The MUSIC guide to key-parameters in High Pressure Die Casting

Edited by

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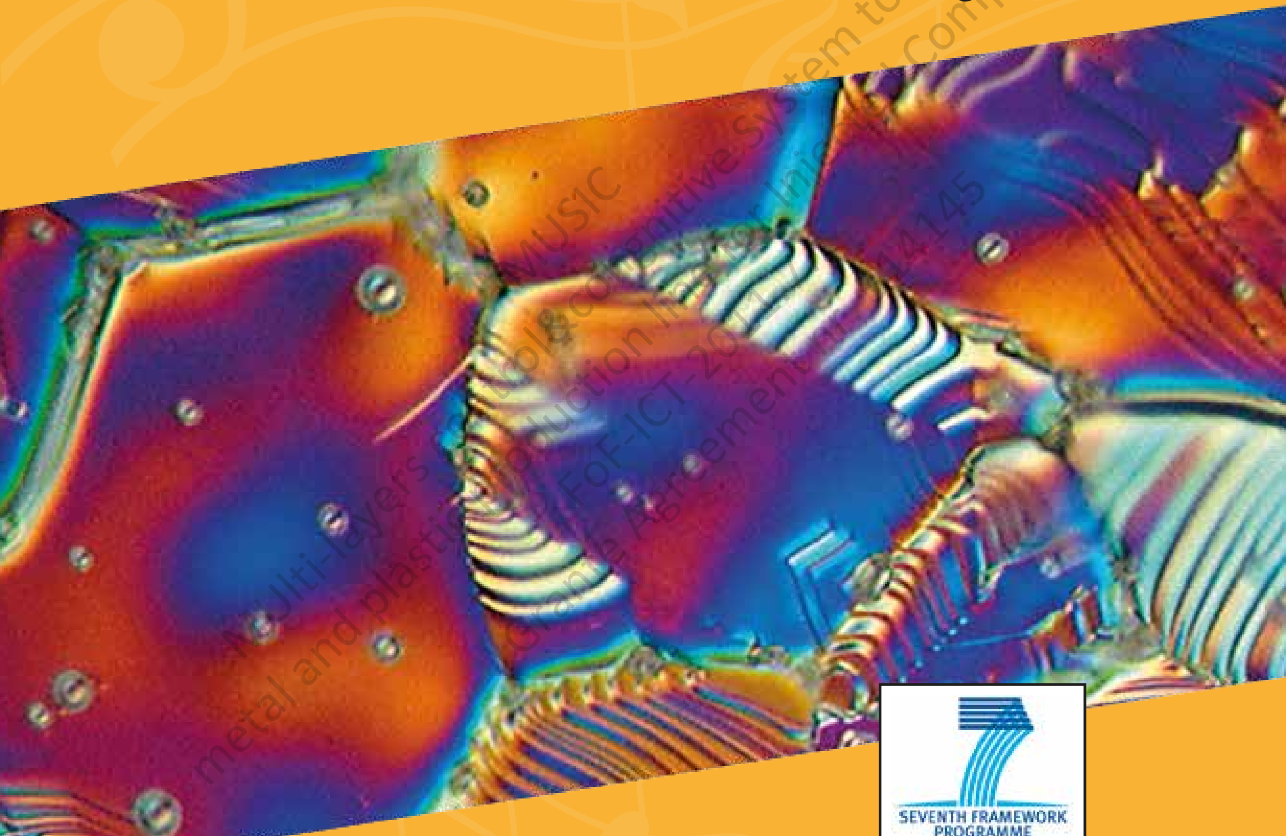

SEVENTH FRAMEWORK PROGRAMME

Assomet Servizi Srl

EnginSoft SpA

The MUSIC guide to key-parameters in High Pressure Die Casting

MUSIC: MUlti-layers control&cognitive System to drive metal and plastic production line for Injected Components

Collaborative IP Project - FoF-ICT-2011.7.1:Smart Factories:
energy-aware, agile manufacturing and customization
Contract no. 314145

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*** Photo on the cover by Amit Shyam - Oak Ridge National Laboratory (Tennessee)**
Title: "Silver Cermet" - This thin film of silver cermet leaves visible facets when sintered on a ceramic substrate at 950 deg Celsius. The facets are caused by evaporation of silver which is close to it melting point of 960 deg Celsius.

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The MUSIC Project is aimed at developing a ***MUlti-layers control&cognitive System to drive metal and plastic production line for Injected Components*** *under the Factory of Future (FoF) initiative, targeted at improving efficiency, adaptability and sustainability of manufacturing systems as well as their better integration within business processes in an increasingly globalised industrial context.*

This ambitious and challenging goal can represent a key-action for leading European High Pressure Die Casting and Plastic Injection Moulding Companies to cost-based competitive advantage, achieved by lower scrap generation, efficiency, robustness and minimum energy consumption. The essential tool to do this will be a completely new ICT platform, based on innovative ***Control and Cognitive system*** *linked to real time monitoring and allowing an active control of quality.*

Written at the mid-term of the Project, this book, referred to High Pressure Die Casting (HPDC) of Aluminium alloys, intends to analytically describe methods, tools, parameters and innovative approaches developed to monitor and control the process and the quality product.

The book collects the guidelines to design and implement the ***Intelligent Sensor Network (ISN)*** *in HPDC production line as first outcome of MUSIC project. The monitoring network is able to provide useable, meaningful and quantitative data on product quality, as well as to define strategies (varying production process parameters, changes to the tooling, etc.) to move toward higher quality product with economic efficiency.*

This real time control system capability will be exploited, during next two years, in order to train a ***cognitive-based ICT platform*** *for the industrial optimisation of High Pressure Die Casting production transforming the acquired knowledge and control methods into know-how.*

The final MUSIC outcome, "Control and Cognitive system", will impact on intelligent management of manufacturing information for new smart factory oriented to ***energy-aware, agile manufacturing and customization.***

As Coordinator and Scientific Manager of MUSIC project, our wish is that this book could be useful to the people involved in Light Alloys foundry industry (more than 2000 Companies, mostly SMEs, with an enormous potential due to the increasing demand of lightweight and reliable products in each application fields) and our thanks are for all the colleagues who very cooperatively worked in this Project.

Nicola Gramegna
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CHAPTER 1

Methodology for quantitative classification of quality requirements for HPDC products considering their in-service function and performance requirements

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1. Introduction

The aim of this Chapter is to define the guidelines and standard procedures that characterize the huge variety of aspects related to products coming out from HPDC process. Product requirements include the dimensional tolerance affecting the assembling phase of the single component in the vehicle frame. The maximum acceptable deformation is not clearly defined in the standards and it depends on the joining methods: riveting, welding (linear, spot welds) and adhesive.

The product requirements are fundamental to determine measurable criteria (and their edges) necessary to design a monitoring network (ISN) able to provide useable, meaningful and quantitative data on product quality, as well as to define strategies (varying production process parameters, changes to the tooling, etc.) to move toward a higher product quality.

