Robust Design as a Driver of Engine Cylinder Heads Evolution – a Framework for Identifying Product Improvement Paths

by

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SUBMITTED TO THE SYSTEM DESIGN AND MANAGEMENT PROGRAM IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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May 6th, 2005

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BARKER

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ABSTRACT

The fundamental goal of Robust Design is to improve the quality of a product by minimizing the effects of variation. A key contributor to robustness over the long term is R&D. Therefore, a framework is desired to help managers to identify promising improvement paths that a system may undergo, thus helping out in deciding R&D resource allocation. The goal of this thesis is to contribute to a framework for robustness inventions. This contribution is sought by analyzing the evolution in robustness of a single component in a particular engineering system - the engine cylinder head. By analyzing a series of patents related to reliability and robustness of engine cylinder heads, the author identified generalizable inventive strategies for robust design.

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Chapter 1

Introduction

Reliable, improved products are the result of robust design

Reliability vs. robustness

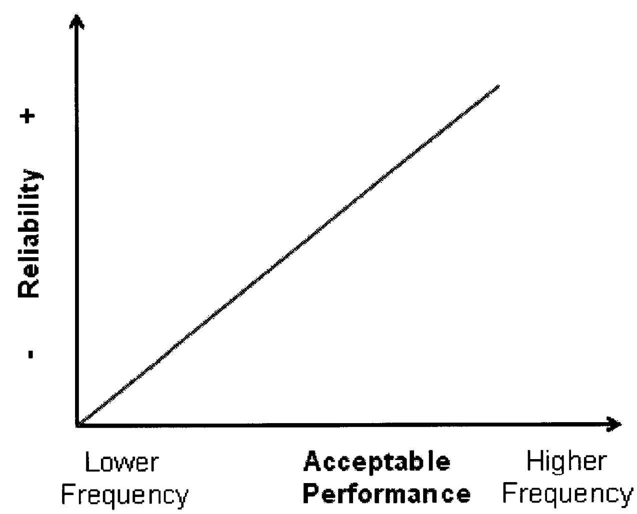
A system can be called reliable when one can expect with certain level of confidence that such system will perform the function for which it was intended within the possibilities provided by its design. In other words, a system can be considered a reliable one when it does what it is supposed to do.

The level of reliability of a system can be defined as a function of the consistency with which the system performs its function to an acceptable extent. For example a system that sometimes exceeds expectations and others does not meet them is not a reliable one. Another system that meets expectations regularly, even when it does not exceed them, is a reliable one. A third system that exceeds expectations with the same frequency than the second meets them is also reliable system, and – arguably – as reliable as the second. Finally, an additional system which meets or exceeds expectations more frequently than the second and third systems is more reliable than such systems.

Assuming that the four systems under consideration are intended to deliver the same function, what makes one more reliable than the others? The system's design does. Some designs result in systems that are more reliable than others, which is one of the reasons for which someone may prefer a product made by one firm over other that it is supposed to perform the same function made by other firm.

In that order of ideas, reliability is a function of system performance – more specifically of acceptable performance consistency – and can be increased (or unintendedly decreased) with design changes.

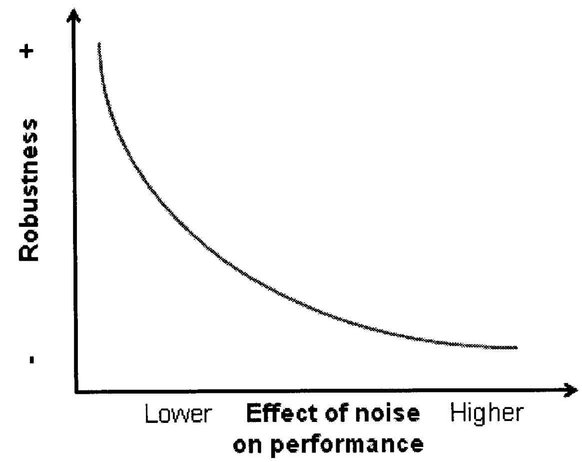
Fig. 1 – Reliability as a function of performance



A robust system is defined as 'one that performs as intended even under non-ideal conditions such as manufacturing process variations or a range of operating situations'.[1] The uncontrolled variations of a system's environment are called noise. Thus, robustness is a function of the effect of noise in the system's performance.

[1] Ulrich & Eppinger, 2003

Fig. 2 – Robustness as a function of the effect of noise on system performance



While reliability is a design intent, robustness could be seen as a design parameter. Systems are theoretically designed to deliver a determined function consistently under the assumed conditions without failing. In reality, systems fail due to considerations that were underestimated, neglected or unknown during the design phase. These considerations (or lack of considerations) are supported by assumptions that dictate the robustness of the end product. The more the design relies on the assumptions made, the less robust the product will be to differences between the reality and the assumed conditions. Fortunately, for most of the systems there is opportunity for making adjustments to the design so their robustness and reliability can be improved. The best way of improving a system is through robust design strategies.

Although a correlation between reliability and robustness can be intuitively derived – "more robust products exhibit more consistent performance thus they are more reliable" – these are separate characteristics of a system that contribute to the perceived system quality.

From the analysis of the scenarios resulting from combining high and low levels in both characteristics, the information depicted in Fig. 3 is concluded.

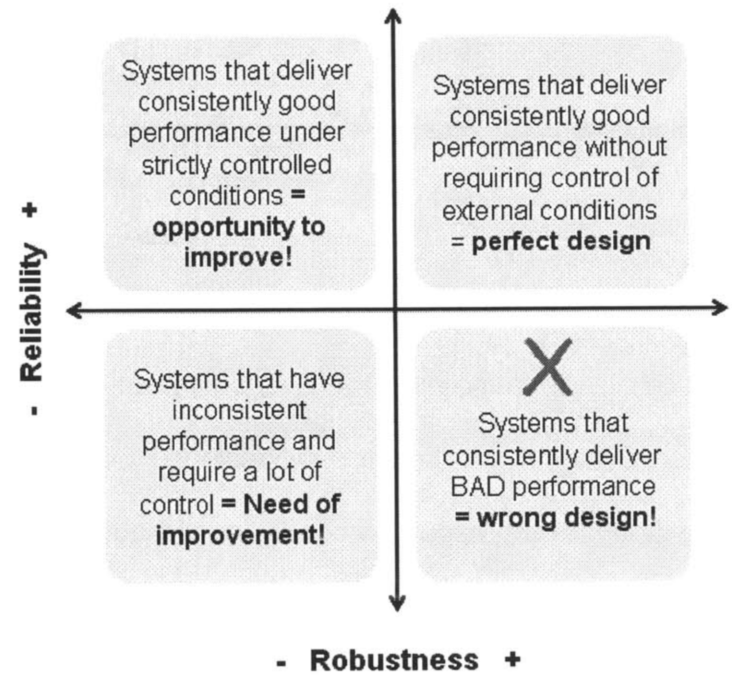


Fig. 3 – Scenarios of robustness and reliability

The High-High scenario represents the "desired-system", which does not have room for improvement without changing the current functionality. The High reliability-Low robustness scenario is reliable as long as there is no noise present in the environment. Many systems exhibit these characteristics during their development phase, when in a low-scale, pilot-version, lab-controlled environment exhibit consistently acceptable performance, but need further improvement to deliver the substantial value of the High-High type of systems.

The Low reliability – High robustness scenario is where the systems have simply bad performance, even though variability is not the exact problem. Systems like this usually correspond to wrong designs. The Low-Low scenario is more of an "unknown" state. Improvement is urgently required in order to figure out whether if the problem is in the variability or in the design.

What is Robust Design?

The following are definitions of robust design:

- "Robust design is the product development activity of improving the desired performance of the product while minimizing the effects of noise." [2]
- "[A] method for designing and conducting experiments to improve the performance of products even in the presence of uncontrollable variations." [3]

One undeniable way of executing robust design is through "brute force" techniques, adding margin to design characteristics or specifying tighter tolerances. Another more sustainable way is through "intelligent design", defining design strategies to counteract the effects of variation thus improving performance consistency.

It is arguable that robust design is, rather than a method, a 'philosophy' that is adopted when the advantages of considering variation and noise since the design phase – to the feasible extent – are realized. To practice it, system engineers

[2] Ulrich & Eppinger, 2003
[3] Ulrich & Eppinger, 2003

must first understand the potential sources of variation and figure out ways to make the system less sensitive to them.

In complex systems, robust design strategies from a component's standpoint can be classified in two categories: 1) intents to reduce component sensitivity to variation, and, 2) intents to reduce system sensitivity to variation that affect the component

Whatever the strategy, the result will be a more reliable system, since its performance will not be affected by changes in the conditions that it is subjected to, thus it will be more consistent.

Thesis objective

Traditionally, robustness has been treated as a design requirement that often interferes with other requirements and design intents, thus trade-offs on one or more desired characteristics being needed.

Based on the correlation that exists between system robustness and system reliability, and understanding that reliability is an implicit design objective of any system; the present thesis proposes the conceptualization of robustness as a strategy for product development and improvement. Moreover, it suggests that product evolution can positively take place successfully if incremental product improvement is driven by robust design applied in a succession of robustness inventions.

The goal of this thesis is to contribute to a framework for robustness inventions. This contribution will be sought by analyzing the evolution in robustness of a single component in a particular engineering system: the engine cylinder head. By analyzing a series of patents related to reliability and robustness of engine cylinder heads, the author attempts to identify generalizable inventive strategies for robust design.

Document structure

The structure of this document is as follows: in Chapter 2, a detailed analysis of the cylinder head is made by first explaining the principles of functionality of the internal combustion engine. Overviews of the engine decomposition, the cylinder head manufacturing processes and the product failures are presented in order to provide the means for understanding the context where the cylinder head coexists and operates.

Chapter 3 walks through the reliability and robustness evolution of the cylinder heads undergone in the past 20+ years. This evolution process is analyzed from two different perspectives: 1) from the system reliability standpoint, how incremental improvements affect a particular component, and, 2) from the components point of view, how the component provides a better 'service' to the system by incrementing local robustness through design changes. Examples including excerpts of relevant patents are presented to illustrate the trends that drove the proposed changes in the cylinder head. Additionally, a quick view of the current art is provided, in order to judge the success/failure of the inventions reported.

In Chapter 4, the author provides insights derived from the research done, proposing three elements for a framework for robustness inventions based on the principles of the robust design discipline. These elements are 1) sources of creativity for robustness inventions, 2) a series of inventing strategies, and, 3) a guideline for identifying promising improvement paths.

Finally, in Chapter 5, a summary of the takeaways drawn from this research and recommendations for further research on this topic are listed.

Chapter
2

Engineering system under study

Cylinder head contribution to the engine delivered function

Internal combustion engines

An internal combustion engine is an engine that is powered by the expansion of hot combustion products of fuel directly acting within an engine. [4] These engines are classified as reciprocating or rotary, spark ignition or compression ignition, and two-stroke or four-stroke. The most familiar combination, used from automobiles to lawn mowers, is the reciprocating, spark-ignited, four-stroke gasoline engine, also known as piston engine. Other types of internal-combustion engines include the reaction engine (jet propulsion, rocket), and the gas turbine.

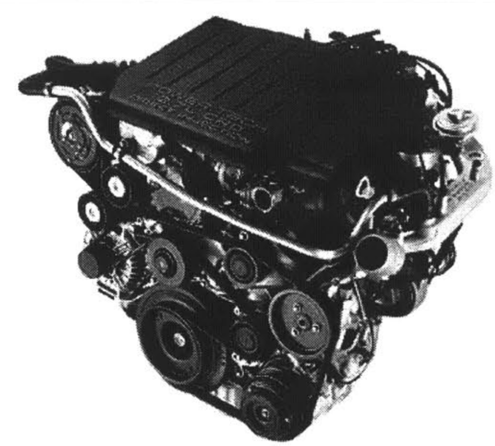


Fig. 4 – A reciprocating, spark-ignited, four-stroke engine: 2003 Jeep® Grand Cherokee Engine[5]

[4] http://www.infoplease.com/

[5] http://auto.howstuffworks.com/

A piston-type engine works by burning hydrocarbon or hydrogen fuel that presses on a piston. The confined space in which combustion occurs is formed by a cylinder. The cylinders are usually arranged in one of four ways: a single row with the centerlines of the cylinders vertical (in-line engine); a double row with the centerlines of opposite cylinders converging in a V (V-engine); a double zigzag row somewhat similar to that of the V-engine but with alternate pairs of opposite cylinders converging in two Vs (W-engine); or two horizontal, opposed rows (opposed, pancake, flat, or boxer engine).

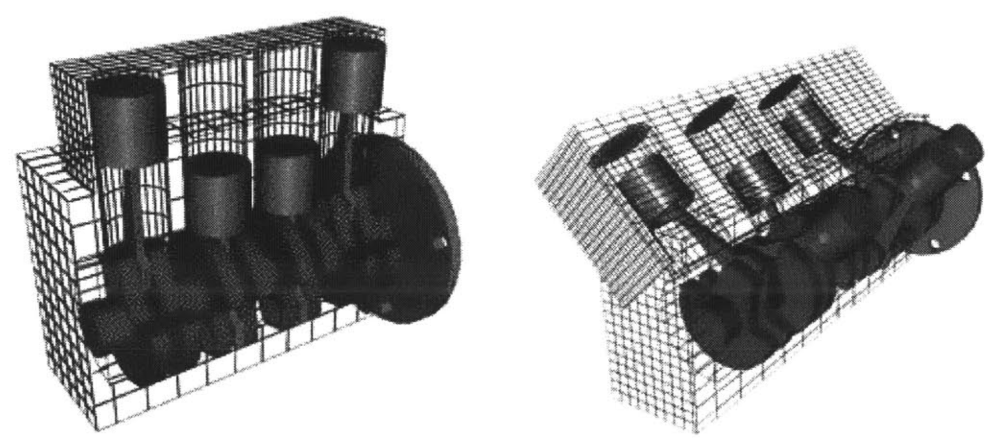


Fig. 5 – Most common piston-type engine configurations: left, Inline arrangement; right, V arrangement.

How piston-type internal combustion engines work

The piston engine follows the operating principles of the four-stroke cycle. The four-stroke cycle was invented by Nikolaus Otto in 1876, and is also called the Otto cycle. It is more fuel-efficient and clean burning than the two-stroke cycle, but requires considerably more moving parts and manufacturing expertise and the resulting engine is larger and heavier than a two-stroke engine of comparable power output. [6]

The four strokes of the cycle are intake, compression, power, and exhaust. Each corresponds to one full straight movement in a single direction of a piston inside a cylinder; therefore the complete cycle requires two revolutions of the crankshaft to complete. The four strokes of the cycle are depicted as follows. [7]

Intake

During the intake stroke, the piston moves downward, drawing a fresh charge of vaporized fuel/air mixture. The illustrated engine shown in Fig. 6 features a 'poppet' intake valve which is drawn open by the vacuum produced by the intake stroke. Some early engines worked this way; however most modern engines incorporate an extra cam/lifter arrangement as seen on the exhaust valve.

