Feasibility Study on:
dPI Hydrogen Removal Method
for Cast Metals

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Executive Summary

The **dPI Hydrogen Reduction Method**, a new technology, has been presented, able to reduce hydrogen content in high-performance steel. Hydrogen embrittlement is a serious problem with many high performance alloys, and high strength steels in particular.

The technology used nowadays to avoid hydrogen embrittlement, like Vacuum Casting (VC), requires huge investments, in the order of 60 million Euro. The **dPI Hydrogen Reduction Method** has tiny implementation costs in comparison (in the order of 3% of that of VC).

Given the soundness of the research and engineering development behind the **dPI Hydrogen Reduction Method** technology, and specially given the low acquisition costs of the Intellectual Property -Patents- behind it compared to present technologies like VC, **it is recommended** that the rights on this technology be acquired, either for the **expected profitability** of its industrial implementation or as a **strategic** component in a Defensive IP Portfolio.

Contents

1 Background: Industry

World production of steel has grown to over 1,600 million tons (Fig.1). Of these, the larger producer, ArcelorMittal produces around 98,000 million tons a year, and the following four producers (Nippon Steel, Hebei, Baosteel and POSCO), around 50,000 million tons each.

Although it is difficult to define what would be the size of a typical metallurgical plant, due to large variations among industrial groups and countries, we could define a small to medium sized plant that which produces some 300 million Euro, and a medium to large one that which produces 3000 million Euro per year. A typical operating margin in metallurgical plants ranges around 5 to 15 %.

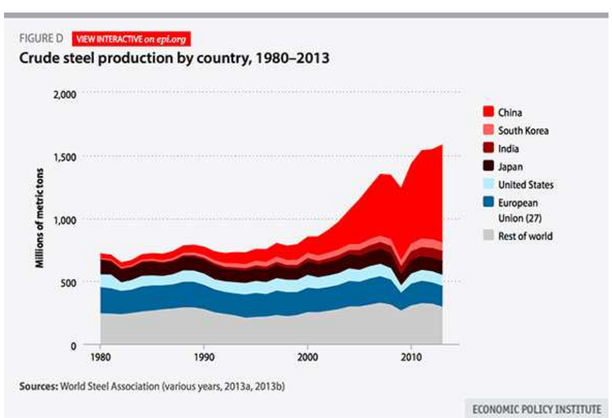

Figure 1: Production of crude steel.

An estimate of 15 to 20 % of the total steel production corresponds to high strength and special alloys, and growing. As industry progresses, safety standards become stricter and steel requirements more demanding, the proportion of high strength steels and special steels produced keeps increasing year on year (Fig.2).

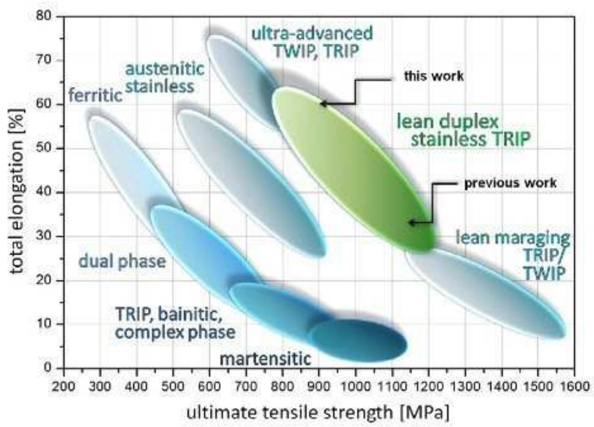

Figure 2: Properties of different grades of steel.

Many different technologies and transformation routes are applied to different alloys (Figure3). A simple distinction could be made between continuous casting methods, used primarily to produce long or flat products and non-continuous casting, for iron and steel castings and ingots. Continuous casting is applied to around 78% of world production while the remaining non-continuous casting processes are applied to the remaining 22% of the world production.