This Chapter will

- offer an up-graded survey of the EU High Pressure Die Casting (HPDC) manufacturing field;
- identify the approaches adopted to specifically define quality requirements;
- evaluate the placement of MUSIC HPDC (AUDI, RDS) Partners, with respect to the EU scenario for HPDC quality requirements.

2. Quality requirements for classes of HPDC components

A general description of HPDC requirements in terms of quality can be done only after that a proper knowledge of this manufacturing field on a EU basis has been achieved. This knowledge is referred to

- characteristics of EU HPDC Companies,
- alloys mainly used in production of components,
- main classes of products,
- typical in-service functions & requirements for these products,
- typical defects and imperfections associates to these products,
- methods adopted for quality control,
- quantitative approaches implemented in quality control,
- frequency of defects.

Once this knowledge is obtained, the placement of HPDC MUSIC Partners can be evaluated, and proper strategies and approaches for the set up of monitoring networks can be elaborated.

2.1. Foundries and alloys

NOTE: Paragraph 2.1 has been elaborated on the basis of public data and of the survey carried out by EU StaCast project (New Quality and Design Standards for Aluminium Alloys Cast Products, FP7-NMP-2012-CSA-6, PROJECT n. 319188, www.stacast-project.org). The sharing of these data has been approved by MUSIC and StaCast Consortia, in the frame of a policy of cross-cutting cooperation among EU projects.

Geographical distribution of EU HPDC foundries

The World business environment for the whole Aluminium industry is shown in Figure 1.

The relevant figures about the situation of EU Al alloys foundries are the following ones [sources: ASSOFOND, Report on EU & Italian Foundry in 2011, Assofond, Milano (2012); EAA Annual reports, Bruxelles (2012), in http://www.alueurope.eu/; CAEF, Annual reports, Bruxelles (2011), in http://www.caef.org/; Organisation of the European Aluminium Recycling Industry, http://www.oea-alurecycling.org/en/recycling/ eckdaten.php]:

- there are roughly more than 2000 Aluminium alloys foundries in Europe (Table 1); the number of Companies in the supply chain can be estimated as equivalent;
- they are basically SMEs, with an average number of employees around 50 (but major part of them has less than 20 employees),
- the end users of cast products are the transport industry (60%), mechanics (7%), electro-mechanics (9%), civil engineering (20%), with a growing trend in automotive and transportation, motivated by the achievable reduction in fuel consumption and emission;
- the production, due to the well-known effects of crisis, has been strongly reduced in 2008 and 2009, with a partial recovery in 2010 and 2011 (see Table 2);
- the total number of persons directly employed in the field in Europe can be estimated in a range between 80.000 and 90.000; the total number of persons employed in the supply chain can be estimated as equivalent.

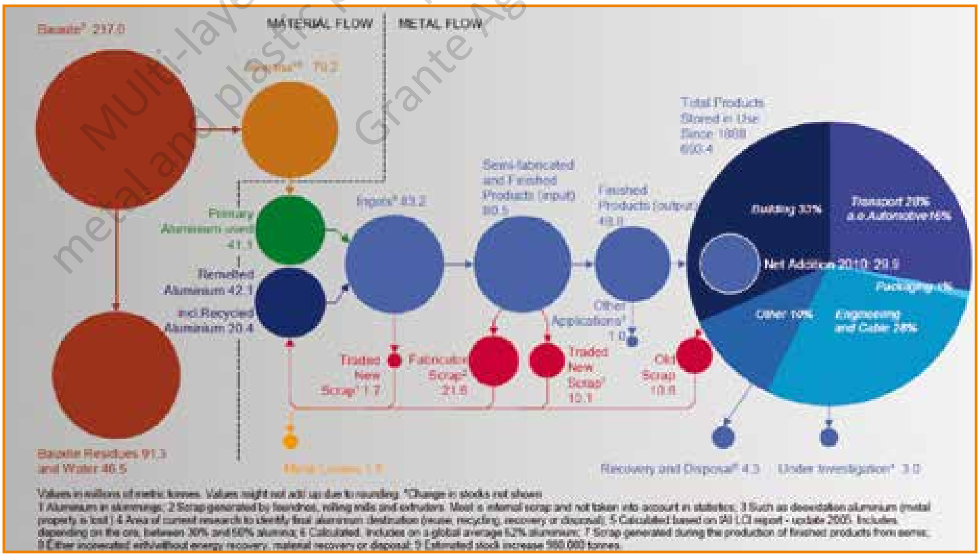


Figure 1. The World business environment for the whole Aluminium industry

	Italy	Germany	France	Poland	UK	EU
2008	960	346	335	245	236	~ 2550
2009	920	344	319	245	220	~ 2450
2010	917	345	315	245	216	~ 2800
2011	914	344	311	n.a.	210	~ 2600

Table 1. Number of non-ferrous foundries in Europe (Al alloys foundries can be estimated as 80% of them)

Country	2006	2007	2008	2009	2010	2011
Germany	773.000	882.000	802.000	560.000	797.000	844.000
Italy	897.000	912.000	820.000	560.000	730.000	833.000
Spain	129.000	125.000	110.000	81.000	100.000	113.000
Sweden	55.000	57.000	51.000	31.000	32.000	41.000
EU	**n.a.**	**3.070.000**	**2.940.000**	**2.100.000**	**2.815.000**	**3.022.000**

Table 2. Production of Al alloys castings in some European Countries (values in tons)

The more relevant foundry processes adopted are High Pressure Die Casting (HPDC, about 60-70% of European Aluminium alloys foundry production), followed by Gravity Casting (GC), Low Pressure Die Casting (LPDC) and Sand Casting (SC).

Typical structure and size of HPDC foundries

In order to adequately define the characteristics of EU HPDC foundries, it is very useful to consider the results of the survey recently carried out in the frame of the EU StaCast (New Quality and Design Standards for Aluminium Alloys Cast Products, www.stacast-project.org) Project (n. 319188 in the frame of FP7-NMP-2012-CSA-6). The survey was carried out on 82 Companies and Institutions, split as follows:

- 58 Foundries (HPDC, LPDC, permanent mold casting)
- 11 Providers of Materials and Services
- 2 Die-Makers
- 3 End-Users
- 8 Universities and RTD Centres

Among the HPDC foundries (43 companies), the majority (Figure 2) is constituted by SMEs (55.8%), while large industries (IND) correspond to 44.2%.