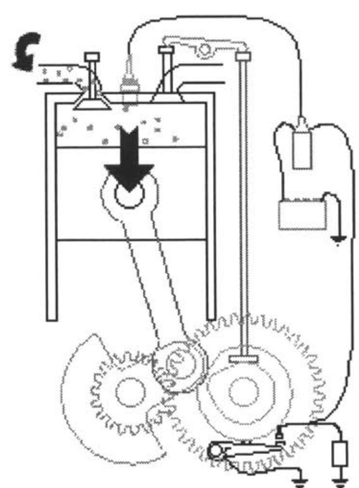


Fig. 6 – Intake stroke

[6] http://www.keveney.com/, http://en.wikipedia.org
[7] Source: http://www.keveney.com/

Compression

As the piston rises the poppet valve is forced shut by the increased cylinder pressure. Flywheel momentum drives the piston upward, compressing the fuel/air mixture.

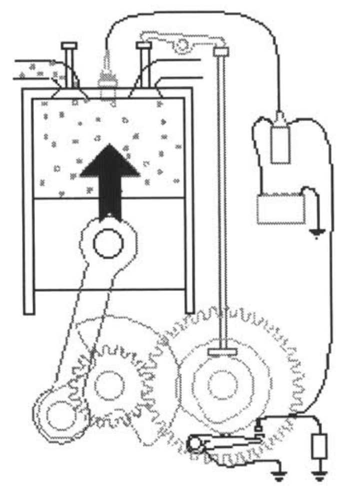


Fig. 7 –Compression stroke

Power

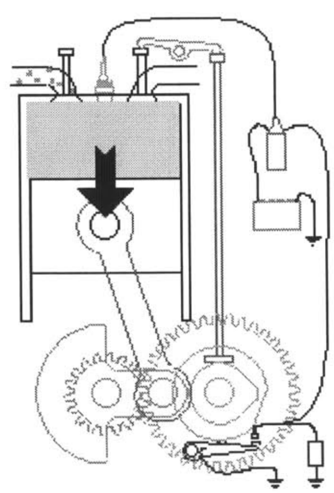


Fig. 8 – Power stroke

At the top of the compression stroke the spark plug fires, igniting the compressed fuel. As the fuel burns it expands, driving the piston downward.

Exhaust

At the bottom of the power stroke, the exhaust valve is opened by the cam/lifter mechanism. The upward stroke of the piston drives the exhausted fuel out of the cylinder.

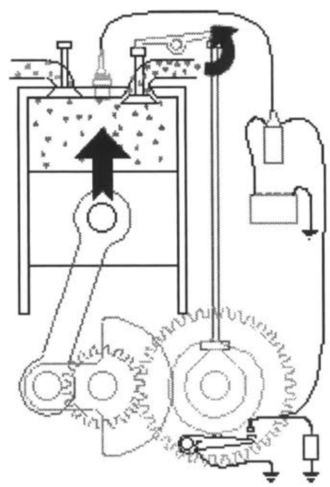


Fig. 9 – Exhaust stoke

Larger four stroke engines, like the ones used in automobiles, include more than one cylinder, have various arrangements for the camshaft (dual, overhead, etc.), sometimes feature fuel injection, turbochargers, multiple valves, etc. None of these enhancements changes the basic operation of the engine.

The parts of the engine

As a result of the four-stroke cycle, in each cylinder a piston slides up and down. One end of a connecting rod is attached to the bottom of the piston by a joint; the other end of the rod clamps around a bearing on one of the throws, or convolutions, of a crankshaft; the reciprocating (up-and-down) motions of the piston rotate the crankshaft, which is connected by suitable gearing to the drive wheels of the automobile.

The top of the cylinder is closed by a metal cover (called the head) bolted onto it. Into a threaded aperture in the head is screwed the spark plug, which provides ignition. The openings in the cylinder head through which the gasses enter and exit are called ports. The intake port admits the air-gasoline mixture; the exhaust port lets out the products of combustion. A mushroom-shaped valve is held tightly over each port by a coil spring, and a camshaft rotating at one-half engine speed opens the valves in correct sequence.

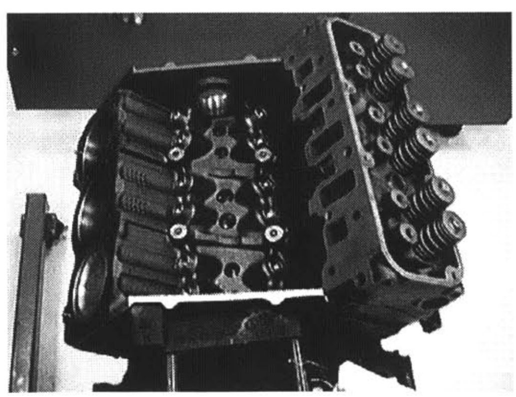


Fig. 10 – Engine subassembly, shows V engine block and one cylinder head with valve springs[8]

[8] Source: http://www.thinkythings.org/

Many other components support engines in delivering their function. The ones mentioned are relevant for us because they happen to be located in the cylinder head or they are intimately related to it. As one can gather from understanding the complex processes that take place in an engine, the cylinder head is related to the core processes in an internal combustion engine, since it is in this structural part where there are located most of the features used to complete the fundamental engine cycle.

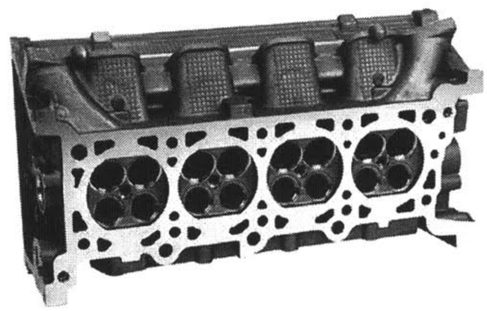


Fig. 11 – Aluminum cylinder head [9]

The cylinder head

As briefly explained, in an internal combustion engine, the cylinder head sits atop the cylinders and consists of a platform containing most part of the combustion chamber and the location of the valves and spark plugs. The top half of the cylinder head contains the camshaft in an overhead cam engine, or another mechanism (such as rocker arms and pushrods) to transfer rotational mechanics from the crankshaft to linear mechanics to operate the valves.

[9] Source : Nemak, S. A.

Internally the cylinder head has passages for the fuel/air mixture to travel to the inlet valves from the intake manifold, for exhaust gases to travel from the exhaust valves to the exhaust manifold, and for antifreeze to cool the head and engine. The number of cylinder heads in an engine is a function of the engine configuration. A V engine usually has two cylinder heads, one at each end of the V. A straight or inline engine has only one cylinder head.

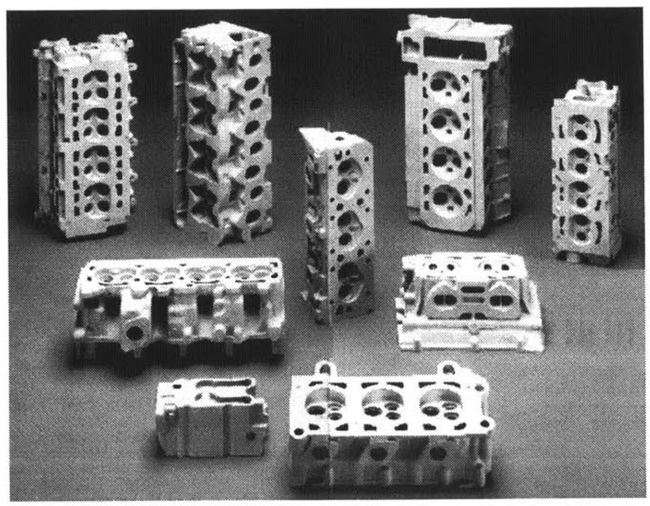


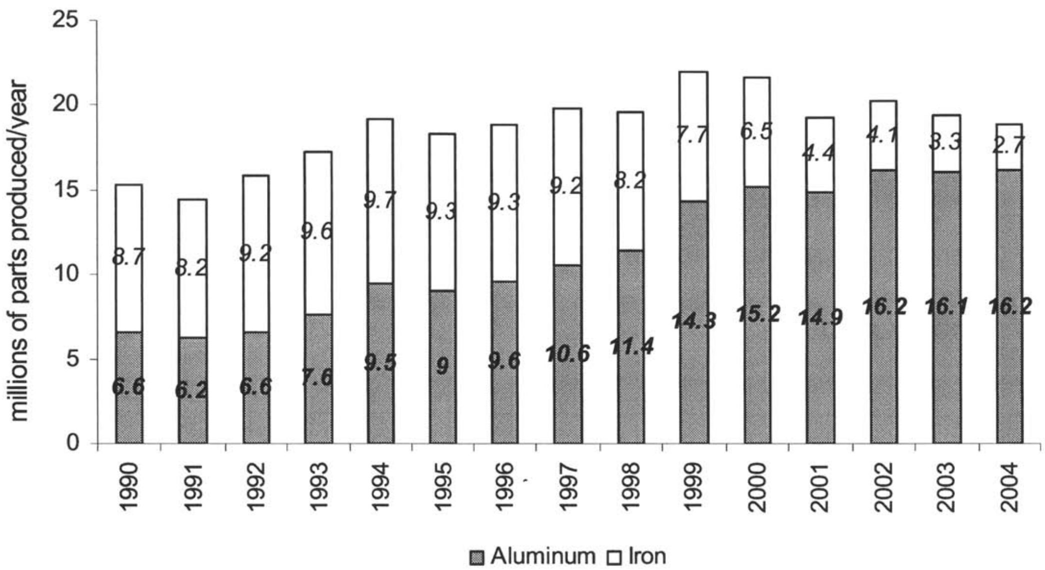
Fig. 12 – Aluminum cyinder heads of various designs.[10]

The cylinder heads are castings having numerous machined surfaces to provide a precision fit to mating parts.[11] In the past they used to be made mostly out of iron. Nowadays, the material of choice is aluminum alloys, although there are still a few models in the market made of iron. This trend began in the early 1970s in Japan and Europe with the pressure for lighter and more efficient vehicles. Figure

[10] http://images.google.com/
[11] http://www.carcarecouncil.org/

13 shows the dramatic rate of material replacement that the U.S. automakers experienced, particularly during the 90's.[12]

Fig. 13 – Material used by the American 'Big 3' in the cylinder heads specification[13]



The cylinder head is key contributor to the performance of the internal combustion engine, as the shape of the combustion chamber, inlet passages and ports (and to a lesser extent the exhaust) determines a major portion of the volumetric efficiency and compression ratio of the engine.

How cylinder heads are produced

As already mentioned, most cylinder heads are made of alumminum alloys. The processes for producing aluminum castings vary depending on the mechanical properties and dimensional characteristics of the product. For manufacturing aluminum cylinder heads, the processes most widely applied are the following.

---

[12] Source : Landin (2004)

[13] Source : Nemak, S. A.

Permanent (or semi-permanent) mold casting

This process receives its name after the type of mold used as pattern to give shape to the casting. It is called permanent mold because it is made out of steel and a large number of castings can be produced with one single mold. In the case of semi-permanent molds, the outer faces of the castings are shaped using the patterns in the permanent mold while the internal cavities and figures are made using sand cores. Sand cores are not permanent, as they are destroyed once the casting is made. The sand used for the cores can be treated in order to be re-used.

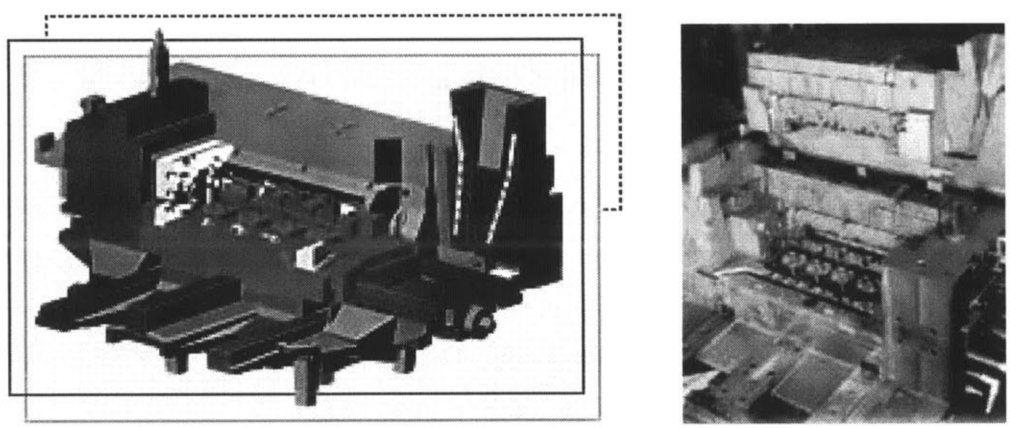


Fig. 14 – Left, model of semi permanent mold for cylinder head casting, features drag with combustion chambers pattern and side slide with pouring sprout. Right, actual appearance of the same kind of mold (note that they are for different castings).[14]

Permanent mold castings are usually gravity-fed and pouring rate is relatively low, but the metal mold produces rapid solidification. Other feeding processes like low pressure die casting are also applied in the industry. Permanent mold castings

[14] www.uribesalgo.com, www.fataaluminium.com

exhibit excellent mechanical properties. Castings are generally sound, provided that the alloys used exhibit good fluidity and resistance to hot tearing.

Mechanical properties of permanent mold castings can be further improved by heat treatment. If maximum properties are required, the heat treatment consists of a solution treatment at high temperature followed by a quench and then natural or artificial aging. Sometimes, air or water cooling lines are implemented in the molds in order to manipulate solidification direction and rates thus providing the casting with improved mechanical properties. This can eliminate the need for posterior heat treatment.

Sand casting

Sand casting involves the forming of a casting mold with sand. The sand mold, also called package, is formed around a pattern using a mixture of sand with the proper bonding agent. Then the pattern is removed, leaving a cavity in the shape of the casting to be made. If the casting is to have internal cavities or undercuts, sand cores are used to make them.

Molten metal is poured into the mold, usually by means of a low pressure pump that injects molten aluminum in the package and after it has solidified the mold is destroyed in order to remove the casting.

Casting quality is determined to a large extent by foundry technique. Proper metal-handling practice is necessary for obtaining sound castings. Complex castings with varying wall thickness will be sound only if proper techniques are used.

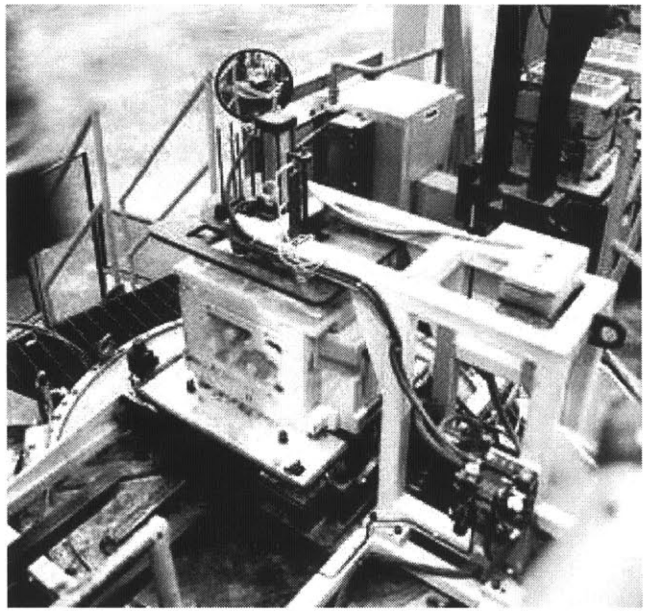


Fig. 15 – Sand casting. The sand package lies over a base (called pallet) having an opening aligned with the feeding coming from the low pressure furnace below it.[15]

The picture in Fig. 15 corresponds specifically to the proprietary *Nemak Low Pressure Precision Sand (NLPPS)* casting process. It is mostly used for making aluminum engine blocks, but it is also used in the manufacture of engineering prototypes of aluminum cylinder heads.

