

# Micro-shrinkage in Ductile Iron / Mechanism & Solution

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## ABSTRACT

The demand for increasing levels of quality in iron castings continues relentlessly.

Safety critical castings for the automotive industry have two requirements : The first is linked to the qualitative aspects that bring the metallurgical performance, the second is purely economical; the cost of the casting directly influencing its survival.

Improvements of the mechanical properties of the castings cannot be achieved by ignoring the influence of certain mechanical defects.

The need for control of chemical analysis and microstructure is well documented and there are new tools available to the increasingly sophisticated foundry industry.

When considering the "health" of castings ; micro-shrinkage, grain boundary dislocations, intergranular segregation, risk of inclusions etc... the state of knowledge of the cause of them and solutions to eliminate them, is quite weak.

We would like to share with you , the advancements made in both research and industrial applications on the theme of the elimination of micro-shrinkage.

The work is supported by several industrial examples.

## BACKGROUND

It has been admitted for some years that lanthanum has particular effects on cast iron compared to all other rare earth elements available. A large bibliography is at our disposal on this topic and more than 10 articles referred to the effects of pure lanthanum on iron properties, some of them are listed in the references attached.

### 1) Uses of Lanthanum

#### 1-1 History

The use of lanthanum has been recognized since a long time to improve various iron properties. For example, a 1956 patent (ref.1) claims that the use of lanthanum alone (as for Sn, Pr or Nd without Ce)

improves machinability. Digging further into the topic, its main obvious metallurgical effects can be noted during nodularization and inoculation practices. Indeed, later in 1978 (ref.2 & 3) the use of lanthanum is identified as an efficient element to counter micro-shrinkage appearance. Since this discovery, the use of lanthanum has known a growing industrial development.

#### 1-2 Practical uses

A typical example is given by the use of SIMAF, a pure lanthanum bearing FeSiMg used for in-mold nodularisation, patented by PEM in 1978 . Since this date, the use of SIMAF has developed to reach a consumption of 4000 t/y, corresponding to a SG iron production of 500 Kt/year of automotive safety parts in Europe.

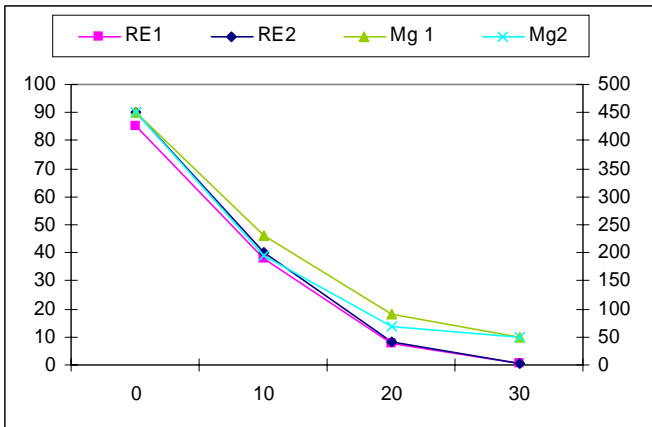
#### 1-3 Possible further uses of lanthanum element

The use of lanthanum bearing FeSiMg added up stream (ex: FeSiMg sandwich process) within the metallurgical foundry process has been explored. Laboratory experiments have shown:

- rapid fade of the lanthanum content within molten iron, accentuated by the increase of iron temperature needed to accept the heat loss noted during conventional FeSiMg treatments.
- difficulty in maintaining into an industrial environment the adequate and repeatable amount of lanthanum content in order to exercise on the molten iron the desire effects.

### 2) Behavior of Lanthanum (fading)

To illustrate the difficulty of controlling the fading property of the lanthanum introduced up-stream within the iron process, we must refer to the relative decrease of magnesium and lanthanum contents as shown on figure 1. The fading tendency of both elements have been studied during laboratory experiments, the curves are the following :



**Figure 1:** Relative concentration (Cr) decreases more rapidly for RE than for Mg - Cr is  $C(t)/C_i$   
 C(t): concentration at a given time  
 C<sub>i</sub>: Initial concentration before fading

It can be noticed that an increase in residual Mg content will promote shrinkage formation (ref 4).