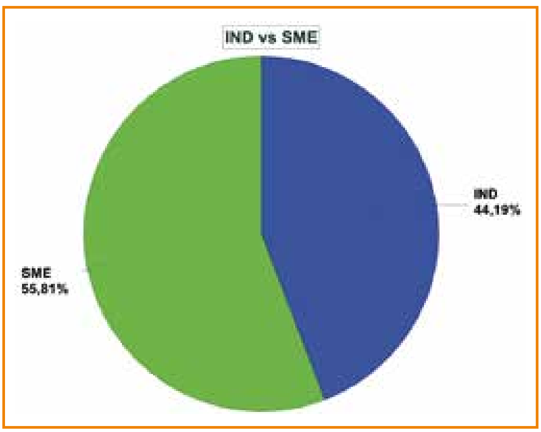


Figure 2. Partition SME vs IND of Foundries which answered the StaCast Questionnaire

As far as the production data is concerned (Figure 3), there is a relatively homogeneous distribution of the foundries among the 5 individuated categories. More than

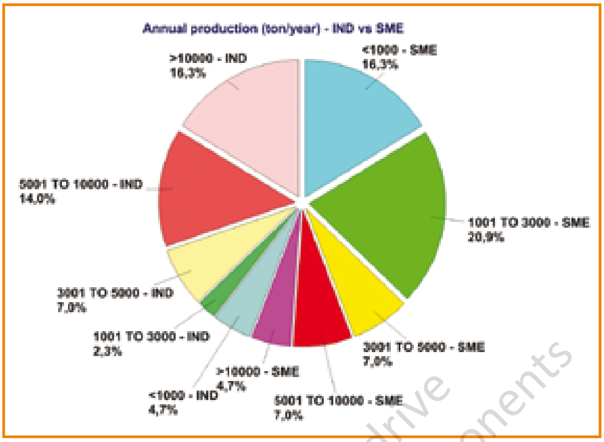


Figure 3. Production data (Tons/Year) for the HPDC Foundries

a half of the HPDC foundries, being SMEs, has a year production lower than 3000 tons (37.3% less than 1000 tons/year, 14% from 1000 to 3000 tons/year). On the other side, a significant part of foundries (16.3%), essentially IND, has a production higher than 10.000 tons/year.

Considering the average production data for the first four classes of production (less than 1000 tons/year, from 1001 to 3000 tons/year, from 3001 to 5000 tons/year, from 5001 to 10.000 tons/year) and a conservative value of 15.000 tons/year for the fifth class (more than 10.000 tons/year), the overall production of the "StaCast" foundries can be estimated in terms of almost 250.000 tons/year, roughly representing more than 8% of the annual EU production. This estimation gives a further and good support in terms of reliability of the performed survey.

Alloys used by EU HPDC foundries

Figure 4 collects the information concerning the alloys used by HPDC foundries. The alloy which has the widest diffusion is EN AB 46000 (Al-Si9-Cu3(Fe)), which is used by almost 75% of foundries, followed by EN AB 43400 (Al-Si10-Mg(Fe)) and EN AB 47100 (Al-Si12-Cu1(Fe)), both used by 51% of the foundries.

It can be observed that alloys which are not included in the actual CEN 1706 standard are very few, and mentioned only by 30% of foundries.

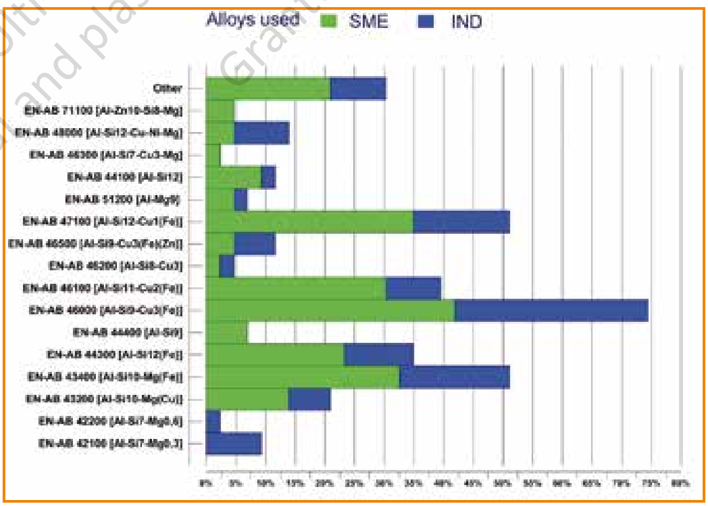


Figure 4. Alloys used by the HPDC Foundries which answered the StaCast Questionnaire

2.2. HPDC products

Main classes of HPDC products

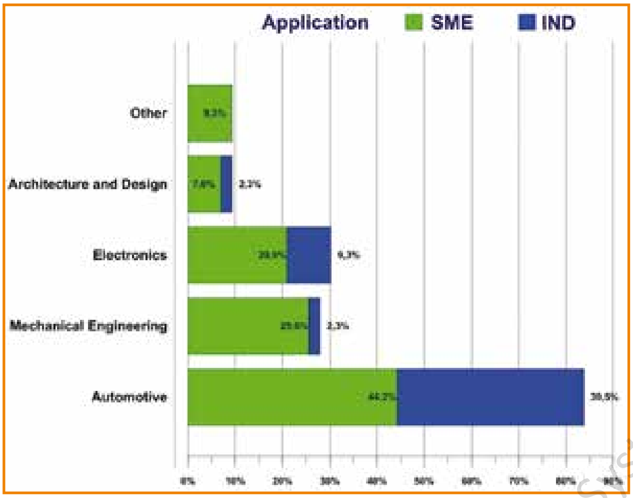


Figure 5. Final applications of castings produced by HPDC

From Figure 5, it can be observed that 83.7% of the HPDC foundries are manufacturing castings for automotive applications (with a similar percentage for SMEs and IND), followed by Electronics (30.2%), Mechanical Engineering (27.9%), and Architecture and Design (9.3%). In the "Other" category, mainly applications for mechanics and engineering have been mentioned.

Among the various categories of HPDC castings, a useful classification was suggested some years ago by the Italian Association of Metallurgy *(Ref.: Gruppo di Lavoro Qualità dei Getti Pressocolati: "Qualità dei getti pressocolati: Indagine sulla situazione attuale, prospettive di una norma sulle condizioni di fornitura dei getti pressocolati"; Centro di Studio Pressocolata, Associazione Italiana di Metallurgia, Milano, 2006),* and adopted by StaCast:

- Housing and Covers,
- Thin wall components,
- Safety components
- Engine blocks.

Figure 6 shows the partition of castings among these classes.

Among the various suggested categories, HPDC foundries are mainly producing Housing and Covers (32.6%), followed by Thin wall components (27.9%), Safety components (14.0%) and Engine blocks (4.7%). Engine blocks are almost exclusively produced by IND, which are also predominant in the production of safety components (in both cases, they are critical castings, requiring

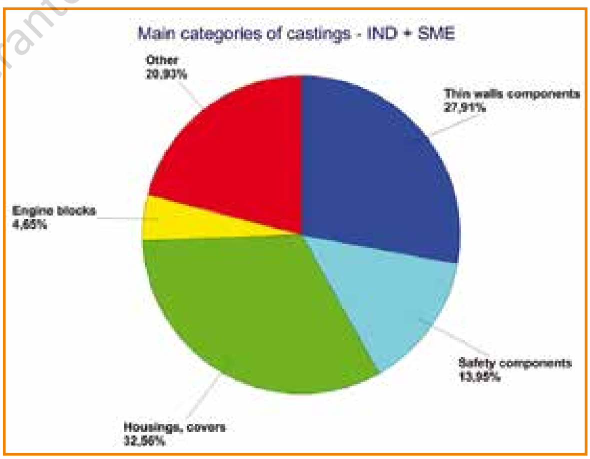


Figure 6. Main fields of application of castings manufactured by the Foundries which answered the StaCast Questionnaire

high reliability in manufacturing and in quality control procedures). For Housing and covers there is a substantial balance between IND and SMEs, which, on the other side, are predominant in Thin wall components manufacturing.