Cylinder head failures

The main enemy of the cylinder head is overheating.[16] Overheating can warp aluminum cylinder heads and contribute to head gasket failure, the most common engine failure associated with the head. Other failures are cracks, which can be caused by mechanical fatigue, thermal fatigue or a combination of both, and hot spots. Hot-tiers, porosity and surface roughness are most commonly treated as casting defects, and are usually handled by the manufacturers.

[15] Source: Nemak, S. A.
[16] http://www.carcarecouncil.org/

Head gasket failure

To seal properly, the finish on the face of the cylinder head and block deck must be relatively flat, smooth and clean. Warping on either surface, deep scratches, corrosion, pitting, gouges, excessive roughness or waviness can all reduce a gasket's ability to seal and allow combustion gases and/or coolant to leak.[17]

The cylinder head of an engine actually moves on and against the deck of the engine block. This is due to the expansion and contraction that the cylinder head experiences as a result of temperature changes during operation. While the head is clamped down, the clamping pressures being applied by the fasteners vary as the temperature of the cylinder head changes. Additionally, the pressures of combustion act in opposite direction, trying to lift the head off the deck. If too much expansion occurs, the fastener holes may over stretch thus losing clamping pressure to support the gasket and causing gasket failure. [18]

Other failures related to engine overheating

Other failures that may occur when an engine overheats are cylinder heads cracks (especially if someone dumps cold water into the radiator in an attempt to "cool off" the engine). In addition, combustion chambers can become so hot that a spark is no longer needed to ignite the fuel, leading to a condition known as "pre-ignition" where the engine misfires and runs erratically. Air/fuel mixtures are upset, and gasoline becomes less able to resist detonation. Oil thins out and is less able to protect the engine's internal components against friction and wear.

[17] http://www.federal-mogul.com/
[18] http://www.racecarservice.com/

Wear

The valve seat portions of a cylinder head are very liable to wear, because they are repeatedly impacted by the intake or the exhaust poppet valves while the internal combustion engine is in operation, while simultaneously being exposed to extreme conditions of temperature and shock and gas abrasion and the like caused by the explosion of air-fuel mixture in the combustion chambers of the engine.[19]

Aspects of robustness in cylinder heads

Upon understanding these failures, one can conclude that among major factors of noise for an operating cylinder head is the heat, or engine temperature. Hence, a very important robustness feature in cylinder heads is to be related with resistance to high temperatures. Additionally, by analyzing how a cylinder head contributes to the engine functionality, it can be realized what are the most relevant areas of the part design that will contribute to the overall system robustness. It is noticeable that being the combustion practically the central function of an engine of the type we analyze in this document, the portion of the cylinder head that contributes to such operation should receive particular attention when looking into design strategies to increment system reliability.

In the following chapter, a summary of the evolution in terms of robustness that the cylinder head has experienced over the last couple of decades is presented. From the more than 8,000 patents of inventions applied to engines that are related in some way to the cylinder head in the last 20+ years and disclosed by

[19] US Patent 4723518

the United States Patent and Trademark Office, the author has selected those that are relevant to improvements in robustness of the cylinder head or improvements in reliability of the engine that directly affect the design of the cylinder head.

That is the case of the inventions related to different configurations of combustion chambers and structural enhancements of the cylinder head to resist operational conditions.

Attention is also provided to a few cases of robustness inventions that are developed in parallel to the cylinder head evolution in order to become the state-of-the-art at some point. This is done in order to illustrate the fact that some robustness inventions, even when they contribute to the increased robustness of the product, may encounter barriers to application due to the disruptive nature of the invention or to the lack of robustness and/or reliability in aspects of the invention application per se.

Chapter

3

Evolution of the engine cylinder head

Robustness inventions related to cylinder heads

The present chapter is divided in three sections. The first two are defined according to the classification of robust design strategies formulated by the author in Chapter 1. According to such classification, robust design strategies can attempt to either increase system reliability or improve component robustness. The third explains the current state-of-the-art of the product.

On the first section a number of inventions affecting the cylinder head combustion chamber configuration are analyzed. Such inventions are relevant to robust design in the way that they correspond to design strategies to increase reliability of one engine function in which the cylinder head is involved. It is important to realize that these inventions usually do not have the explicit intent to increase the robustness of the part itself, but rather to increase the ability of the part to handle variability in order to provide means for improvement of a function of the whole system, in this case the combustion.

The second section includes a more straightforward kind of robustness inventions, analyzing those that are intended to improve the ability of the part to endure operational conditions providing robustness to the component per se.

From the database used for this research, most of the inventions falling under this category were related to structural improvements, some localized and some applied to the overall cylinder head, thus the examples selected to illustrate the author's conclusions correspond to this kind of improvements.

Finally, in the last section the state-of-the-art concerning commercial cylinder head designs is exposed. This is made with the purpose of comparing the inventions in the context of what has successfully being applied to the actual product and what remains to be improved before becoming a common art.

Combustion Chambers

The combustion chamber is the cavity formed by the engine cylinder and the cylinder head – as depicted in Fig. 12 – but also is commonly referred to as the surface in the cylinder head that tops the cylinder and that supports the valves and spark plugs. It can be considered as the very heart of the engine, since the fundamental processes of the engine cycle – intake of air and fuel, combustion, and exhaust of combustion products – occur inside it with every stroke. During the compression stroke, when the piston is in the highest position, the remaining volume available for the compressed fuel/air mix surrounding the spark plug is provided by this surface in the cylinder head. [20]

[20] This is true for engines with flat pistons. Some designs applied to direct injected engines use pistons with cavities in the crown thus the remaining volume when the compression stroke is complete is the sum of the volume of the cylinder head combustion chamber and the piston crown.

Hence, one of the critical quality characteristics in a cylinder head is the combustion chamber volume, in addition to the mechanical properties and dimensional specifications.

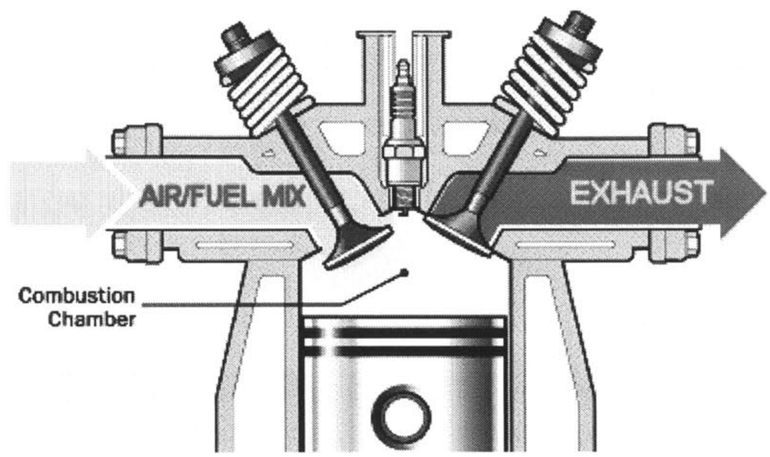


Fig. 16 – Diagram showing combustion chamber[21]

The combustion chamber geometrical characteristics are practically unique to each engine model. OEMs feature all kinds of designs from two to four valves per cylinder with one or two spark plugs applied to their commercial models and most rarely up to 6-valve arrangements per cylinder.

In designing combustion chamber configurations, the requirements of good fuel consumption, stable combustion, and good exhaust gas quality must all be considered. Robustness is regarded as a very relevant influence in combustion chamber design (and in cylinder heads design in general) due to the fact that this surface is continuously exposed to extreme conditions – high temperature, pressure, gas abrasion, etc. – during the engine operation.

[21] http://www.boostcontroller.com/

As a result of the research done for preparing the present thesis, it has been found that in addition to inventions oriented to increase cylinder head resistance to extreme and changing operating conditions, many of the robustness inventions that affect the combustion chamber design are intended to increase reliability of one engine function in particular: the combustion.

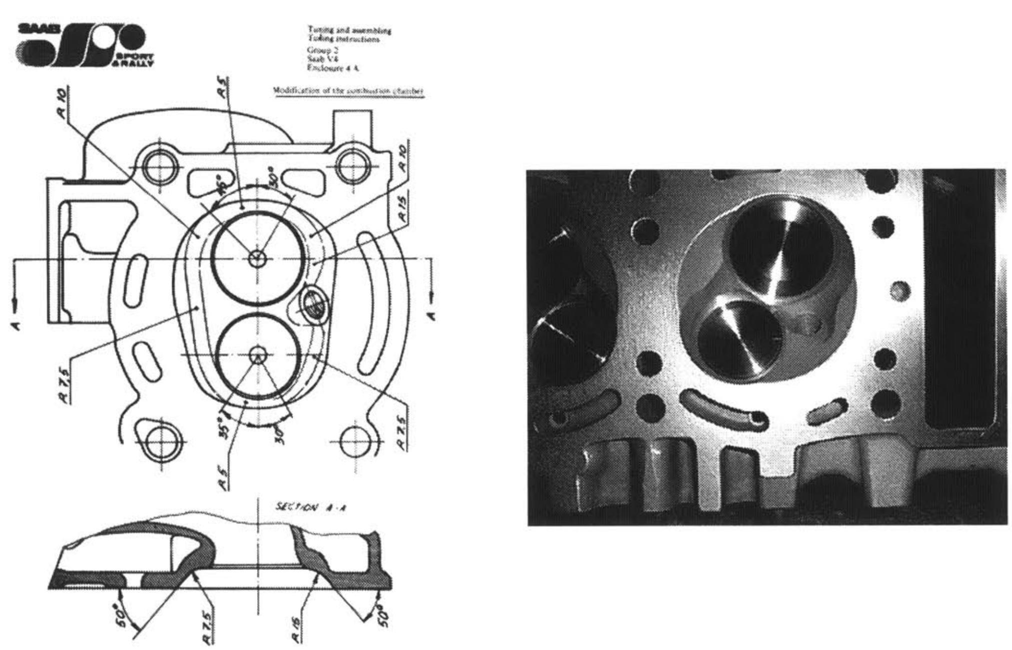


Fig. 17– Left, drawing of the combustion chamber portion contributed by cylinder head. These feature a single valve for intake and exhaust respectively plus a threaded hole for the spark plug between valves. Other designs feature multiple valves.[22]

As already explained in past sections of this document, combustion occurs in the combustion chambers as a result of the ignition of the compressed mixture of air and fuel. The Otto cycle, in which the principles of operation of internal combustion engines rely, is based on certain assumptions of ideality made around the combustion process:

[22] http://sg.geocities.com, http://images.google.com

1) the fuel/air mixture is perfectly homogeneous and stoichometric,

2) the combustion is complete the only products of it being CO_2 and water, and,

3) the operational conditions do not change over the period of operation of the engine.

None of these assumptions actually occurs. Fuel injection systems provide imperfect mixtures and inconsistent flows (variability in fuel supply); flame propagation degrades and combustion rates aren't the needed in order to allow for complete combustion (variability in combustion rates); besides, excess in fuel dosage above the stoichiometric ratio also provokes unburned gas remainder and combustion sub-products to be present in the exhaust gases, contributing to the deterioration of other engine parts such as the piston and the valves (variability in combustion process performance).

In addition, the operational conditions are not constant. Engines start running cold and heat up as they continue operating, depending only on auxiliary cooling systems to maintain temperatures within desired ranges. Different parts of the engine wear with time and use, also contributing to changes in the operation conditions. These are only a few of the noises that affect the combustion process in an internal combustion engine.

The noise factors mentioned, among others, contribute to the lack of reliability in executing the combustion process. From the analysis of patents related to cylinder head robustness, it is evident that this is a problem that design engineers have been aware of for a long time. During the entire timeframe of the research (between 1985 and 2005), inventors consistently claim novel ways of eliminating the effect of one or more of such noise factors.

For instance, a variety of combustion chamber configurations have been proposed over time in order to induce/control the behavior of the gas inside the combustion chamber to minimize the effect of variability in a series of conditions such as the supply of fuel, the flow patterns of the fuel/air mixture, and the mix quality.

The relevance of the "combustion completeness" issue to engine robust design is unquestionable and affects greatly the cylinder head design. It is also evident that it is an issue to which no definite solution has been found, since, as per the patent database, every OEM is still looking into new ways of addressing it.

Fig. 18 depicts a diagram summarizing the trends on research and development that influenced the evolution of combustion chambers in the past 20 years from the robustness standpoint. It is noticeable that all along such timeframe, the manipulation of the gases inside the combustion chamber remains being the robustness strategy of choice in many inventions, yet it appears that it has not been achieved a reliable method for consistently doing it, at least not one that is applicable to every model.

The analysis that follows features a selection of patents that are related to robustness inventions which are intended to be representative of the trends followed by the generality of firms and inventors in addressing robustness issues affecting combustion chambers over different periods of time.

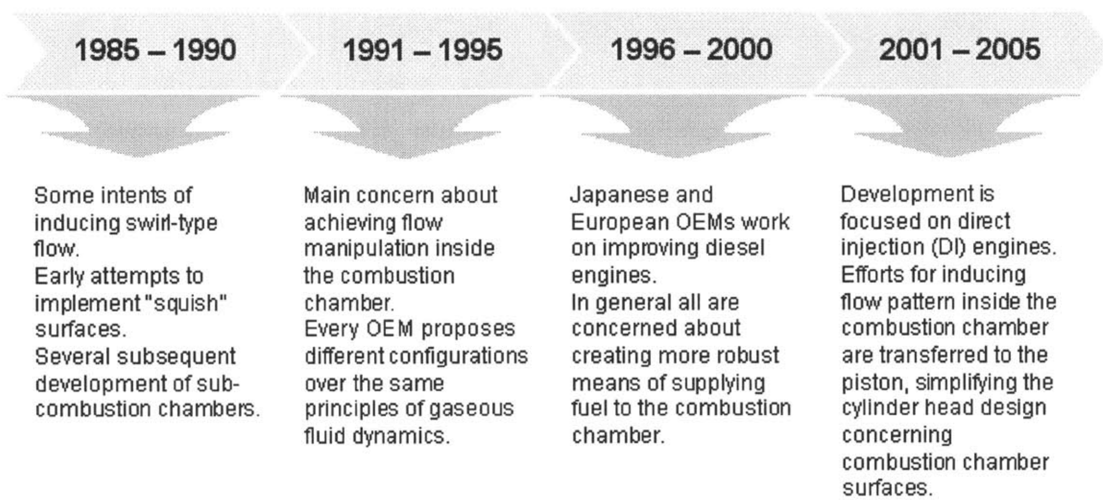


Fig. 18 – Evolution of combustion chamber design on cylinder heads in order to improve reliability of combustion process in engine.

1985 - 1990

During this period, and even prior to it, a lot of activity towards defining the "right" shape of the combustion chamber takes place. Almost every OEM claims a different combustion chamber configuration that induces *swirl-flow*, turbulence inside the combustion chamber, or favors the completeness of the combustion by allowing a better mix of the intake gases.