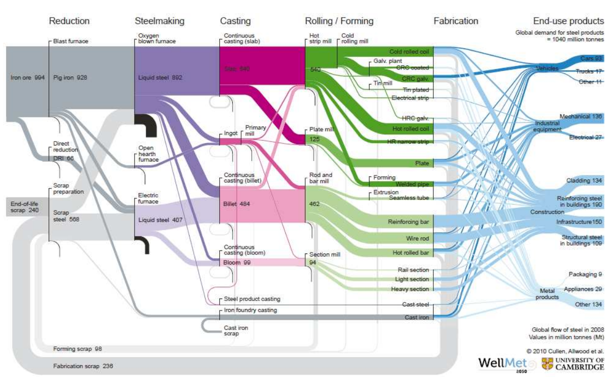

Figure 3: Steel production methods

2 Background: Hydrogen Embrittlement

Exposition to hydrogen is unavoidable in most industrial manufacturing practices, as hydrogen is an integral part of, for instance, moisture in the air. The problem raises from the fact that hydrogen is highly soluble in metal at high temperature, but much less soluble at lower temperatures, at which minute contents in hydrogen are able to cause a variety of defects that reduce the toughness and ductility of the metal.

Hydrogen embrittlement is a phenomenon that hardly affects construction steels and other moderate strength alloys. However, hydrogen is becoming more of an issue with high-strength steels because these often present a larger risk of hydrogen embrittlement as their strength increases.

This phenomenon was already suspected upon towards the end of the 19th century, and prevention measures and partial solutions do already exist. Some heat treatments like baking (long low temperature treatments) are used with various degrees of success. However, they tend not to be effective with all alloys and component types, and only for low hydrogen supersaturations. The reasons of this unreliable outcome have only become apparent with recent physical modelling of this treatment[1]. In other cases, AOD technology has used to try to obtain small reductions of hydrogen content, but this is not the aim of this treatment, thus the results regarding hydrogen reduction are usually poor.

The standard know-how in steelmaking has traditionally been that any component above a certain size (*i.e.* 20cm) and with a risk of being susceptible to hydrogen embrittlement should be subjected to a stage of vacuum treatment or manufactured by vacuum casting (CV) to reduce the hydrogen content to levels considered safe.

Vacuum casting however, requires substantial investment which are beyond the capability of most metallurgical plants, except for the largest ones or the ones specialised in high strength steels.

3 Description of Technology

Minute amounts of hydrogen are responsible of producing serious damage to many metallic alloys, like high strength steels. The precise mechanisms responsible for that embrittlement are still being discussed in the scientific community, but due to the technological and economic relevance of this problem, it is important to develop effective solutions to prevent it. Actual methods to prevent hydrogen embrittlement include extremely expensive technology like vacuum casting (VC) and heat treatments like 'baking' that are not suitable for all alloys or applications[1].

Present technology to perform vacuum treatment or vacuum casting is expensive, with typical installation costs in the order of 60 million Euro.

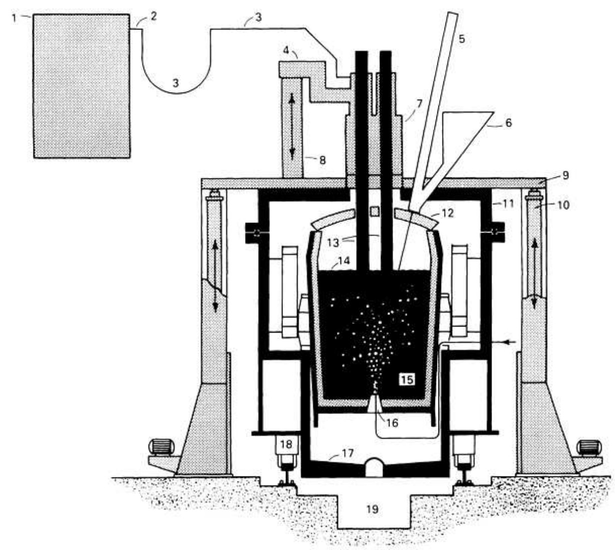

Figure 4: Vacuum casting equipment

That is often too expensive for a small to medium sized steelworks plant. On the other hand, not having a technology able to reduce hydrogen content makes such plants unable to produce components of large size and/or high performance alloys with reliable quality. Typical examples of components affected by this problem include energy plant shafts, public work machinery components, defence components, and others.