Main in-service function and performance requirements (by classes)

In Figures 7-11, with reference to the main classes of HPDC castings (Housing and Covers, Thin wall components, Safety components, Engine blocks, Others), the main function/performance requirements asked by end-users are reported.

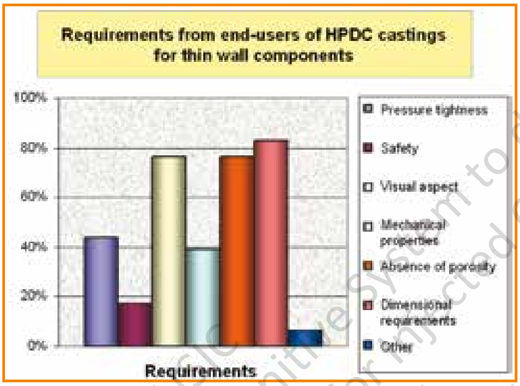


Figure 7. Requirements for HPDC thin wall components

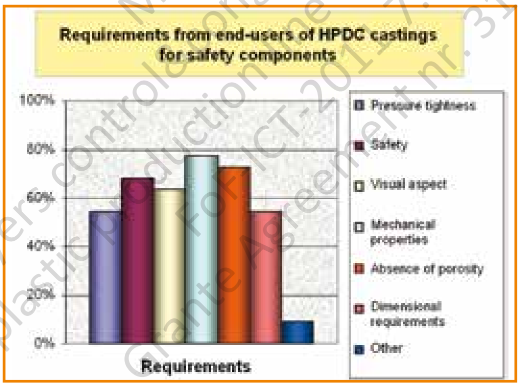


Figure 8. Requirements for HPDC safety components

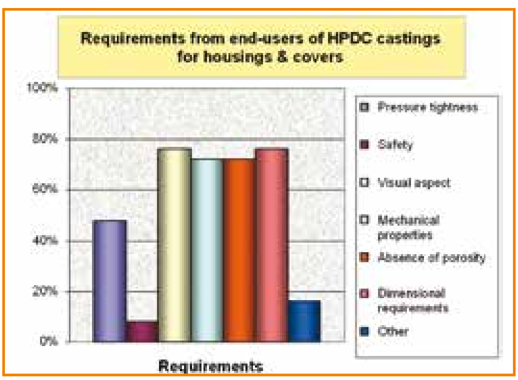


Figure 9. Requirements for HPDC housings and covers

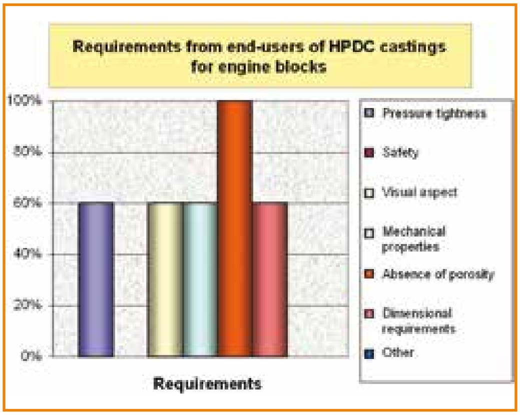


Figure 10. Requirements for HPDC engine blocks

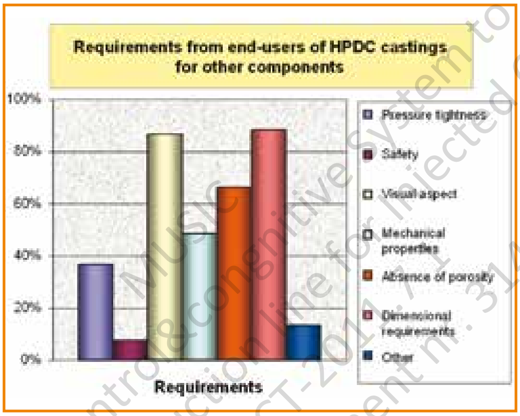


Figure 11. Requirements for HPDC other components

2.3. Quality control and classification

Classes of defects in HPDC products

Defects are intrinsically generated by casting processes, due to several reasons. The final properties and in-service behaviour of castings are always related to microstructural features and to defects: both microstructure and defects are the results of process stages, alloys properties and dies & tools design.

From these considerations, it seems that the potential of high-pressure die-casting will be completely exploited only when the quality level will be perfectly optimised. On such regard, the analysis of defects allows the foundry to monitor the products quality with respect to a quality standard. Further, the analysis of defects provides to the foundry useful correlations between defects type/distribution and their origin, so that it could be possible to define process modification for quality improvement.

The Italian Association of Metallurgy and, subsequently, the StaCast Project, after a 3-years survey carried out involving about 50 Al-alloys foundries, has recently suggested a new classification approach, based on a 3-levels defects individuation (see also **Annex 1**):

- morphology/location of defects (internal, external, geometrical);
- metallurgical origin of defects (e.g. gaseous porosity, solidification shrinkage, etc.);
- specific type of defects (the same metallurgical phenomenon may generate various defects).

The **level I** is based on morphology/location of defects, with reference to the investigation techniques suitable for their detection (visual inspections and controls involving the bulk material): there are internal and external (or surface) defects. Sub-surface defects (i.e. so close to the surface that they can affect the external aspect and be detectable by conventional surface investigation techniques), are considered surface defects. Finally, the geometrical defects refer to the casting shape in terms of dimensions and tolerances.

The **level II** is mainly focussed on the metallurgical origin of defects. Defects are grouped into several classes according to their general metallurgical origin:

- defects related to the presence of gas (gas-related defects);
- defects related to material volume contraction during metal solidification (shrinkage defects);
- defects related to thermal contraction prevented by previously solidified metal or by the die (thermal contraction defects);
- defects related to incorrect filling of the die-cavity (filling defects);
- defects related to metal/mould interaction;
- defects related to the presence of unsuitable phases (undesired phases), originated by the interaction of the metal with external environment during melting, casting, filling or extraction/ejection from the mould.

As previously observed, the knowledge of metallurgical origin could supply starting points for corrective actions (including process parameters).

The **level III** is used to identify the specific types of defects. Usually, the term adopted to describe a particular type of defect allows a better definition of the metallurgical origin of the defect itself, which was preliminarily identified in the previous level.

Such approach has been widely described in a published report *[E. Gariboldi, F. Bonollo, P. Parona, Handbook of defects in HPDC, AIM, Milano]*, and certainly constitutes the basis for the first relevant StaCast Objective, i.e. the definition of a New Standard on defects classification. The present classification of defects is of hybrid type and multi-level, as schematically shown in Tables 3, 4 and 5.

he proposal refers to metallurgically-based defects of HPDC and permanent mould casting products. Defects directly related to handling, finishing, machining operations, following ejection from the die, are excluded from the classification, even if they could be possible causes for product rejection. In this way, the range of defect types is not excessively wide.