That is the case of Toyota's invention disclosed in US patent number 4 367 707, titled *"Combustion chamber for internal combustion engine"*. It refers to a combustion chamber (refer to Fig. 19) having an approximately semi-spherical shape and single "squish" area (A) being formed on one side of the peripheral inner wall of the cylinder head. The invention proposed the intent for an "optimum" arrangement of valves and spark plug in combination with what's known as "squish" area, formed when the correspondent surfaces in the piston and the cylinder head met during the compression stroke.

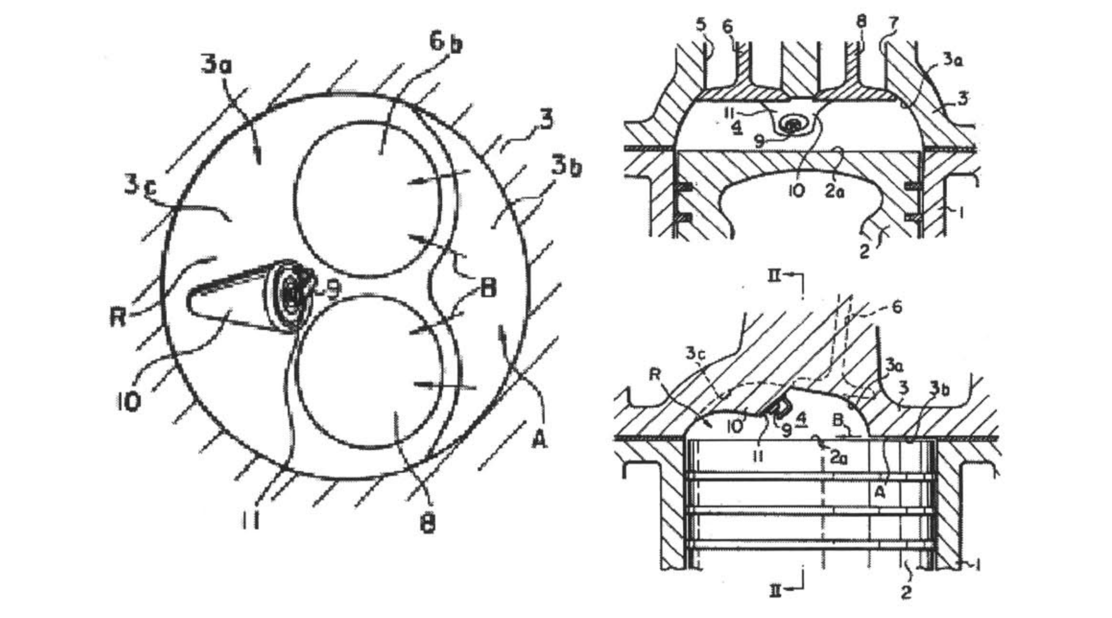


Fig. 19 – Excerpt of drawings depicted in patent 4 367 707

"In order to increase the burning velocity in the combustion chamber of an engine, there has been known a method of creating a strong turbulence in the combustion chamber by the squish flow which is spouted out from the squish area [A] formed between the inner wall of the cylinder head [3b] and the top face of the piston [2a]. However, as a result of many experiments conducted by the inventor, it has been proven that the arrangements of the squish area and the spark plug have a great influence on the burning velocity in the combustion chamber."

In 1998, Glotur Trust disclosed a similar approach in patent number 4 759 323, titled *"Combustion engine with one or more 'squish' spaces between the piston and the cylinder head"*. The proposed design features specific characteristics in the cylinder head surfaces around the valves (in addition to some changes in the design of the crown of the piston, not relevant for our study) that allow appropriate combustion of gases *even when air in excess of up to 30% is present*. It also claims inducing combustion characteristics such that the combustion temperature is lower than under regular conditions, favoring less severe conditions of operation.

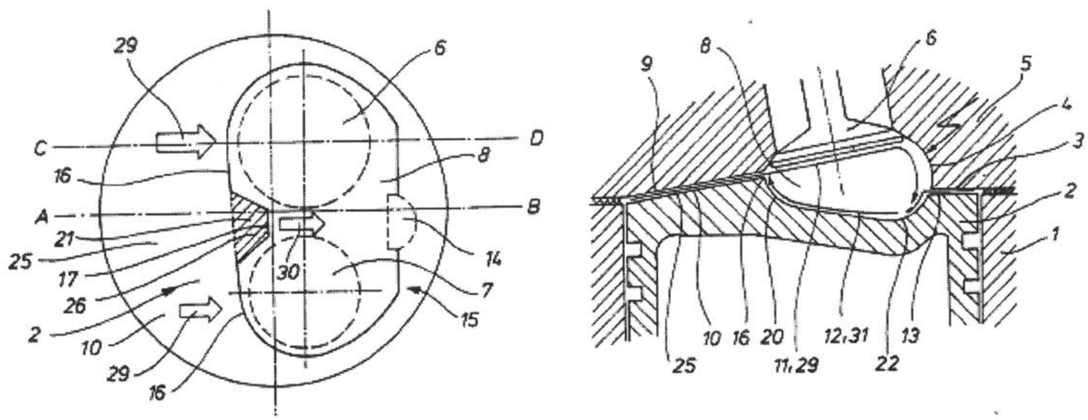


Fig. 20 – Excerpt of drawings depicted in patent 4 759 323

"A feature of the present invention is, therefore, that adjacent to the previously-known "squish" space flow, a further central "squish" space flow is created which is led directly onto the spark plug. In this way, ... a greater "squish" path is created for the air-fuel mixture by this central "squish" space than as compared to the previously known "squish" space flow. ... By means of the differing speeds of rotation in the area of the spark plug in comparison to the neighbouring areas, the combustion process is, among others, accelerated in this way in that the flow vortices have differing speeds of rotation and the central vortex rotates faster than the neighbouring outer ones. ... swirling them so that they quickly and intensively mix with the ignition jet and burn through."

It is worth recognizing that this kind of design favor the manufacturability of the cylinder head by simplifying the design of the combustion chamber thus the design of the pattern to cast them. Additionally, less critical characteristics relying in the cylinder head casting allow for less control needed in the casting process.

During the same period of time, Ford Motor Company proposes an alternative approach for allowing proper mixture and compression of the combustion gases by introducing a swirl-type inlet. They use a significantly shorter squish surface of only between 5 and 15% of the cross-sectional area, but in exchange they add odd tangential surfaces to the rest of the combustion chamber that will contribute to induce the gases to move as desired.

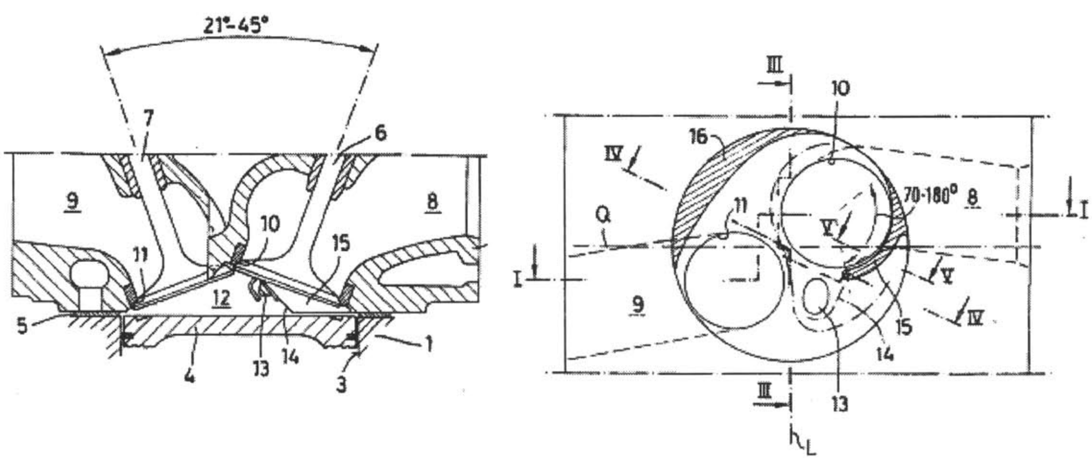


Fig. 21 – Excerpt of drawings depicted in patent 4 706 622

"The object of this invention is to design a mixture-compressing internal combustion engine, ..., in such a way that it has a more compact combustion chamber than the prior art, and one that has an increased lean-mixture combustibility. ... A swirl inlet passage is provided that acts upon the air-fuel mixture to supply it to the inlet valve opening tangentially. ... As a result of all this, a stabilization of the inlet swirl imparted to the air-fuel mixture is achieved in the immediate vicinity of the spark plug, and a stable combustion action is attained with an extremely lean mixture preparation."

The details of this invention are disclosed on US patent number 4 706 622, titled *"Engine combustion chamber construction".* The proposed design results in increased complexity for the manufacturing process due to the characteristics of the required patterns.

This particular kind of design shows propensity to casting defects like scratching or tiring occurred during drafting and also dimensional inaccuracies that are difficult to control in the foundry.

The European OEM SAAB, claims in patent number 4 706 623 *"Cylinder head for an internal combustion engine"* that its combustion chamber design provides the adequate geometrical characteristics for inducing swirl flow with a totally different configuration of combustion chamber compared to those already exposed, applied in a 4-valve cylinder head, requiring specific positioning of the valves, especially the intake ones, in order to create swirl effect. This invention also highlights the shape that the ducts.

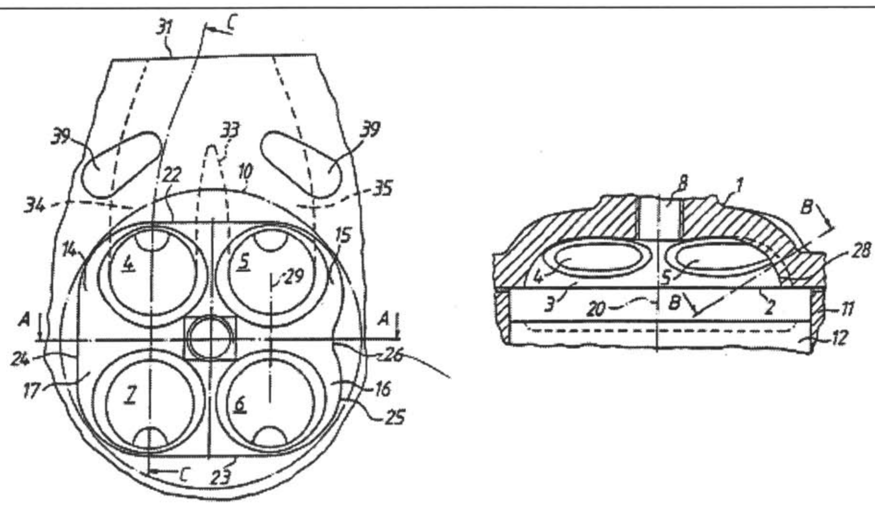


Fig. 22 – Excerpt of drawings depicted in patent 4 706 623

"With the object of facilitating gas flowing into the combustion chamber to swirl about the cylinder axis, the invention is essentially distinguished in that the interior surface of the combustion chamber between an inlet port and an exhaust port is implemented with a swirl-generating means... To reinforce the swirl generation, the inlet duct, ... , is formed to give the gas a direction...

Also during the same period (and the following too), a number of patents attempting to provide robustness to a specific combustion chamber design appear. This combustion chamber design refers to the creation in the cylinder head casting of what is called a "sub-combustion chamber". There are records of proposed configurations of such sub-combustion chamber from the previous decade, but none seems to had been successfully applied due to different drawbacks concerning component robustness and, especially, manufacturability.

Toyota claims one of the several original designs for a sub-combustion chamber in the US patent 4 041 909 *"Internal-combustion engine having a sub-combustion chamber"* in 1977, indicating the advantages that the design offered regarding superior ignitability and a faster speed of combustion, resulting in better engine efficiency and an favorable rate of fuel consumption. This development implies a series of changes in design, the most important being the addition of a *sub-chamber element being forcedly fitted into a recess arranged in said cylinder head.* [23]

Posterior inventions related to this particular design attempt to increase its robustness by implementing changes in the material for the sub-chamber

[23] US Patent 4 041 909

element (US patent 4 714 062 *"Sub-combustion chamber of an internal combustion engine"*, US patent 4 899 707 *"Engine cylinder head with pre-combustion chamber using ceramic insert"*), or by designing means for mounting such element (US patent 4 699 102 *"Structure for mounting sub-combustion chamber in an internal combustion engine"*, US patent 4 704 998 *"Mounting structure for ceramic sub-combustion chamber"*).

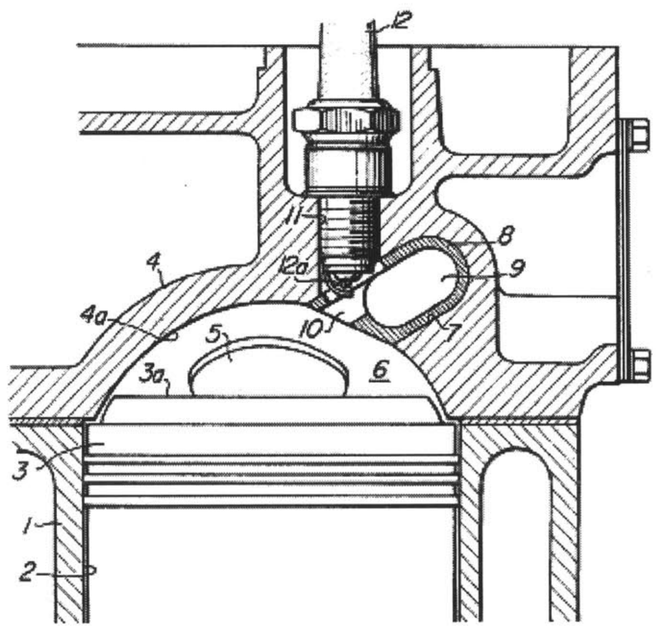


Fig. 23 – Excerpts of drawings depicted in patent 4 041 909

This particular case will be further discussed in other sections of the present document to analyze the convenience of developing robust design derived from inventions not yet fully applied.

1991 – 1995

In the period from 1991 to 1995, the design efforts around combustion chambers in cylinder heads continued to work in the manipulation of gas flow inside the combustion chamber but taking into account that not only turbulent flow is desired but also that such turbulent flow remains around the spark plug (or ignition device) at the moment of ignition thus ensuring fast flame propagation.

By analyzing the next group of patents it will be evident that a transition is taking place towards novel robustness strategies that seek increasing combustion reliability. Inventions vary as designs compromise a lot more than only the shape of the surfaces in the combustion chamber that are in contact with the gas. As a result, they turn out to be of more complex implementation. They usually affect more than one part of the engine and more than one structure in the cylinder head, like for instance combustion chamber and intake ports shape, valves positioning and spark plug location. The goal remains as increasing the reliability of the combustion process.

Mazda, in US patent number 4 951 642 *"Combustion chamber of internal combustion engine"*, indicates that by allowing the gas to be compacted around the spark plug soon enough before the ignition, the appropriate flame propagation and combustion speed can be obtained. It also claims to improve the exhaust gas evacuation and the intake gas mixture quality by providing the appropriate positioning of the valves and spark plug and the appropriate surface shape, resulting in a presumably more robust design.

All this can be accomplished by 1) a combustion chamber structure defined by the cylinder head and the piston, 2) an exhaust recess for an exhaust port, 3) an intake recess smaller than the exhaust recess in volume or diameter, 4) an extended wall portion formed at a boundary portion between the intake and exhaust recess, and, 5) an ignition plug arranged in the vicinity of a tip end of the extended wall portion.