**3) Late uses of Lanthanum**

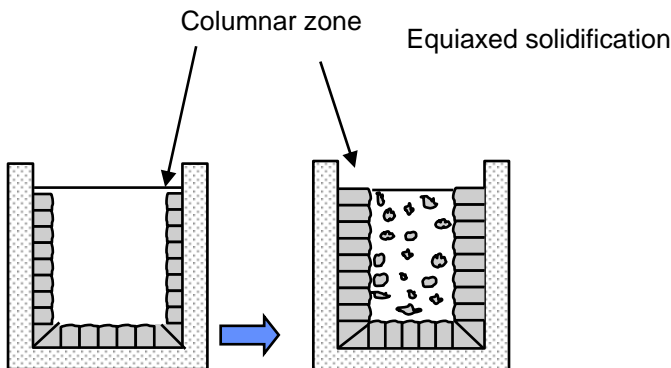
In order to solve this predominant fading tendency, the use of lanthanum has naturally found its applications during the iron treatments achieved at the latest stages of the metallurgical foundry processes.

Late additions of inoculants are nowadays well established in all foundry processes. Dedicated commercial products are also available for precise control of their uses. The effect of lanthanum on the iron solidification behavior and the optimization of its benefits can then easily be monitored and proven.

**4) Metallurgical effects of Lanthanum**

**4.1 Solidification behavior**

Through molten iron solidification process, different stages of grain growth occur:



**Figure 2:** solidification process of molten iron

First solids appear on mold walls, near locations of severe heat loss. Grains grow toward the opposite direction of the heat flow, usually perpendicular to mold walls. This growing behavior is named “columnar growth”, referring to the growing grain shape. Growth and definition of these grains are determined by the thermal properties of the mold.

When heat flow through mold walls has reduced, columnar growth is less favored. Particles of the columnar grains detach to grow freely in the liquid. This second solidification behavior is named “equiaxed growth”. Liquid iron convection motions and viscosity property dictate, in the mold, directions taken by growing grains. Within growing grain particles, heat flow and solidification directions are identical.

Influencing factors:

- high nucleation within molten iron favors equiaxed growth behavior as more solidification sites are available.
- equiaxed growth behavior is favored by stirring motions (ref.5)
- several other phenomena affect the transition point from columnar to equiaxed solidification behavior such as, heat flow characteristics, nature of solute elements at the molten iron solidifying front (segregation, ...)

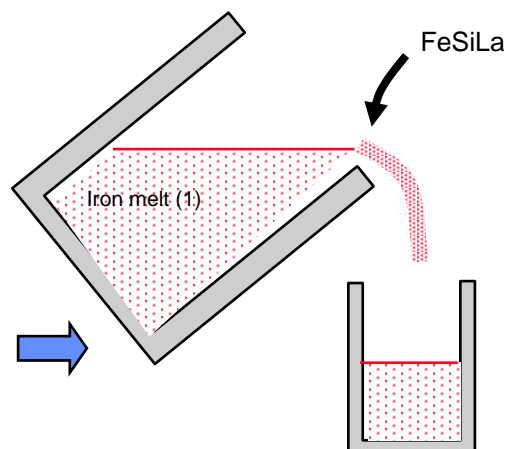
This behavior is typical of primary solidification but applies also to the divorced Fe-C-Si eutectic (ref 6).

**4.2 Experiments**

**4.2.1 Principle**

Dimensional characterization of columnar solidification behavior growth zone at given solidification times and lanthanum addition rates will demonstrate the effect of lanthanum on iron solidification growth process.