The technology presented here, **dPI Hydrogen Reduction Method**, is protected by several patents ([2]), and provides an inexpensive and effective alternative to vacuum technologies to reduce hydrogen content on metals. The **dPI Hydrogen Reduction Method** is based on sound physical research and state-of-the-art modelling of hydrogen redistribution in steels[3, 4, 5, 6, 7]. The **dPI Hydrogen Reduction Method** is based on the use of a customised heat treatment to modify the hydrogen distribution in the metal. In this way, it is possible to avoid the apparition of hydrogen supersaturated regions in the metal, and at the same time it allows to remove the excess of hydrogen.

While other technologies used nowadays to try to remove hydrogen from metals have mixed effectivity, like 'baking' heat treatments, or involve very expensive equipment, like vacuum casting, the method proposed here, has the advantage of a much lower implementation and operation costs, as compared to some present methods, while at the same time it could be used in addition to present methods to obtain alloys with even lower hydrogen contents.

In summary, the technology presented here, **dPI Hydrogen Reduction Method**, is based on sound physical and engineering R& D. Its results have been corroborated by industry. This technology provides an economic treatment that could be used as a substitute or to complement present hydrogen methods[3, 4, 5, 6, 7].

The main area of application of the method presented here lays in processes involving non-continuous casting and where it is possible to apply a heat treatment to the recently solidified metal. The costs required to use this technology include a one-time cost to acquire Intellectual Property - patent- (let's assume around 1,5 million Euro) and development costs to implement this method at any plant. These additional costs are estimated in less than 60-70,000 Euro. In total, less than 3% of the cost of acquiring Vacuum Casting equipment.

4 History of the Technology

dgaude Prime Innovation SLU is the engineering company in Barcelona responsible for the development of **dPI Hydrogen Reduction Method**, a new technology to remove hydrogen from metallic alloys, and therefore, reduce the risk of embrittlement. This company has been founded by a researcher with 15 years' experience in R&D at prestigious institutions including the French Commissariat de Energie Atomique and Cambridge University.

A research project was started in 2008 to study the redistribution of hydrogen in metallic alloys. This project has been able to describe and predict the hydrogen fluxes and redistribution during a number of industrial processes. The results of this project have been corroborated by industry and academia, and some of its results presented at international conferences[3, 4, 5, 6, 7].

During this project, a new method was developed to remove hydrogen from metal alloys, and therefore reduce the risk of embrittlement. The **dPI Hydrogen Reduction Method** is based on the use of a customised heat treatment to modify the hydrogen distribution in the metal. In this way, it is possible to avoid the apparition of hydrogen supersaturated regions in the metal, and at the same time it allows to remove the excess of hydrogen. This new technology is specially suited to be applied in alloy casting operations. The **dPI Hydrogen Reduction Method** has been awarded patents in the United States, China and Spain, and it's still under examination at the European and Brazil's Patent Offices[2].

- Awarded Patent (**US**): US 8,286,692 **Awarded: 16th October 2012**.
- Awarded Patent (**Spain**): 200900505 **Awarded: 30th November 2012**.
- Awarded Patent (**China**): 2010800089104 **Awarded: July 2014**.
- Patent Application (**European**): 10708807 Examination phase.
- Patent Application **(Brazil)**: PI 1005819-2 Examination phase.

5 Requirements for Industrial Implementation

The **dPI Hydrogen Reduction Method** for the reduction of excess hydrogen in cast metal components is well defined at the conceptual level, but it would nevertheless require some engineering study to develop the customised solution for a specific plant or application.

The development needed falls into two areas: On a first stage, the development of the general technology to apply the treatment and its control system, which would only need to be developed once, and then a second stage where the small modifications to apply this general implementation to each different configuration or component type.

The first stage of development required would only involve the choice of equipment implementation, as it requires rather standard industrial components (heating elements, control systems, temperature sensors, etc.). At most, the development of the general implementation would incur in some 50,000 Euro in costs.

The second stage of development involving the customised implementation for each component could cost around 2,000 Euro each. For 5 different configurations that could amount to 10,000 Euro.