In the frame of the 1st Intermediate Meeting of MUSIC Project (March 2013), a fourth class of defects have been introduced (post-production defects).

Further considerations have been added:

- for each defect, it is fundamental to establish both the **presence** and the **level**;
- it must be distinguished between "Short Term" and "Long Term" defects (as described in Table 6a-b).

1st Level	2nd Level		3rd Level	
A Internal Defects	A1	Shrinkage defects	A1.1	Macro-shrinkage
			A1.2	Interdendritic shrinkage
			A1.3	Layer porosity
	A2	Gas-related defects	A2.1	Air entrapment porosity
			A2.2	Hydrogen porosity
			A2.3	Vapour entrapment porosity
			A2.4	Lubricant entrapment porosity
	A3	Filling-related defects	A3.1	Joint
			A3.2	Lamination
			A3.3	Cold shot
	A4	Undesired phases	A4.1	Inclusion
			A4.2	Undesired structure
	A5	Thermal contraction defects	A5.1	Crack
			A5.2	Hot tear

Table 3. Classification of internal defects.

1st Level	2nd Level		3rd Level	
B Surface Defects	B1	Shrinkage defects	B1.1	Sink
	B2	Gas-related defects	B2.1	Blister
	B3	Filling-related defects	B3.1	Joint and Vortex
			B3.2	Lamination
			B3.3	Cold shot
	B4	Undesired phases	B4.1	Surface deposit
			B4.2	Contamination or inclusion
	B5	Thermal contraction defects	B5.1	Crack
			B5.2	Hot tear
	B6	Metal-die interaction defects	B6.1	Erosion
			B6.2	Soldering
			B6.3	Thermal fatigue
			B6.4	Ejection mark
			B6.5	Corrosion of the die

Table 4. Classification of surface defects.

1st Level	2nd Level		3rd Level	
C Geometrical Defects	**C1**	Lack of material	**C1.1**	Incomplete casting
	C2	Excess of material	**C2.1**	Flash
	C3	Out of tolerance	**C3.1**	Deformed part

Table 5. Classification of geometrical defects.

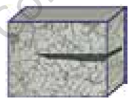
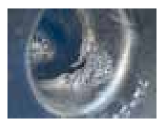
	Defect	Parameter	Defect Characteristics
Short Term Defects	Air entrapment	• 1st phase • 2nd phase • Switch over point • Velocity phase I • Velocity phase II • Gating depth (self- adaptive system) • Venting cross section (self- adaptive system)	
	Lamination	• Metal Temperature • Die Temperature • Melt velocity	
	Cold laps	• Metal Temperature • Die Temperature • Melt velocity • Local Flow Directions	
	Shrinkage	• Metal Temperature • Die temperature • Intensification pressure (at the moment represented by feeding effectivity) • Local squeezed Volume • Gating depth (self- adaptive system)	
	Hot cracks	• Metal temperature • Die temperature	
	Distortion	• Local Casting Temperature • Die Temperature	
Long Term Defects	Erosion	• Melt velocity (2nd phase) • Residence time • Gating depth (self- adaptive system)	
	Die soldering	• Die temperature • Metal temperature • Residence time	
	Mold cracks	• Local Die Temperature • Differences (caused by spraying intensity and time • Spray Intensity (local HTC) • Metal temperature • Die temperature	

Table 6a. Short and long term defects, and related process parameters.

	Defect	Potential of Simulation	Simulation result	Example by MAGMASOFT
Short Term Defects	Air entrapment	Simulation model needs to be extended: Shot Chamber Simulation. New result Advanced Air Entrapment is developed.	• Air entrapment • Advanced Air Entrapment	
	Lamination	Local temperature indicates that there might be lamination. New result Fluidity is developed	• Local Casting Temperature at the end of filling? • Fluidity	
	Cold laps	Local temperature indicates that there might be cold laps. New result Fluidity is developed.	• Local Casting Temperature at the end of filling? • Fluidity	
	Shrinkage	Possible. Direct correlation between feeding effectivity and intensification pressure to be developed (further investigations required). New result Pore free Zone is developed.	• Feeding & Porosity • Pore free Zone • Weighted Volume Feeding	
	Hot cracks	Possible	• Hot tear criterion	
	Distortion	Possible	• Distortion	
Long Term Defects	Erosion	Possible, but more information about critical velocity and critical residence time required.	• Die Erosion (Where a critical melt velocity exceeds a defined residence time)	
	Die soldering	Possible, but more information about critical temperature and critical residence time required	• Melt velocity (2nd phase) • Residence time • Gating depth (self- adaptive system)	
	Mold cracks	Possible	• Die Life	

Table 6b. Short and long term defects: potential of simulation for their prediction.

"Short Term" means that changes in process parameters will typically lead to a visible change on this defect after a reasonably low number of cycles.

"Long Term": meaning defects that only appear after a significantly large number of cycles due to metal-die interaction as indicated by B6 class.

Another key-aspect is referred to development/training of meta-models of defects. If the meta-model deals with "Short Term" defects, the development/training seems not to be critical. If the meta-model deals with "Long Term" defects, the effect of process parameter changes are only visible after long periods of time. A sub-model for these defects must be developed based e.g. on laboratory scale experimental work and/or on literature information.

Methods for quality control

Techniques usually employed for Quality Control are based on

- Visual inspection,
- Radiographic inspection,
- Leak tightness testing,
- Density measurements,
- Liquid penetrant inspection,
- Ultrasonic testing,
- Destructive testing (machining, sawing, metallography, fractography).

They can be applied on 100% of castings or on a statistical basis.

The above-mentioned StaCast Project verified the degree of usage of these Quality Control Methods, with reference to the main categories of defects identifiable by grouping the classes of defects reported above. Six main groups of defects can be identified:

- Gas/Air porosity,
- Inclusions,
- Shrinkage,
- Cracks,
- Filling-related defects,
- Metal-die interactions.

In Figs 12-17, the use of the different methods for quality control, referred to the six groups of defects, is described.