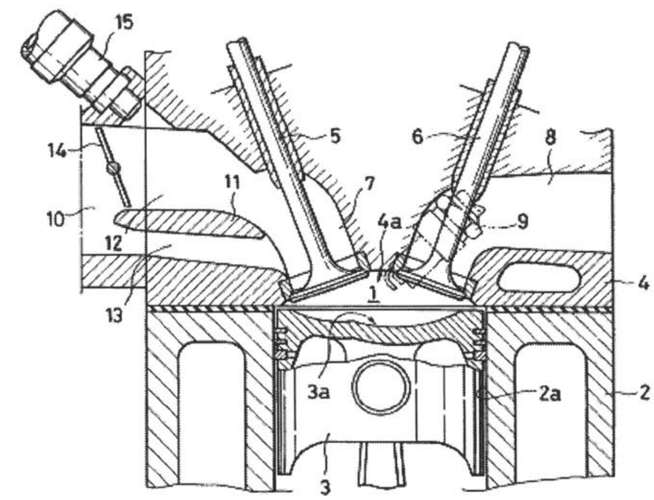


Fig. 24 – Excerpt of drawings depicted in patent 4 951 642

"...it should however be noted that [by the prior art] a combustible mixture cannot be supplied sufficiently around the ignition plug during a compression stage causing a deterioration of a flame propagation. In addition, an exhaust gas tends to stay around the ignition plug during an intake stage and a hydrocarbon compound may deposit on the plug because of a poor scavenging effect so that a combustion property may be eventually deteriorated. It is therefore a primary object of the present invention to provide a compact structure of a combustion chamber of an internal combustion engine in which an improved combustion property of the engine can be obtained."

US patent 5 390 634, *"Internal combustion engine having high-performance combustion chamber"*, assigned to S & S Cycle Inc., is concerned to minimize the problem of autoignition (noise). Autoignition is frequently triggered in high compression ratio engines by the normal process of ignition. The spark plug ignites the compressed fuel-air mixture, and as the flame front begins to travel from the spark site through the chamber, the fuel-air mixture in the cylinder farthest away from the spark plug is additionally compressed by the expansion of the gases behind the flame front. The mixture is already at high temperature and pressure due to its previous compression, additional causes further temperature and pressure increase, providing the conditions for autoignition.

While autoignition may be decreased by using a fuel with a higher ignition temperature (as it is the case of the high octane fuels) it is also helpful to increase the speed of combustion, leaving little time for autoignition to occur. This invention proposed to increase such speed by providing turbulent flow conditions inside the combustion chamber just before and during the ignition.

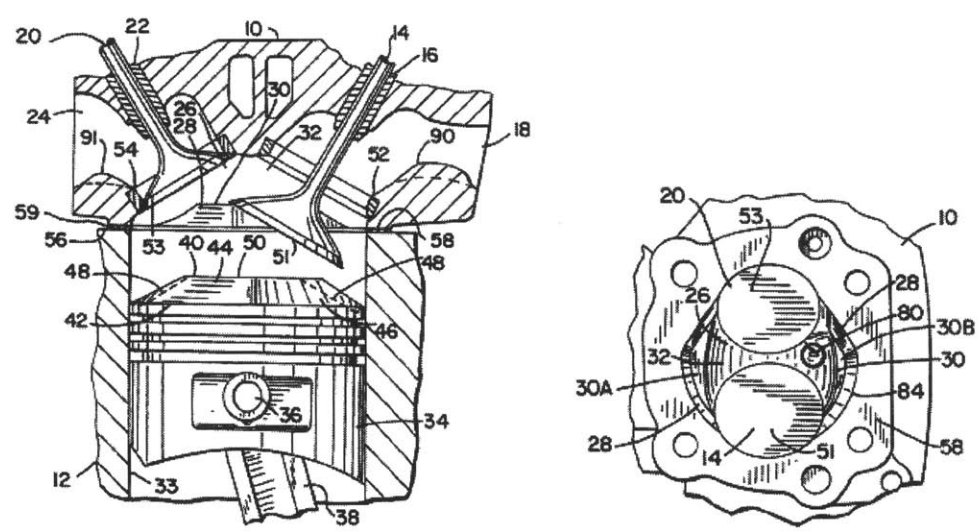


Fig. 25 – Excerpts of drawings depicted in patent 5 390 634

> *"Autoignition is present in almost all internal combustion engines to some extent, and is difficult to totally eliminate. The goal of high-performance engine design is to minimize autoignition to such an extent that it no longer harms the engine's performance or its structure, while at the same time obtaining the highest compression ratio possible."*

A design from Toyota, disclosed during this period in US patent number 5 115 774, *"Internal combustion engine"*, is an early example of what eventually has become the state-of-the-art regarding fuel injection. This design works providing specific shapes on the surfaces that form the combustion chamber but in addition considers that the fuel/air mixture is injected directly to the combustion chamber by means of air blast valve (refer to detail #18, Fig. 26). The prior art, showed in Fig. 24 (refer to detail #15) which is still used, contains a nozzle installed in the intake port. The fuel is injected inside the duct and arrives to the chamber through the intake valve, mixed with air.

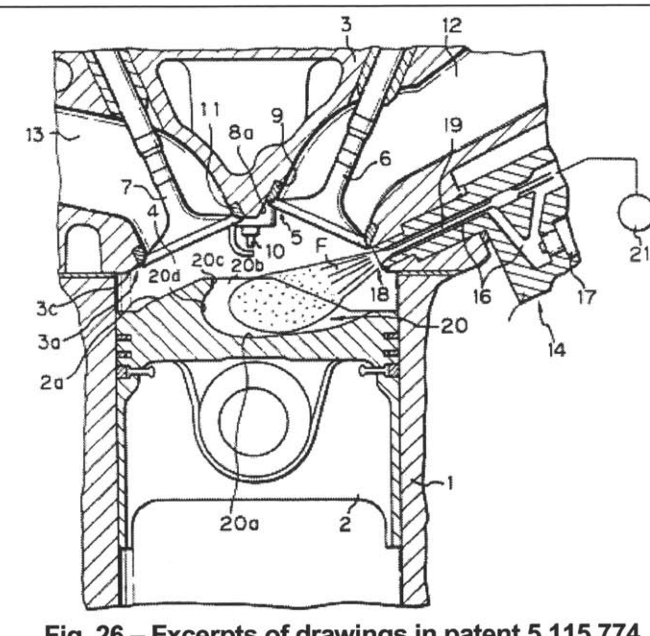


Fig. 26 – Excerpts of drawings in patent 5 115 774

"An object of the present invention is to provide an engine capable of forming a proper air-fuel mixture around the spark plug, regardless of the load under which the engine is running."

1996 - 2000

During this period, the difference in inventing strategies that the American OEMs followed compared to those that the Japanese and the European pursued become evident.

Especially, the later showed more interest in developing the diesel engine. The results can be realized from the diffusion of that type of engines in Europe while in America the state-of-the-art continues to be gasoline engines.

Diesel engines have few differences compared to gasoline engines but they are still fundamental from the standpoint of this analysis since the combustion chambers in the cylinder heads of diesel engines are flat.

The author does not consider the development on diesel engines for this analysis.

One of the few Japanese inventions related to gasoline engines that are registered in this period is Toyota's US patent number 5 649 513, *"Combustion chamber of internal combustion engine".* According to this patent Toyota realizes that the problem of adequate mixture of air/fuel in the combustion chamber is not only a matter of providing conditions favoring certain flow characteristics inside the combustion chamber, but also a matter of providing appropriate filling or intake. Toyota claims to address this by using a particular configuration of 4-valve per cylinder. Concepts proved in the past are present like the squish areas and walls around the intake valves.

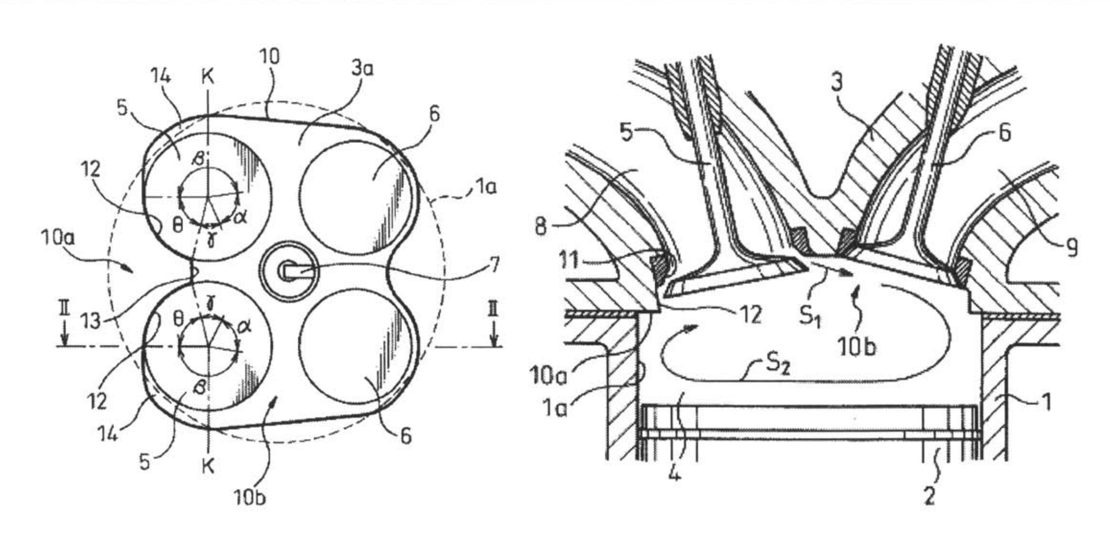


Fig. 27 – Excerpt of drawings depicted in patent 5 649 513

> *"...the object of the present invention is to provide an internal combustion engine in which a sufficiently high filling efficiency and a sufficiently strong tumble flow can be simultaneously secured."*

Later, James J. Feuling, experiments with 3-valve arrangements, disclosing what he claims to be the best configuration for that type of arrangement in US patent number 5 873 348 *"Combustion chamber system having an improved valve arrangement"*. Feuling claims that this arrangement provides adequate filling. Fig. 28 shows the preferred embodiment featuring only one spark plug. The patent drawings also include another arrangement of 3 valves with 3 spark plugs thus needing less squish areas.

> *"This invention provides a fast and uniform lean burn, permits use of a high compression ratio and lower octane unleaded gasoline and provides improved thermal efficiency. ...Yet another object is to provide a system capable of operating at high compression ratios with a variety of different fuels."*

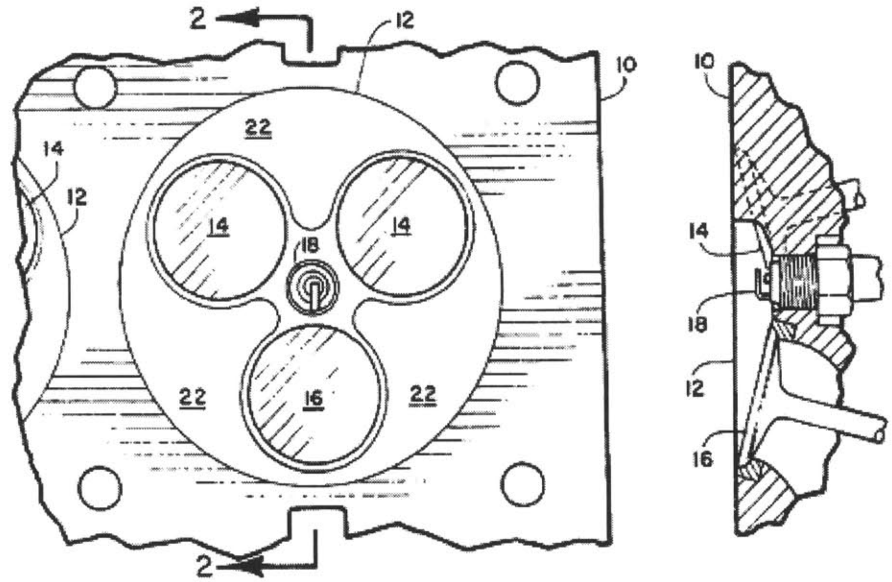


Fig. 28 – Excerpt of drawings depicted on patent 5 873 348

In 1998, following the trend of looking into more reliable means of providing the combustion chamber with the fuel needed for the combustion process, Ford Global Technologies, Inc. discloses their proprietary design of cylinder head with direct injection of fuel to the combustion chamber in the US patent number 5 785 028, *"Internal combustion engine with spark plug ignition and direct cylinder fuel injection"*. Ford explains that prior art in direct injection results unsuccessful for concentrating the compressed gas towards the piston instead that towards a surface in the cylinder head (the combustion chamber) which is cooler thanks to the water jacket provided in the cylinder head.

Ford determines that the necessary characteristics that the direct injection engine should have include a combustion chamber whose configuration induces the gases to concentrate towards the cooler area of the combustion chamber before ignition. This invention corresponds to the classic example of robust design applied to increase reliability of a new technology in order to make it more attractive to adopters.

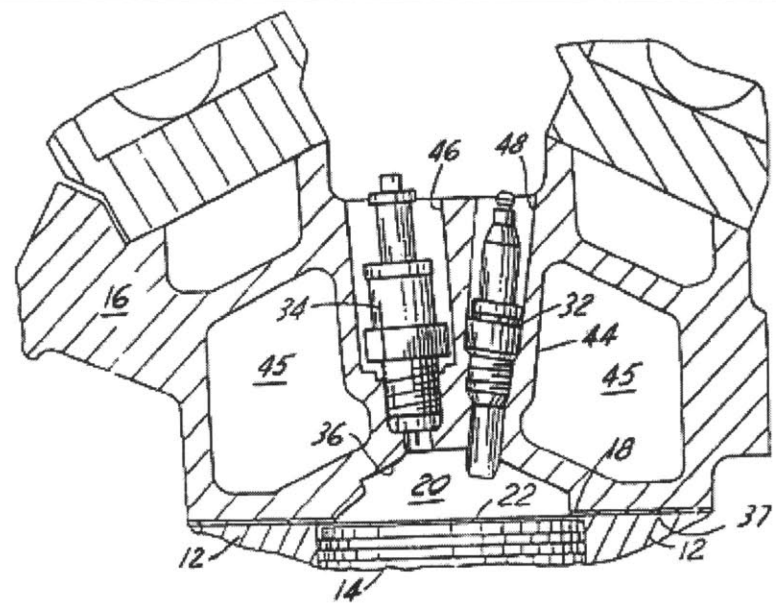


Fig. 29 – Excerpt of the drawings depicted in patent 5 785 028

> *"...An engine according to the present invention is intended to provide direct cylinder injection of gasoline without these drawbacks. This is accomplished by positioning the spark plug closer to the exhaust valves than the position of the injector with respect to the exhaust valves, and by having an asymmetric combustion chamber with a greater volume concentrated about the cooler intake valves as opposed to the hotter exhaust valves."*

2001 – Present

Development is focused on direct injected engines since 2001. Upon the successful implementation of direct injection (DI) of fuel in the combustion chamber, a number of robustness inventions have been developed in the last 5 years in order to improve this kind of engines. Practically every OEM holds proprietary designs of DI engines. A few of them are presented in this section.