**4.2.2 Experimental design:**



Treatment and filling of the mold (2)

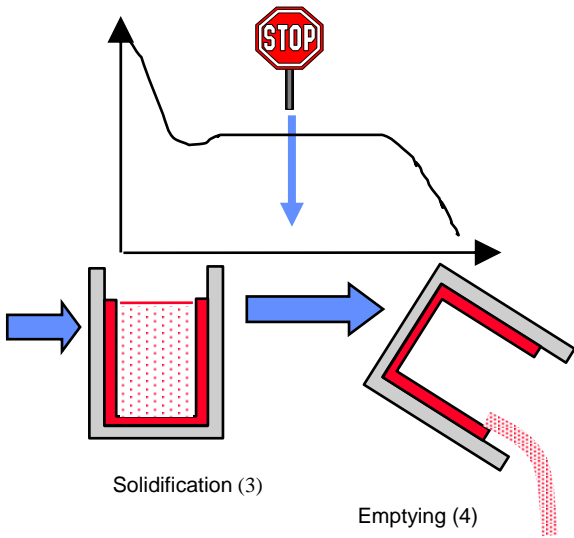


Figure 3: Scheme of the experimental design

An iron melt (1), is treated by 0,15% of late stream inoculant containing 0% up to 2,4 % of lanthanum (2). Treated melts are poured at the same temperature into cylindrical moulds. Solidification starts and progresses (3). At a given time then a given iron liquid/solid ratio, moulds are emptied of their remaining semi-solid iron (4). Temperatures are monitored, specific solidification time is targeted to reach 50% iron liquid/solid ratio. Thicknesses of remaining solidified irons (shells) taken off from mold walls are measured.

4.2.3 Results

Resulting solid shells are compared:



Image 1: solid shell inoculated without La and its section view



Image 2: solid shell inoculated with La and its section view

1<sup>st</sup> trial results:

Inoculant La content (%)	Resulting thickness
0%	8 mm
0,8%	2 mm
2,4%	1,1 mm

2<sup>nd</sup> trial results:

Inoculant La content (%)	Resulting thickness
0%	6 mm
1,2%	2 mm
2,4%	0,5 mm

Table 1: Thicknesses of resulting solid shells at 50% iron liquid/solid ratio. (2 trials)

4.3 Conclusion

Lanthanum element promotes the equiaxed solidification behavior by:

- developing a higher nucleation power, therefore more solidification sites within the molten iron.
- modifying the molten iron viscosity favoring stirring motions within molten iron.
- restricting the growth of columnar grains. This phenomenon is dictated by the physico-chemical properties of the Fe-La alloy binary diagram.

It has been demonstrated that alloying elements showing a high  $m(k-1)$  \* factor are able to slow down the grain growth rate . It is the case for Lanthanum.

\*m being the liquidus slope and k the distribution coefficient of the Fe-“element” binary diagram:

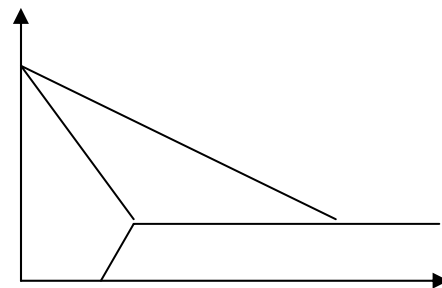


Figure 2: binary diagram

Liquidus:  $T = T_f + m C$

Solidus:  $T = T_f + \frac{m}{k} C$

### 5) Consequences for shrinkage and micro-shrinkage

At a given solidification stage, when lanthanum is added, the equiaxed solidification behavior is favored. Consequences are that:

- the thickness of the columnar solidification behavior grown zone is reduced, leaving larger free flowing passages for the remaining molten iron to travel within channels feeding casting areas in the one the need of liquid iron is essential to minimize the formation of shrinkage defects.
- the semi-solid iron contains more solid particles. After having feed a given casting volume, less liquid is needed to compensate the resulting solid contraction.

note: Thixotropic molding process used for the manufacturing of aluminum castings is based on same principals.

### 6) Others metallurgical effects

It is known that Lanthanum has positive effect on nucleation (ref.7) and graphitization (ref.8). Lanthanum has the advantage of being an element able to generate stable sulphides and oxysulphides (ref 9 and 10) increasing the nucleation power of the liquid bath.

### 7) Industrial examples

#### 7.1 Lanthanum bearing treatment alloy

Lanthanum bearing inoculants are available under diverse chemical compositions and dedicated to the late stream inoculation practice (ex: FeSiLa, Win-4, etc.).