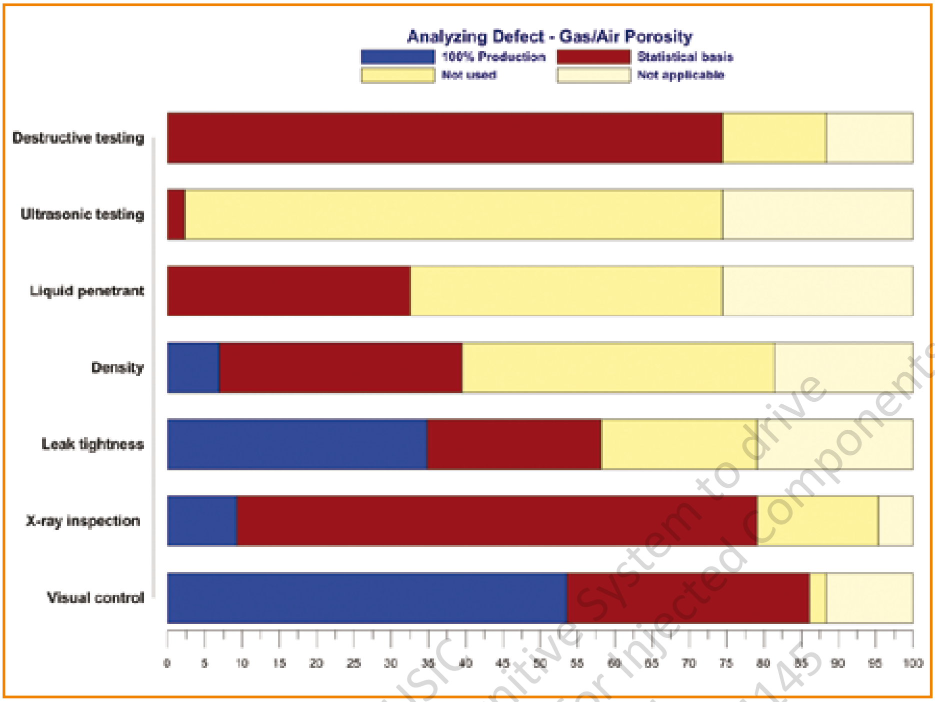


Figure 12. Use and approach (100% Production or Statistical basis) of various investigation techniques to detect Gas/Air porosity defects by HPDC Foundries

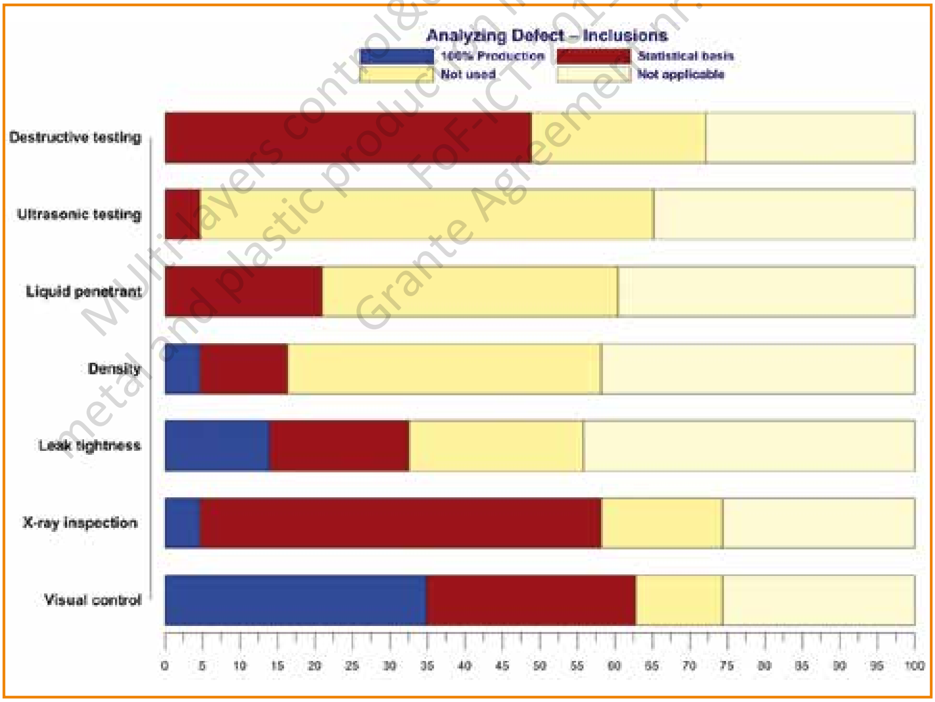


Figure 13. Use and approach (100% Production or Statistical basis) of various investigation techniques to detect Inclusions defects by HPDC Foundries

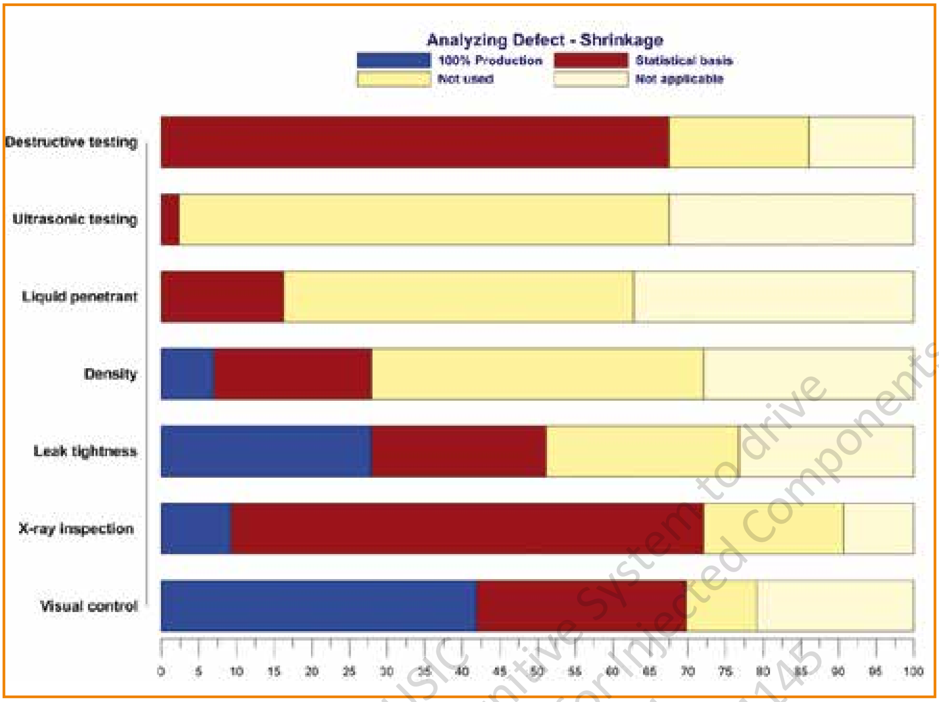


Figure 14. Use and approach (100% Production or Statistical basis) of various investigation techniques to detect Shrinkage defects by HPDC Foundries