Efforts for controlling or creating reliable flow patterns inside the combustion chamber are transferred to the piston. This in turn favors the cylinder head casting manufacturability since less critical areas have to be controlled in the casting process.

US patent 6 494 178, *"Combustion chamber including piston for a spark plug ignition direct injected internal combustion system"*, assigned to GM Corporation focuses on the advantages of having a considerable portion of the remaining volume in the combustion chamber at piston "top-dead center" in the piston crown.

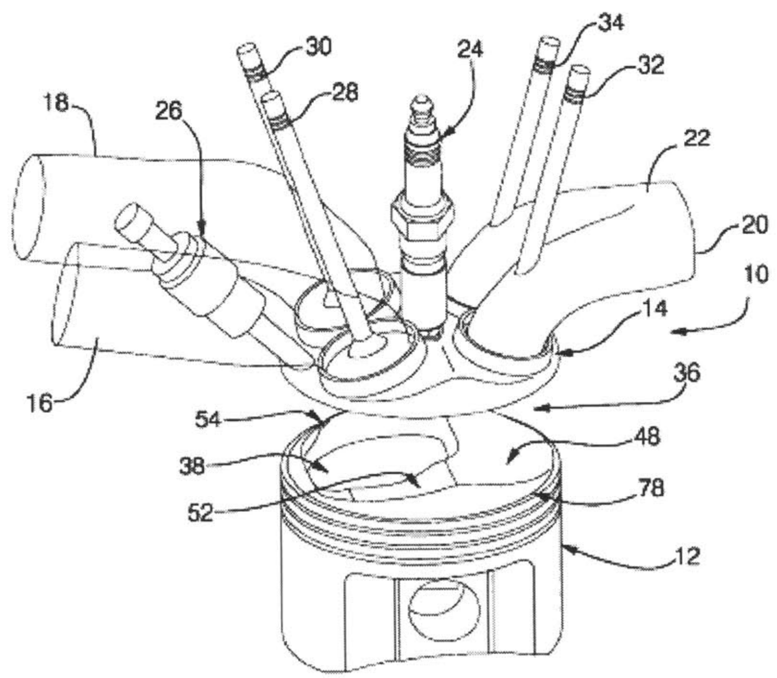


Fig. 30 – Excerpt of drawings depicted in patent 6 494 178

"It is an object of the present invention to provide an improved combustion chamber having a portion thereof defined in the piston head."

With the proposed design 50% or less of such total volume is in the cylinder head. The shape of the combustion chamber is limited to the necessary surface to house the valves, spark plug and fuel injector. This simplifies the cylinder head design from the manufacturing standpoint, making it less susceptible to casting defects thus more robust.

DaimlerChrysler focuses on defining the appropriate position of the spark plug in order to maximize flame propagation and rapid combustion in direct injected engines are per US patent number 6 575 132 *"Direct-injected spark plug-ignition internal combustion engine"*.

In the conventional direct injection gasoline engines, the combustion chamber perimeter must be precisely designed at a high expense, especially through the inner wall of the cylinder head, in order to obtain the desired hydromechanical effects to form the ignitable mixture vortex.

The conventional combustion chamber configuration with the combustion chamber shape necessary to form the mixture vortex and the spark plug necessarily arranged near the injector often cannot achieve optimum combustion or ensure the desired operating performance of the internal combustion engine.

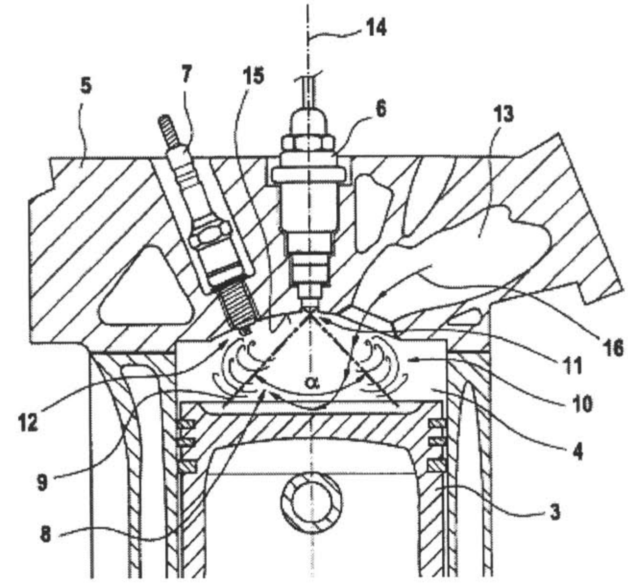


Fig. 31 – Excerpt of drawings depicted in patent 6 575 132

"In order to bring an ignitable mixture between the electrodes and to ensure an optimal operating performance of the internal combustion engine by improving the combustion process, the combustion chamber is configured so that the cone of fuel is injected in a free jet that is substantially unaffected by the perimeter of the combustion chamber, and the electrodes of the spark plug project inside a fuel vortex which emerges from the lateral surface during injection".

Hyundai proposed a totally different configuration for direct injection engines. Disclosed in US patent 6 612 282 *"Combustion chamber for DISI engines"*, Hyundai's invention refers also a simple configuration of combustion chamber in the cylinder head, changing the position of the injector (Fig. 32, detail #36) and the spark plug (detail #60) and focusing on creating turbulent flow inside the combustion chamber by means of specific shapes in the piston crown surface.

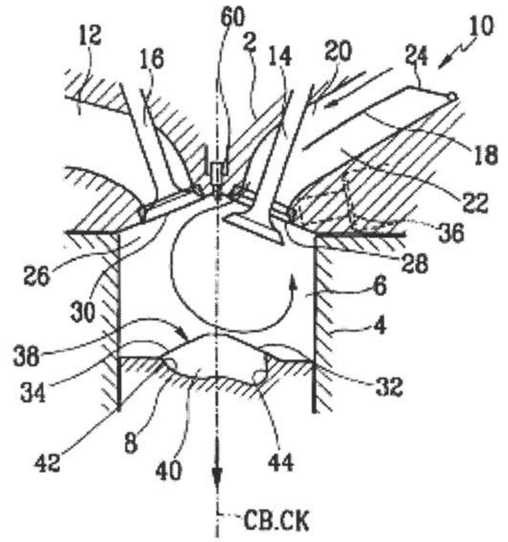


Fig. 32 – Excerpt of drawings depicted in patent 6 612 282

"...turbulent flow is generated to some extent when fuel passes from a lower portion of a cylinder head to an upper portion of the piston, and then from the upper portion of the piston to the lower portion of the cylinder head."

After this analysis, we have now an idea of the cylinder head evolution due to improvements in engine reliability. From the changes implemented in the area of the combustion chamber in order to increase reliability of the combustion process, some actually improved cylinder head robustness. In a more general sense, we will now explore the evolution in robustness of the overall structure of the cylinder head.

Overall Structure

Another aspect of the cylinder head that has obvious robustness implications is the part overall structure. Up to this point, the inventions analyzed have been related to increase reliability of a process or function delivered by the larger system where the product operates. Now we turn our attention to the development of the cylinder head characteristics that enhance the robustness of the product itself, making it less susceptible to the effects of heat, mechanical stress, and other operational conditions.

The introduction of Al-Si alloys as the material of choice for cylinder heads provided a series of advantages that contributed to the general adoption of aluminum as the material specified for almost every cylinder head. The aluminum alloys most commonly used in cylinder heads are A319 and A356 (or proprietary variants of these). These alloys exhibit good thermal and mechanical properties that make them suitable for their application on cylinder heads, while providing the most desirable characteristic of [relatively] low density. Nonetheless, they also contribute to product robustness issues derived from the ability of aluminum alloys to resist the cylinder head operation conditions.

In the case of sections of the cylinder head that are liable to wear for being subject to particularly severe operation conditions, the use of liners and inserts made out of other materials has come to solve many resistance problems that the aluminum by itself may has not been able to overcome. That is the case of the valve seats. The valve seat portions of a cylinder head are very liable to wear, because they are repeatedly impacted by the intake or the exhaust poppet valves, while simultaneously being exposed to extreme conditions of temperature and shock and gas abrasion and the like caused by the explosion of air-fuel mixture in the combustion chambers of the engine[24]. The valve seats are iron rings that are installed in the cylinder head combustion chambers by forcing them into a machined recess. Many efforts and research resources have been invested in finding a way to eliminate the disadvantages of this method and configuration (which will be explained as the specific patents are deployed) and more specifically to create a more robust bonding between the ring and the cylinder head.

In general, the use of aluminum triggered the development of many robustness inventions related to improve structural characteristics.

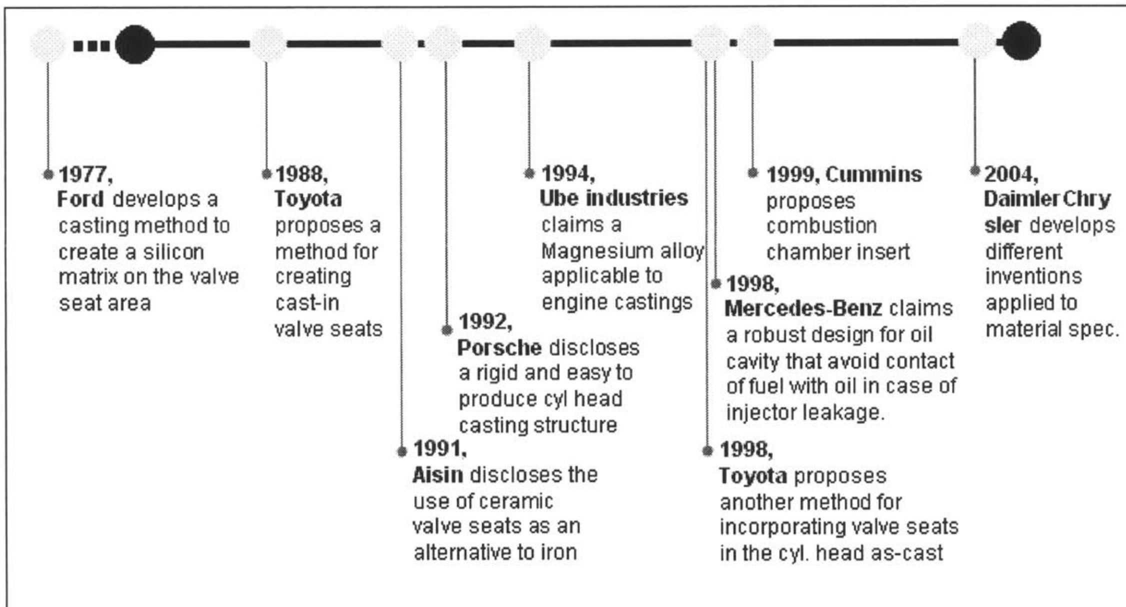


Fig. 33 - Robustness inventions timeline for cylinder head structural improvements[25]

The timeline depicted in Fig. 33 shows a sequence of selected robustness inventions related to structural improvements. Some of them concern about the valve seat issues in particular. A few more are intents to provide robustness to

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[24] US patent 4 723 518

[25] Source: USPTO patent full text and image database, http://www.uspto.gov/patft/

specific regions of the head. Others propose material alternatives to provide integral improvement to the product.

A little beyond the timeframe of the research but very relevant to illustrate the importance that aluminum's robustness issues had even before the diffusion of its application, it is the invention proposed by Ford in 1977, disclosed in US patent 4 028 062 *"Aluminum cylinder head valve seat coating transplant."* In this patent, Ford recognizes that the aluminum properties need improvement to suit the requirements of particular areas in the cylinder head. Realizing that adding more silicon to the aluminum alloy had demonstrated to be an effective way of increasing material robustness, discards the increase of the alloy silicon content as a viable alternative due to cost and manufacturing issues.

This invention relates to a process for providing a specific surface of the casting with high silicon content, thus improving thermal and mechanical properties in localized areas. Since the Si matrix is created in the casting process, the bonding is perfect and there are no problems of air insulation, which are characteristic of the conventional valve seat inserts.

The problem with this invention, though, is in the implementation in mass production of such process. Additionally, casting dimensions are not accurate enough, so the surface still needs machining to fit the valve. Since the silicon matrix is claimed to be ultra-thin, this represents complications in the manufacturing process.

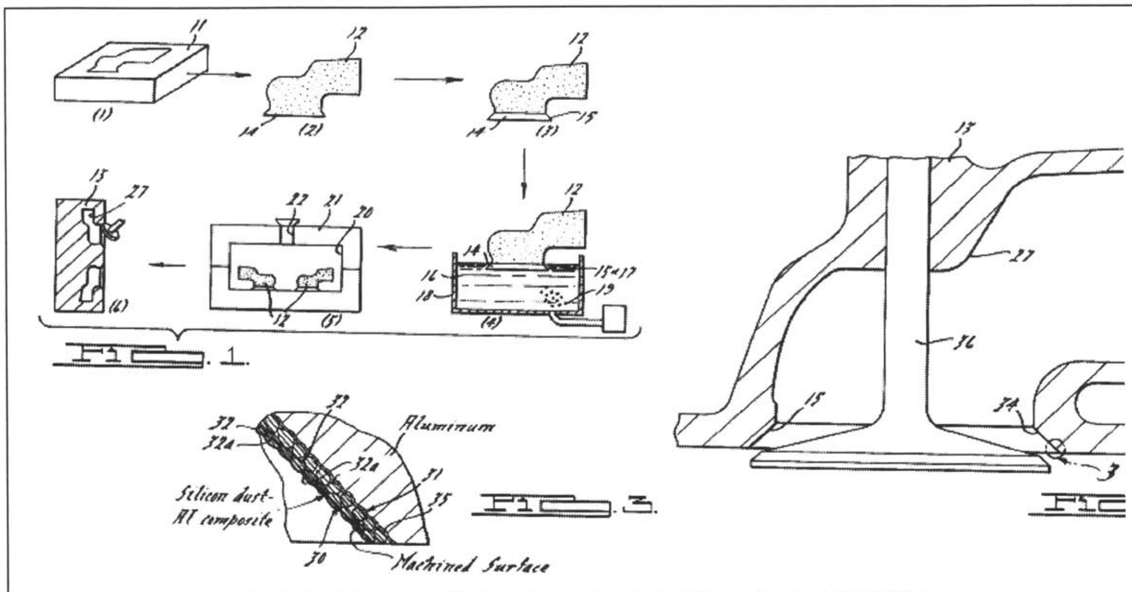


Fig. 34 – Excerpt of drawings depicted in patent 4 028 062

> *"... a more simple aluminum material (less alloyed) is utilized while effecting some form of wear resistance at preferential selected surfaces of the casting where the latter is primarily required. The prior art is unable to provide and has not appreciated the benefits that can be obtained by providing a restricted zone with sufficient silicon particle surface area exposed for wear resistance and yet ultra-thin to insure adequate bonding of each particle to the aluminum substrate".*

About a decade after that, Toyota proposes a similar solution using an alternative material for providing high-resistance. In US patent 4 723 518 *"Aluminum alloy cylinder head with valve seat formed integrally by copper alloy cladding layer and underlying alloy layer"* the benefits of using a copper alloy in the valve seat area are disclosed. Toyota claims that the problem of air insulation derived from the insertion of valve seat can be solved by creating an integral layer of different material during the casting process. It also mentions some of the drawbacks of methods and materials proposed in the past with similar intentions – such as the one just exposed– and claims that this new method addresses them properly.