Opposite to that solution, implementing a Vacuum Casting system would require an investment of the order of 60 million Euro, and adding to that up to half million Euro of engineering development to integrate that system in the present plant.

6 Financial Projections, Comparative with Present Technology

	dPI H. Red. Method	Vacuum Casting
Intellectual Property	1.5 million	—
Vacuum Casting System	—	60 million
Plant Impl. Devel.	50,000	0.5 million
Component Impl. Devel. per 5 comp. types	(2,000 per comp. type) 10,000	— —
Total (Euro)	1,560,000	60,500,000

7 Alternative Investment Strategy: Defensive Portfolio

Another argument to acquire the technology presented by **dgaude Prime Innovation SLU** is to add it to a defensive portfolio of Intellectual Property. Given the moderate cost of the patents involved, compared to the costs of implementing a Vacuum Casting system, it makes sense to protect this technology to avoid competitors using such **dPI Hydrogen Reduction Method** technology to gain a substantial cost advantage.

8 SWOT Analysis

Strengths:	Weakness:
S1: Minute implementation costs compared to alternative technologies like VC. S2: Method endorsed by numerous scientific publications and top research background.	W1: Some In-Plant implementation engineering study still required, although only requiring standard components.
Oportunities:	**Threats:**
O1: To be first in Market with cost and technology advantage. O2: Develop and sell fully implemented technology. O3: Block other actors to use this technology	T1: Competitor adquiring technology and keeping it for internal use. T2: Competitor adquiring technology to block other actors T3: Missed opportunity at plant costs reduction

S1: The **dPI Hydrogen Reduction Method** requires much smaller investment compared to present technologies like Vacuum Casting producing the same effects.

S2: The **dPI Hydrogen Reduction Method** is endorsed by sound physical research and numerous scientific publications. This method has been developed by people with top research background.

W1: The **dPI Hydrogen Reduction Method** still requires some design and development engineering before being implemented at the actual plant floor, although only on aspects related to th elast stages of implementation (choice of heating elements, control systems, etc.).

O1: Being the first in the Market with the new **dPI Hydrogen Reduction Method** would provide at the same time a technological and cost advantage over other Companies in the Market.

O2: Being the first to develop new solutions based on the **dPI Hydrogen Reduction Method** would provide substantial advantage over later adopters.

O3: At the same time, by the acquisition of the Intellectual Property -Patents- protecting the **dPI Hydrogen Reduction Method** an early adopter will be able to block other companies out of the Market for this technology.

T1: If a competitor company acquired the rights on this technology, they could keep the advantages granted by the **dPI Hydrogen Reduction Method** for their only internal use.

T2: If a competitor company acquired the rights on this technology, they could keep other Companies out of the Market for this technology.

T3: Missing the chance to acquire the **dPI Hydrogen Reduction Method** technology, implies missing the chance for cost reduction and quality increase at plant level.

9 Conclusions and Recommendations

The **dPI Hydrogen Reduction Method**: a new technology, has been presented, able to reduce hydrogen content in high-performance steel. Hydrogen embrittlement is a serious problem with many high performance alloys, and high strength steels in particular.

Technology: The **dPI Hydrogen Reduction Method** offers an alternative approach at eliminating hydrogen embrittlement by reduction of hydrogen content, specially suitable for the casting industry.

Physical Feasibility: The **dPI Hydrogen Reduction Method** is backed by sound physical research and engineering.

Financial Costs: The **dPI Hydrogen Reduction Method** presents very low implementation costs (in the order of 3%) compared to present technology, like Vacuum Casting.

IP Defensive Strategy: Given the low acquisition costs of the Intellectual Property -Patents- behind the **dPI Hydrogen Reduction Method**, this technology comprises a good choice for a Defensive IP Portfolio.

As **Conclusion**, given the industrial importance of hydrogen embrittlement and technology to avoid it, and having confirmed the soundness of the **dPI Hydrogen Reduction Method** technology, and specially given the low acquisition costs of the Intellectual Property -Patents- behind it compared to present technologies, **it is recommended** that the rights on this technology be acquired, either for the **expected profitability** of its industrial implementation or as a **strategic** component in a Defensive IP Portfolio.

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