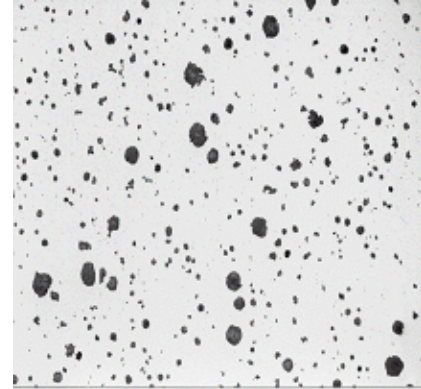
#### 7.2 Examples of Lanthanum bearing alloy uses

##### 7.2.1 Crankshafts ( courtesy Française de Mécanique)

Within the production of crankshafts, the effect of FeSiLa has been assessed. Results on microstructures and number of castings per mold (iron yield) are shown hereafter:



**Image 3:** SG iron structure without La showing micro-shrinkages



**Image 4:** SG iron structure with lanthanum clear of micro-shrinkages



**Image 5:** cluster of 4 crankshafts developed without lanthanum



**Image 6:** same crankshaft cluster redesigned after lanthanum addition. 6 crankshafts are placed within the same volume.

7.2.2 Further examples

Following are some images of castings for which FeSiLa had to be used to avoid micro-shrinkages.



**Image 9 : Caliper**



**Image 10 : Steering Knuckle**



**Image 11 : Exhaust Manifold**



**Image 12 : Exhaust Manifold (flange view)**

**SUMMARY**

Knowing and understanding lanthanum properties enable foundrymen to optimize their overall iron yields and to minimize the appearance of micro-shrinkages. The ideal use of lanthanum in late stage inoculation practices can be summarized as follow:

- Lanthanum effect is consistent and more reproducible towards minimizing the risk of fading.
- optimization of the inoculation treatment cost as the late stage inoculation rate would be smaller than all other upper stream inoculation practices that would have to take in consideration the dominant fading property of the lanthanum.
- optimization of lanthanum nucleation and graphitization effects as they are naturally more effective when added late in the process.

**REFERENCES**

1. patent US 2.970.902 – (1956) Production of ductile iron having improved machinability (using La based Rare Earth)
2. patent EP 4819 (1978) Ferrous alloys preparation with incorporation of Lanthanum for improved mechanical properties.
3. patent FR 024855 cast iron or steel containing small amount of Lanthanum improving their mechanical properties
4. R. Hummer, Cast Metals, volume2, number 2, 1988
5. Qiu P., Nomura H. and Takita M. Int. J. Casting Res., 2000, 13, 93-98
6. Ruxanda R., Beltran-Sanchez I., Masson J. and Stefanescu D.M., AFS Transactions 01-066, 1-12
7. Harding R.A., Campbell J., Saunders N.J. The inoculation of ductile iron: a review of current

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understanding. Conference; Solidification Processing Sheffield 97 4-6 july

8. Stefanescu D.M. , Loper Jr C.R. Effect of Lanthanum and Cerium on the structure of eutectic cast iron; American Foundrymen's society, Transactions, Vol 89, Cincinnati, Ohio Apr.-1 May 81

9. V Cochard. Inoculation od spheroidal graphite cast iron. Master of Philosophy. University of Birmigham. 1995

10. F Bachelot. Inoculation mechanisms of ductile iron. Master of Philosophy. University of Birmigham. 1997.

11. Zeji S.H. ,Yulin T., Binghuan J., Deshan L. The analysis of the effects of RE on graphite crystallization. International Symposium on new development of Cast Alloy Technology

12. Shen Z., Tang Y., Jia,g B., Li D., The vermiculizing effect of individuals Rare Earth elements La, Ce, Pr and Nd on graphite in cast iron conference on Rare Earth development and application vol 2

### **ADDITIONAL RESOURCES**

1. Research works done at the IRC, Birmingham University in collaboration with PEM (J. Campbell, R Harding,F Bachelot, N Benailly, F Rossignol)

2. Internal research works done at the PEM Central Research Laboratory