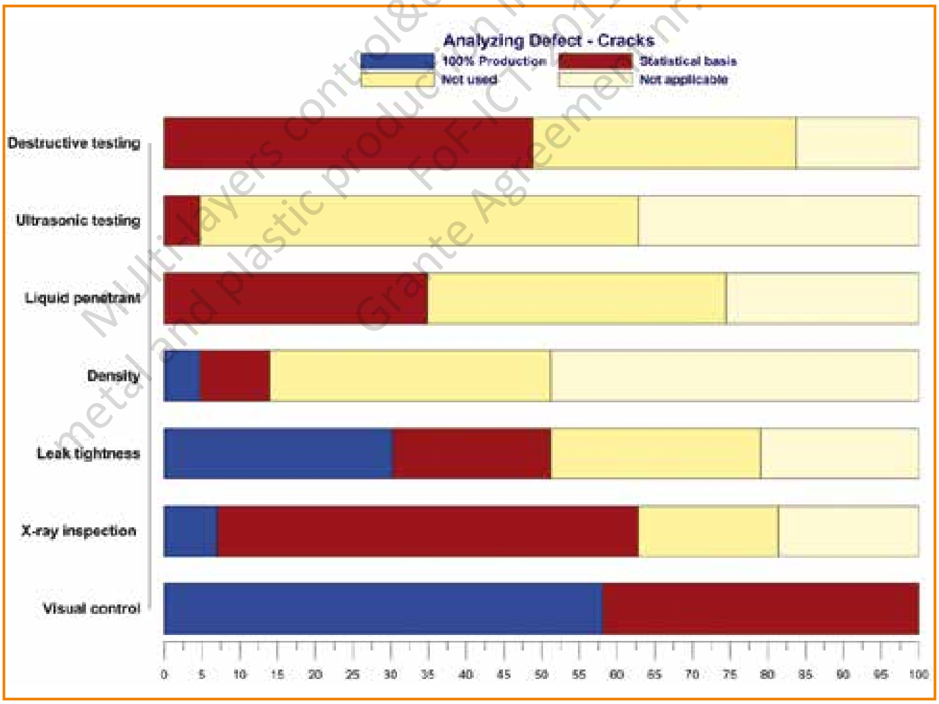


Figure 15. Use and approach (100% Production or Statistical basis) of various investigation techniques to detect Crack defects by HPDC Foundries

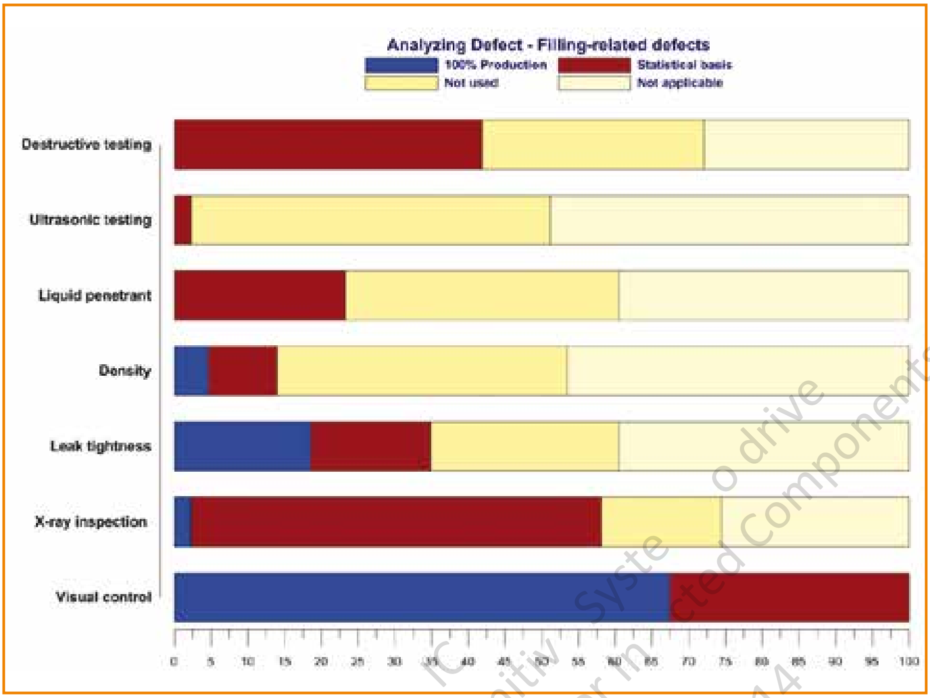


Figure 16. Use and approach (100% Production or Statistical basis) of various investigation techniques to detect Filling related defects by HPDC Foundries

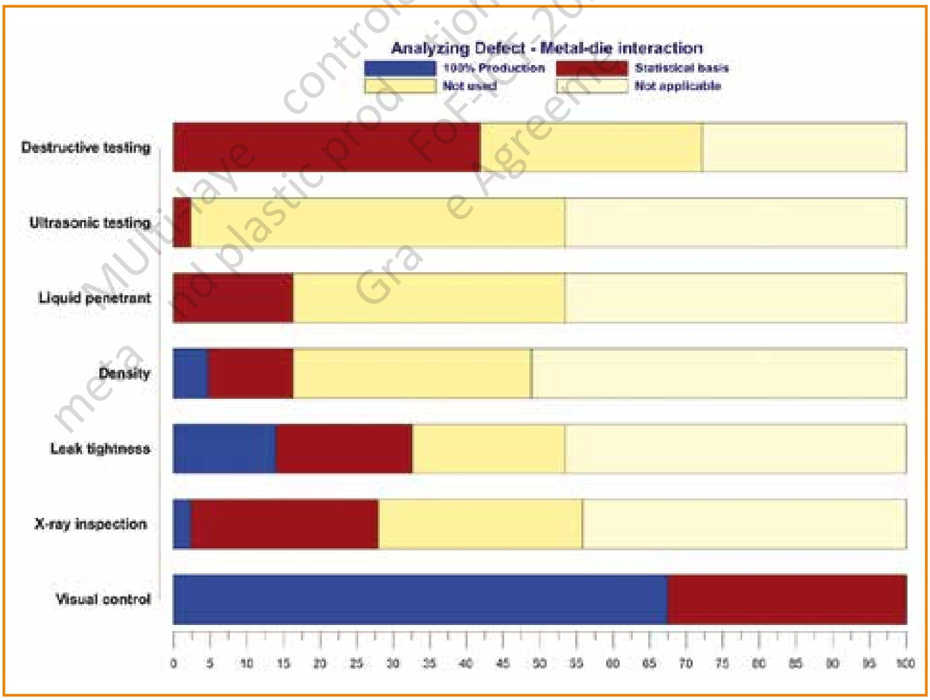


Figure 17. Use and approach (100% Production or Statistical basis) of various investigation techniques to detect Metal-Die Interaction defects by HPDC Foundries

Quantitative evaluation of defects

For all groups of defects, it is relevant to check if they are also measured or quantified (and not only simply detected) by foundries. From Figure 18, it appears clear that quantification is performed (for the majority of foundries) when Gas/Air Porosity (74.4%) or Shrinkage (55.8%) are considered. For these defects, detection is mainly carried out by X-Rays inspection (in the range from 70% to 80% of cases, as shown in previous Paragraphs), which, by means of modern data elaboration systems, can be associated to quantitative evaluations. Furthermore, these kinds of defects in some cases can be accepted in the castings, if they are within a previously identified threshold (in this sense, and according to the definition of EN 12258-1, they can be considered as "imperfections" instead of "defects").

Figure 18. Extent of measurement/quantification of defects

Metal-Die interaction, Filling-related and Cracks defects are basically located on the surface of castings, and basically individuated by visual inspection, which defines whether the casting is or not acceptable. In these cases, defect measurement/quantification is less strategic (carried out, respectively, by 46.5%, 48.8% and 51.2%) of the HPDC foundries.

Inclusions can be detected mainly by metallography, i.e. on a statistical basis; the need to measure/quantify them is probably associated to specific requirements of the castings, and thus carried out only by 41.9% of foundries.