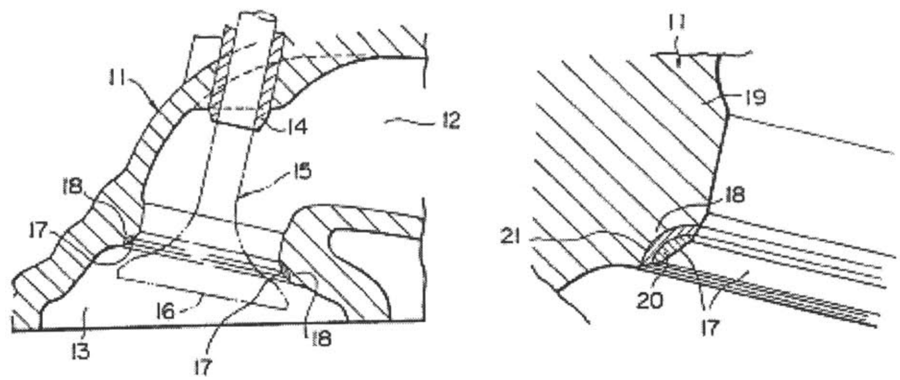


Fig. 35 – Excerpt of drawings depicted in patent 4 723 518

"A cladding layer is formed of copper alloy claddingly laid upon this valve seat surface, and an intermediate alloy layer is present between the copper alloy cladding layer and the main cylinder head portion, this intermediate alloy layer being composed essentially of an alloy between the aluminum alloy of the main cylinder head portion and the copper alloy of the cladding layer. Thereby, the anti-wear properties of the valve seat are desirably improved without making the fabrication process unduly troublesome or costly."

Although the invention claims to be easy to implement from the manufacturing point of view, the reality is that any casting process that requires localized casting properties, moreover, localized chemical composition in a single casting is a difficult one to produce, especially when it comes to configurations as big and complex as cylinder heads.

In 1991, the Japanese company Aisin discloses a different approach for increasing robustness in the area of the valve seat in US patent 5 020 490 *"Valve seat arrangement"*. (Refer to Fig. 36) This comprises an additional insert made of ceramic material (19) that resists the harsh conditions of the operating combustion chamber. This insert is mounted in an iron ring (20), similar to the conventional valve seat insert. Finally, both inserts are installed in a recess in the cylinder head (10).

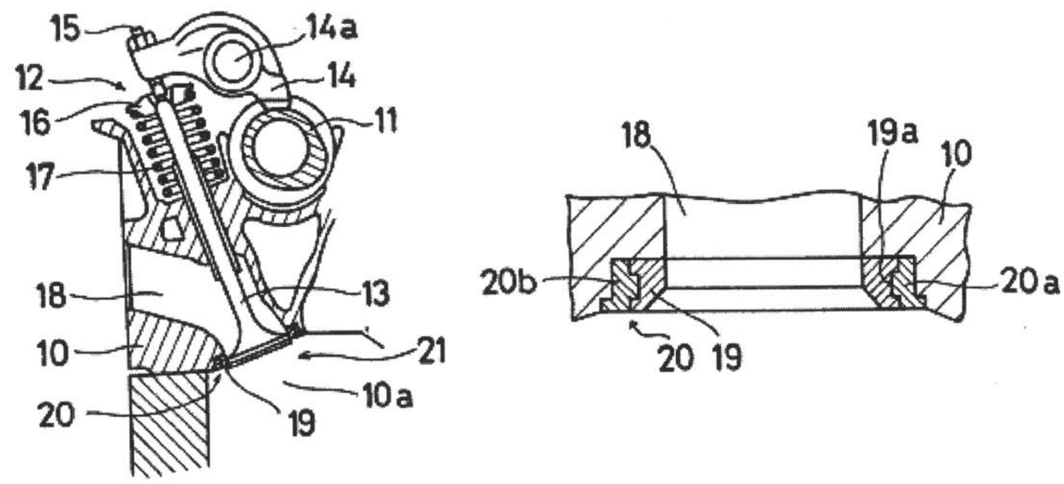


Fig. 36 – Excerpt of drawings depicted in patent 5 020 490

"It is a primary object of this invention to provide a ceramic valve sealing mechanism in an internal combustion engine [and] provide an assembling structure for the ceramic valve sealing mechanism. ... The cylinder head has a valve seating portion at an opening of the exhaust conduit and a valve seat which is made of ceramics is provided at the valve seating portion of the cylinder head."

The invention seeks to improve reliability of the valve sealing during the engine operation. It is argued that the conventional iron ring housed in the aluminum cylinder head does not provide with the appropriate thermal properties to warrant adequate sealing of the valves at high temperatures such as the ones reached during engine operation, due to thermal expansion and probable deformation resulting from the stress caused by the differences in material properties.

In an alternative line of inventions related to robustness of the overall cylinder head structure, in US patent number 5 080 057 *"Cylinder head for an interna combustion engine"*, Porsche discloses in 1992 a way of constructing a rigid cylinder head casting, by adding walls and ribs in areas that need extra mechanical support. This design is more robust not only because of the structural strength provided but because it results to be relatively less difficult to produce.

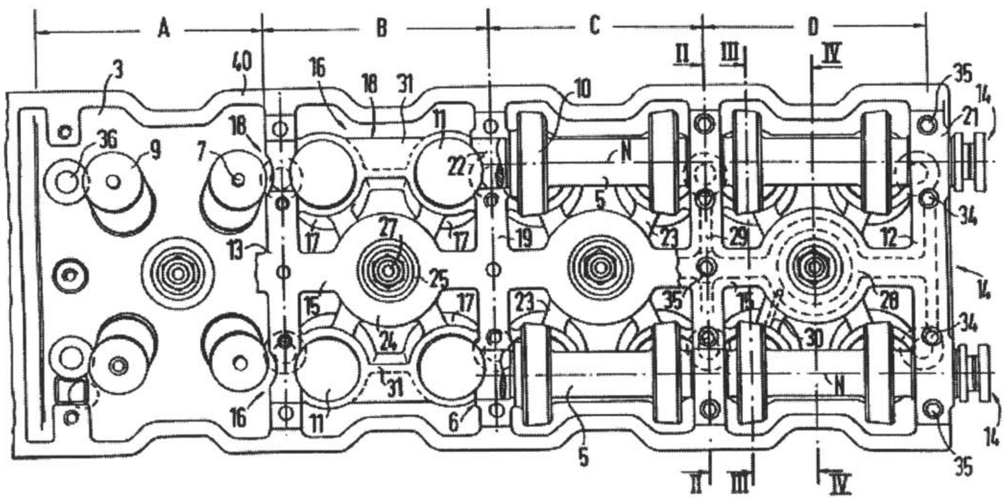


Fig. 37 – Excerpts of drawings depicted in patent 5 080 057

"...The arrangement is constructed rigidly as a result of longitudinal and transverse webs and, by removing the receiving devices from the cylinder housing, permits the use of a simple casting method for the cylinder head housing... The resulting cast structure has high homogeneity and improved material parameters in comparison to the known solutions. As a result, the danger of crack formations in the cylinder head housing is reduced considerably."

The head housing – the upper portion of the head, opposite to the combustion chambers – is designed to receive the camshafts and valve train on the top to later receive locks for this devices that will be fastened to the main ribs of the casting. This design may make a little more complex the cylinder head subassembly process, but it results to be particularly less susceptible to cracks in the area of the housing, which increases the cylinder head robustness.

The following invention happens to be particularly interesting and relevant to structural robustness inventions. It is an example of the kind of disruptive technologies that can be driven by robust design. These are usually developed in parallel with the incremental improvement of the state-of-the-art, and have the same goal of increasing reliability and robustness, but differ in being based on radical changes. This is the case of the invention proposed by Ube Industries in 1994 disclosed in US patent number 5 326 528 *"Magnesium alloy"*, and it corresponds to an improved magnesium alloy suitable as material of machine components to be used at high temperatures, specifically recommended for automotive parts such as the engine cylinder heads, intended to compete with aluminum alloys.

"A magnesium alloy comprises magnesium, zinc in the amount of 4.0 to 15.0 weight % and silicon in the amount of 0.5 to 3.0 weight %, the weight % being based on the total amount of the alloy. The magnesium alloy further may contain manganese in the range of 0.2 to 0.4 weight %, beryllium in the range of 5 to 20 ppm by weight or rare earth metals in the range of 0.1 to 0.6 weights...

In more detail, the magnesium alloy contains no rare earth metals, or contains the metals only in a little amount (not more than 0.6 weight %), so that the alloy can be produced at low preparation cost. Hence, the magnesium alloy of the invention can be advantageously employed as materials of engine components such as engine blocks (cylinder head and cylinder block) and a transmission case of an automobile."

In 1998, Mercedes-Benz discloses a structural design applied in a diesel engine, which could be transferred to gasoline engines as well. It consists of a cylinder head configuration such that the fuel injection device remains completely separated from the oil cavity. The main advantage of such design according to the invention explained in US patent number 5 711 266 *"Cylinder head for an internal combustion engine"*, resides in the fact that fuel cannot flow into the oil if an injector should leak.

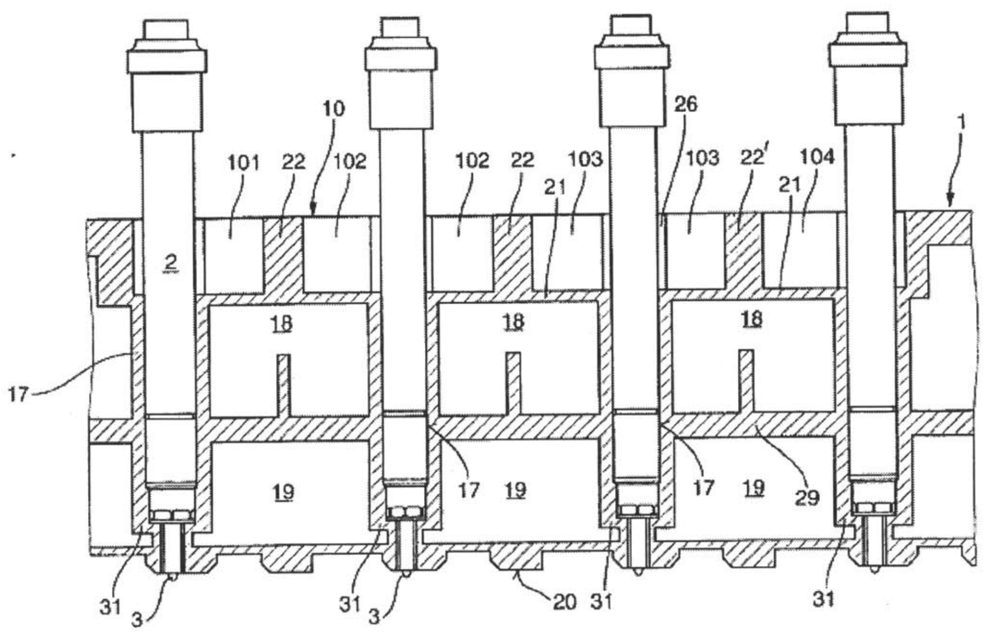


Fig. 38 – Excerpt of drawings depicted in patent 5 711 266

"It is the object of the present invention to provide a cylinder head for an internal combustion engine with two intake and two exhaust valves per cylinder arranged around a fuel injector which is disposed in the cylinder as centrally as possible but wherein the lubricant carrying space in the cylinder head is separated from the fuel carrying injectors trough."

In this sense, the proposed design is a more robust alternative to the common designs were the injector passes through the oil cavity from the top of the head to the bottom. A configuration such as the one used in this invention is also beneficial to the casting process as the vertical columns in the casting connect all the cylinder head decks making easier to feed every section of the part during the pouring and solidification process.

In the same year, another invention from Toyota related to valve seat reinforcement strategies is disclosed in US patent number 5 802 716 *"Method for bonding a valve seat in a cylinder head"*. Such method proposes the insertion of the regular iron-type valve seat in the mold using a series of elements that will enhance the bonding between the ring and the aluminum casting. Among the elements used for this matter are Al-Zn type brazing material containing mostly Zn and a fluoride type flux.

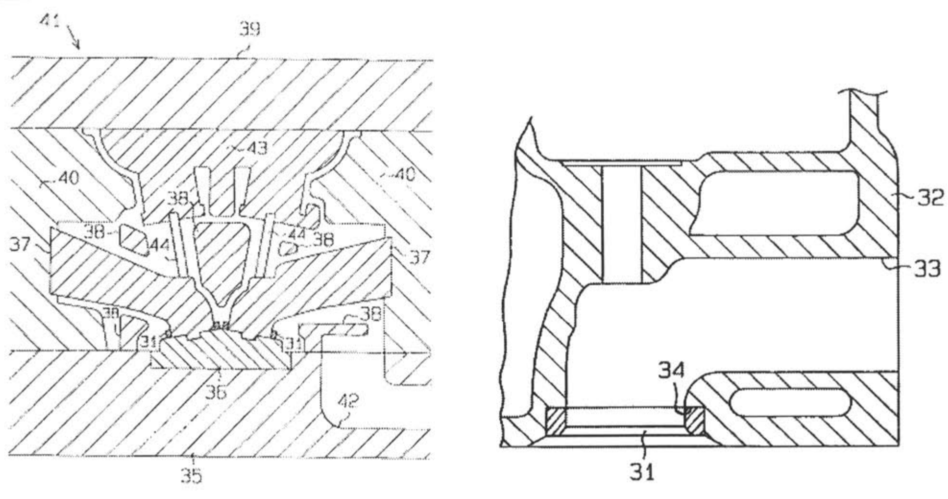


Fig. 39 – Excerpt of drawings depicted in patent 5 802 716

"...in the press-fitting method, it is quite common for a thermal air insulation layer to be formed between the pressed in valve seat and the cylinder head, ... It is difficult to obtain a satisfactory bond between special valve seats, which are infiltrated with materials such as Cu and Al, ... is a primary objective of the present invention to provide a method for bonding a valve seat with a cylinder head such that heat conductivity between the valve seat and the cylinder head is improved.... "

This method definitely results in a more robust valve seat configuration in the cylinder head provided that no dimensional issues arise in the casting process. It actually seems to be very advantageous from the engine assembly process point of view since the operations related to machining the cylinder head valve areas and installing the valve seat can be eliminated. From the casting process' perspective this process could add criticality to their process, thus the need for further process control on this side of the production process.

A year later, in 1999, Cummins Engine Company discloses a more radical approach in US patent number 5 954 038 *"Combustion face insert".* This invention proposes the use of an insert comprising major portions of the combustion chamber face. Although it claims to be applicable internal combustion engines in general, it seems more suitable for diesel engines in particular, which have flat combustion chamber faces in the cylinder heads.

The author presents this invention as an example of similar approaches that to date are know to be under research as alternatives for increasing the cylinder head robustness around the area of the combustion chambers.

Being a separate assembled insert it is probable that this kind of design exhibits the same disadvantages that others are trying to eliminate in the shorter valve seat inserts, not to mention the manufacturability complications embossed to the assembly line.

