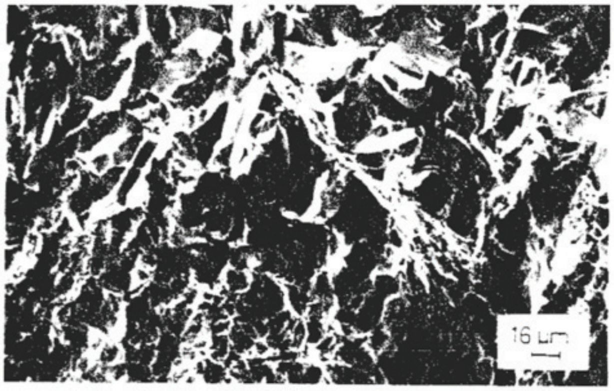

Fig. 11. Brittle – Ductile fracture by tension at +35º C