Frequency of defects

It is evident that the defects genesis is strongly associated to the specific casting process adopted. The situation, in terms of defects frequency, for HPDC is associated to the following ranking (Figure 19):

- Metal/Die interaction (57%): significant frequency,
- Gas/Air porosity (54%): significant frequency,

- Shrinkage (37%): slightly more than occasionally,
- Filling-related (35%): slightly more than occasionally,
- Crack (33%): occasionally,
- Inclusions (24%): less than occasionally.

The relevancy of Metal/Die interaction defects and of Gas/Air porosity defects is significantly high, with respect to other groups.

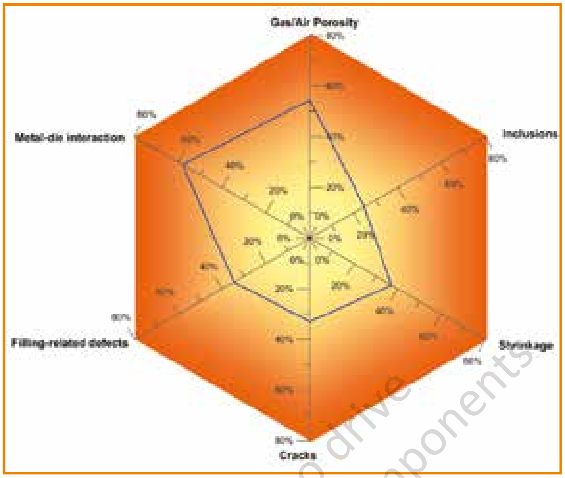


Figure 19. Frequency of defects, as estimated by HPDC foundries

2.4. Template table for the quantitative evaluation of defects

From the above information, it is possible to suggest a template, to be used for quantitative classification of quality requirements for classes of HPDC products, considering both their in-service function and their performance requirements. The needed information to define and standardize the methodology for quantitative evaluation of defects are collected in Table 7. In detail, Table 7 includes the following fields:

Component Category	Part/zone	Performance	Defects	Measurement method(s)	Appl. Level [*]	Threshold acceptance level and related unit
Engine Block Thin wall Safety Covers Others						

Table 7. Template table for quantification of product requirements.
[*] Application Level: I = Industrial Production; P = Industrial Pre-Production; R = Research

- Component Category, according to the categories previously introduced:
  - Housing and covers;
  - Thin wall components;
  - Safety components;
  - Engine blocks
  - Others.
- Part/zone: for each of the aforementioned categories, it is possible to define common parts or zones for all castings: these parts/zones share the same functionalities/performances and, as a consequence, the same product requirements.

- Performance: the product requirements for which the particular part has been designed.
- Defects: defect or defects greatly affecting the product requirements have to be reported, as well as the quality control method expected to be used. The defects are reported on the basis of the classification rules set up in Tables 3 to 5.
- Measurement method(s): they are selected from the methods of quality control mentioned in the previous field.
- Quantity (unit of measure): the parameter used to quantify the defect (with the proper unit of measure).
- Threshold acceptance level: maximum, minimum, thresholds and/or range of acceptance for the particular defect to quantify.

Component Category	Part/zone	Performance	Defects	Measurement method(s)	Appl. Level [*]	Threshold acceptance level and related unit
Engine Block	Bearing support	Yield Stress	[A1.2] Interdendritic shrinkage	Xray	I,P,R	mean shrinkage length (μm)
				Tomography	P,R	
				Metallography	I,P,R	shrinkage area (μm²)
				SEM	P,R	
			[A4.1] Inclusion	Xray	I,P,R	Inclusion size: max 0.75 mm
				Tomography	P,R	
				Metallography	I,P,R	
				SEM	P,R	
			[A4.2] Undesired structure	Metallography	I,P,R	…
				SEM	P,R	…
		UTS	[A1.1] Macro-shrinkage	Xray	I,P,R	mean shrinkage size [mm]
				Tomography	P,R	
				Metallography	I,P,R	Shrinkage area [mm²]
				SEM	P,R	
			[A4.1] Inclusion	Xray	I,P,R	Inclusion size: max 0.5 mm
				Tomography	P,R	
				Metallography	I,P,R	
				SEM	P,R	
			[A2.1] Air Entrapment Porosity	Metallography	I,P,R	
				SEM	P,R	
		Fatigue	[B6.3] Thermal fatigue	Liquid penetrant inspection	I,P,R	
			[B5.1] Crack	Liquid penetrant inspection	I,P,R	

Table 8. Example of application of the template table for quantification of product requirements: case of Engine Block with specific reference to Bearing support areas.
[*] Application Level: I = Industrial Production; P = Industrial Pre-Production; R = Research

An example of application of this methodology for quantitative evaluation of defects is given in Table 8, which has been set up with reference to HPDC engine blocks.

2.5. Information modelling of the product/quality requirements

Once the quality requirements for the HPDC processes are defined, the information has to be "modelled" and stored in a central server that hosts a database and dialogues with the control and cognitive system application. From the analysis of the product requirements, it arises that the following information shall be collected in the database:

- the casting category/family/class;
- the physical areas where specific requirements are defined;
- the type of defect concerning the above mentioned areas;
- the method used for inspecting the item and identifying the defect;
- a measurable (normalized) quantity that defines the intensity of the defect with specific unit;
- a set of thresholds that define the seriousness of the defect and bound the minimum and maximum acceptability ranges.

These parameters can be structured, for instance, as tables in a SQL database.

When deployed, the system undergoes a preliminary phase, called **training phase**. A set of real and simulated designs of experiments (DOEs) are planned and the system observes, acquires and analyzes a big amount of data. The purpose of the training phase is to build the cognitive model for a particular production process.

The analysis of the components and their defects during the real experiments provides the system with the necessary information highlighted above. The data (in particular the quality output) shall be manually or semi-automatically (depending on the inspection methodology) inserted into the database by a human operator using the best method and accuracy.

During the **production phase**, when the system is running, the product information allow to uniquely identify a defect, by its category and location. The quality output by inspection will be investigated only for the "predicted scrap" components, thus updating the database accordingly.

Depending on the specific process, all or just some of the above parameters may be necessary. For instance, the location of the defect may be critical for a particular inspection methodology, or be non-influential for another one. Also, new classes of parameters may be added in particular cases. For example, it may be necessary to insert a new inspection methodology, that is not already present in the database. The last two parameters, namely the defect measure and the thresholds, may be influenced by the other categories. Table 9 summarizes the characteristics of the various parameters, using the SQL terminology. The rows with a X under the column named "Not null" identify the parameters that must always exist. The column "Reference" points out whether and how a parameter is related to other information, probably maintained in specific SQL tables.

Parameter	Not null	Reference	Data type
Casting		The full range of casting categories are defined in a table, which can be customized.	String literal
Location		The locations are inserted in a table, which is dependent on the casting and can be customized.	String literal
Type	X	The full range of possible defects is defined in a table, which is dependent on the casting and location and can be customized.	String literal
Method		The full range of possible inspection methodologies is defined in a table, which can be customized.	String literal
Value	X	A specific measurement unit is associated with the casting/location/type	Integer
Thresholds	X		Ranges

Table 9. Characteristics of quality parameters according to SQL terminology.