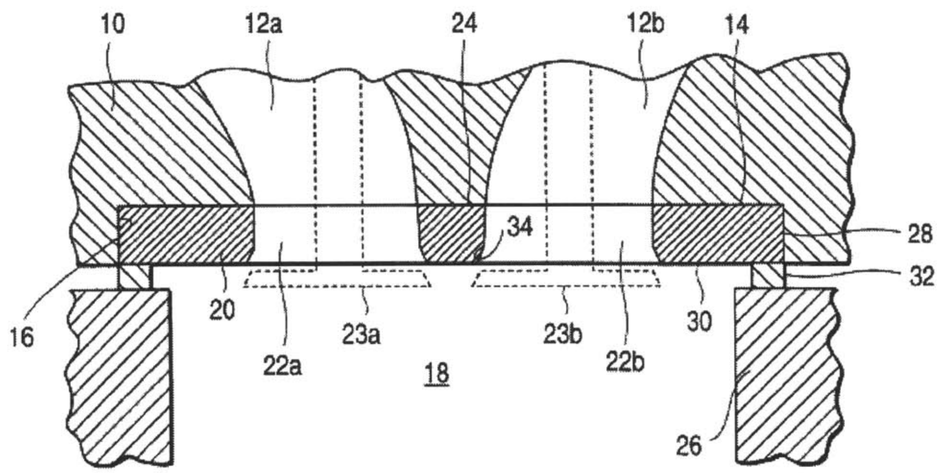


Fig. 40 – Excerpt of drawings depicted in patent 5 954 038

"Accordingly, for an engine having an aluminum cylinder head, an insert must be provided over the combustion face of the cylinder head having specific properties for providing increased resistance to wear and thermal fatigue around the intake and exhaust ports of the cylinder head as well as retaining a high residual hardness in the area adjacent the combustion seal to prevent indentations during deflection of the cylinder head."

More recently, in 2004, DaimlerChrysler discloses a different approach with a similar objective in US patent number 6 753 090 *"Surface layer and process for producing surface layers"*. Realizing that the different regions of the cylinder head structure are exposed to different operation condition thus require of different material characteristics, the inventor proposes the implementation of surface layers over the body of the cylinder head were those layers near the combustion chamber face have more resistance to heat and wear while those near the housing have structural strength, according the function delivered by each section of the cylinder head in the engine.

> *"The invention relates to a surface layer which comprises a plurality of layers, of which one layer is a ceramic wear-resistant layer and another layer is a transition layer to a metallic substrate element. The transition layer comprises intermetallic phases and is formed by a reaction from the materials of the substrate element and of the ceramic layer."*

Although appealing in concept, this process needs further development before been able for implementation in mass production. Nonetheless, it is known that the industry tendency is towards developing this kind of technology in order to break the barriers that the state-of-the-art offers to further development of more powerful and high performance engines.

State of the art

The current art regarding cylinder head design is difficult to define since a large variety of designs are applied even by a single firm in their product portfolio. There is no one single 'right' design but rather there is a variety of characteristics that combined result in many alternatives that are right depending on the particular application. Additionally, proprietary concerns also contribute to the variety of cylinder head designs. As perceived during the patent analysis, every

OEM has a version of the same approach with slightly different characteristics in order to make it proprietary.

Market segmentation is also a contributor to the variety of designs. Every engine platform is oriented to fit the needs of a specific segment of customers. In that order of ideas, usually the high-end segment is provided maximum performance. On the other hand, low-end segments are offered fuel efficiency, among the set of characteristics that are attractive to these customers. The range in between varies greatly as the set of characteristics is provided at different levels of satisfaction. In addition, regulations play a very important influence in engines design. Having all this into consideration, it cannot be said that the high-end models are representative of the state of the art since even those models make trade-offs in performance and reliability characteristics.

The following is a list of the trends followed in particular design characteristics. Being the most widely used, they are representative of what inventions have most effectively been implemented:

- **Material:** about 85% of the cylinder heads are made using aluminum-silicon alloys A319, A356 or the like. Many require heat treatment to enhance material properties; some foundries have been able to manipulate casting process parameters in order to avoid the need of heat treatment. Robust design has played a major role in making possible the transition from cast iron to aluminum, as it has already been explained.

- **Number of cylinders:** the most common designs of heads include 3 or 4 cylinders to fit the V6, I4 and V8 engines. A few models made for high end engines feature 5 or 6 cylinders to fit V10, I6 and V12 engines. The number of cylinders is directly proportional to the required power.

- **Embodiment (structural design):** This is one of the characteristics that most differs from one model to the other. Nevertheless, a few trends are perceptible. Cylinder heads for small engines often show very simple housing configurations. Larger engines usually have designs similar to the one Mercedes Benz and Porsche propose, yet very different in specific details. The general trend in cylinder head's structural design is that new models feature thinner walls in order to achieve lighter structures. This is triggering a lot of activity related to robust design on the side of the manufacturers in order to achieve the required structural characteristics without compromising mechanical strength characteristics.

- **Number of valves:** this is one of the most varied characteristic in engines. Depending on the engine platform there are models featuring anywhere from 2 to 6 valves per cylinder. Perhaps the models with even number of valves are most common. The chosen combination is a function of the design objectives in terms of engine power, fuel economy, emissions, manufacturability, etc. This characteristic drives the design of the combustion chamber and it exercises great influence in the design of the whole cylinder head. Many robustness implications are derived from the designers decision on going for a particular configuration.

- **Number of spark plugs:** Commercial models have 1 spark plug per cylinder. High-end models have 2. It is also a characteristic that depends on particular engine design requirements.

- **Injection configuration:** Although a lot of commercial models still use the injection through the intake ports, the direct injection models, were first applied in high-end. The great design activity that this kind of engines has experienced in the recent years is an indicator of the intention of designers of diffusing this feature on all models.

- **Valve seat configuration:** Despite the efforts for implementing alternative solutions for the valve seat area wear resistance, the use of iron rings applied on cold by pressure in a recess in the cylinder head casting is the dominant design. Nonetheless, in addition to the air insulation issue present on this kind of inserts, it seems to be a goal of the OEMs to get rid of the valve seat insertion operation in their sub-assembly lines, thus, robust design activity is taking place in order to find a robust and reliable alternative to the current art.

Chapter 4

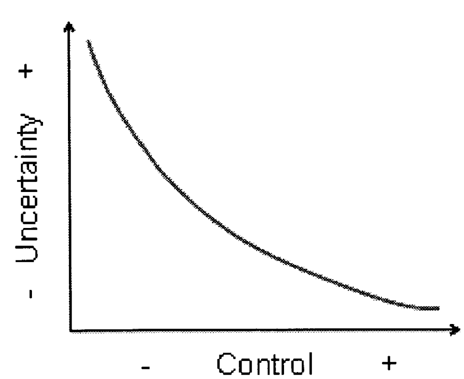
A framework for robustness inventions

How to identify promising improvement paths

A widely accepted paradigm is that creativity and control cannot coexist since they are conflicting attributes of an organizational environment. It is thought that when control is exercised, creativity suffers.

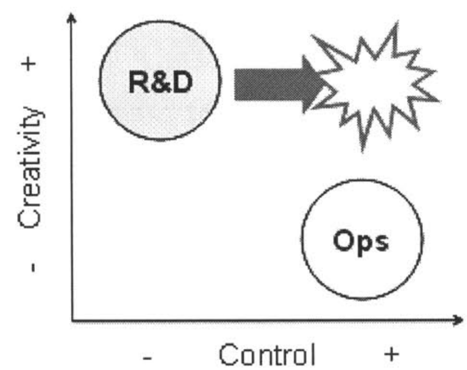
On the other hand, in the organizational setting, the minimization of uncertainty is a desired outcome of control. The more control implemented in an organization through the use of tools, methods, and frameworks, the less uncertain the outcome of the projects is – or the more prepared the organization is to face the uncertainty effects for that matter.

Fig. 41 – Correlation between uncertainty and control



The Research and Development organizational environment does not differ from other organizational settings in that sense. Nonetheless, the relevance of creativity for the fundamental function of R&D – and thus for its performance – makes it particularly difficult for managers to handle properly the trade-offs between creativity and control.

Fig. 42 – The creativity paradigm



What can managers do if they want to reduce uncertainty without compromising creativity? A framework such as the one proposed in this thesis could serve as a tool to address this paradox. The use of frameworks provides a certain level of control without the exhaustion of other control tools, such as standardized methodologies or scorecards.

From the analysis of the patents presented in this thesis, it is gathered that the development of products is actually driven by the contribution of the inventions to product robustness. For example, in the case of the aluminum alloys, these were not successfully applied to the generality of the cylinder heads until it was demonstrated that they provided the robustness characteristics required by the application. On the other hand, other inventions like the sub-combustion chamber or the magnesium alloy have been left behind due to the lack of success in providing robustness characteristics to all stakeholders, including manufacturers. These facts are indicators of the improvement path being traditionally followed; consisting on the generation of an invention that is reliable only under ideal conditions, then developed in robustness, and finally applied. It is therefore concluded that a more effective improvement path could be followed if robustness is considered as the ultimate goal of the invention itself.

Taking into consideration that R&D is the primary contributor to product development, and thus to product robustness, while recognizing the strategic value of robust design as a product development tool [philosophy], it is considered of great benefit to formulate a framework that assists in the systematic pursue of the continuous generation of robustness inventions.

The elements that will be explained as follows are intended to be the base of a suitable framework for robustness inventions. These elements are: 1) sources of creativity, 2) inventing strategies, and, 3) critical analysis of robustness inventions. The first element relates to the realization of the improvement path that a design must follow taking into account a "starting point" based on the current robustness/reliability status and the visualization of the "perfect design. The second involves a series of strategies for either reducing system sensitivity to noise or reducing component sensitivity to noise. The improvement path would imply the use of these either separately or in combination. Finally, the third element is concerned with the assessment of the invention from the system's perspective.

Sources of creativity for "producing" inventions

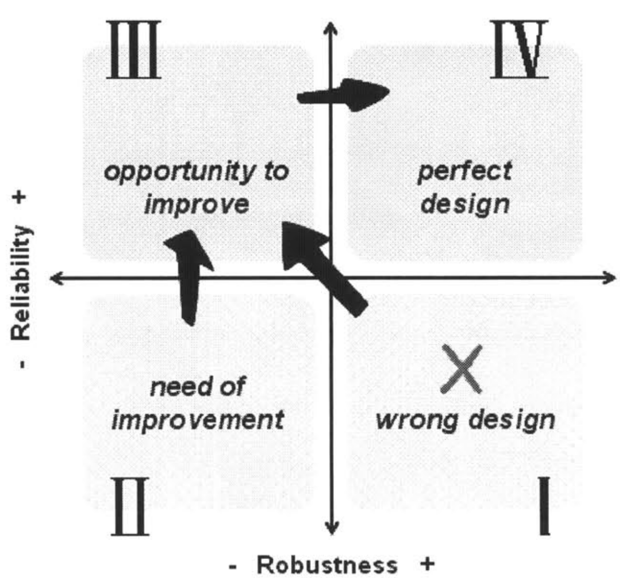
It is arguable that the process of generating inventions could be actually seen as a production process. A production process is thought of as a repeated series of steps or actions that always yield the same result. It requires inputs, and, given certain set of conditions, it generates outputs. Put in a very simple way, the process of producing inventions requires creativity as input to provide the output of a new idea that is demonstrably suitable for a particular application, that is, an invention. Thus, by providing the adequate sources of creativity, one can in a way enhance the 'productivity' of such process and also drive the nature of its results. In the case of our concern the desired sources of creativity are those that lead to robustness inventions.

One of the advantages of putting in practice the robust design philosophy is that it provides with a sustainable source of creativity for robustness inventions. This source of creativity is derived from recognizing the variations that affect the performance, thus identifying the improvement path that a product should follow to achieve the perfect design – a design that provides maximum performance despite the noise on the environment and thus cannot be improved without changing its functionality.

Recalling the robustness and reliability scenarios presented in Chapter 1 (refer to Fig. 3) we can intuitively classify any product or system at any stage of development in one of the four quadrants. In that order of ideas, depending on the starting point, through the traditional approach, there are specific strategies that can be followed in order to achieve the "perfect design".

Consider an example of a system that is not affected by variation, yet does not meet the performance expectations. By the traditional design approach, a system engineer would be concerned first about achieving performance under a set of controlled conditions and only when this has been achieved he/she would start worrying about making the system more robust.

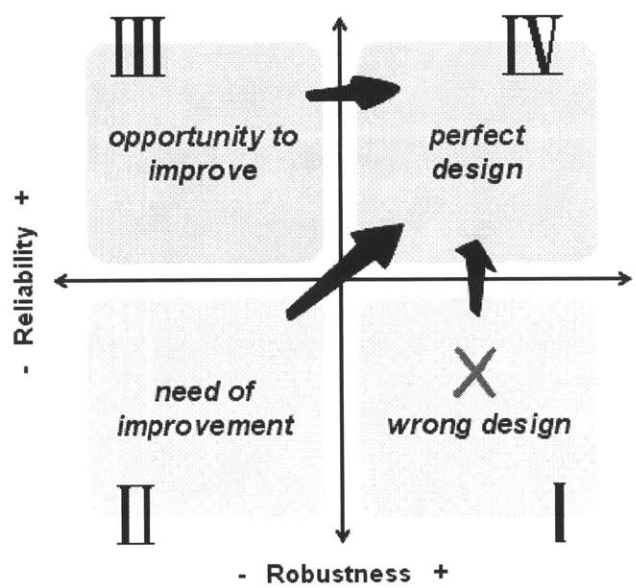
Fig. 43 – Traditional approach for improving a system or product



The strategy described is represented in the diagram shown on Fig. 43 by the path I-III-IV. Note that in the process of transferring from I to III, state II could actually be reached, but it is certainly not the goal, thus it is not explicit in the diagram. On the other hand, consider a system that sometimes exhibits good performance and sometimes doesn't, and it is greatly affected by variation in the environment. The traditional improvement path would involve the transition from state II to state III where, under controlled conditions, reliability is achieved and only then the system engineer would be concerned about increasing the system's robustness.

Alternatively, with the robust design approach, the strategy for improvement is to address both reliability and robustness at the same time, by taking advantage of the benefits in performance (reliability) that are obtained by eliminating the effects of variation.

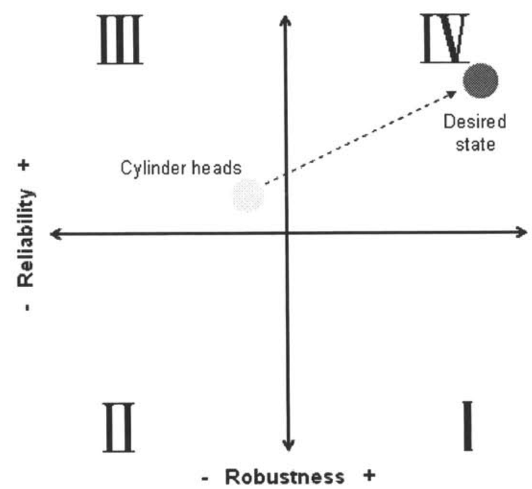
Fig. 44 – Robust design approach for improving a system or product



The sources of creativity provided by the robust design approach derive from the recognition of the state (or quadrant) where the system under question belongs.

To do that, it is necessary the internalization of the concepts of reliability and robustness.

Fig. 45 – Improvement strategy for cylinder heads



Creativity will emerge from the identification of the improvement path that the system should undergo in order to achieve design perfection.

For the purpose of this study, given that we are analyzing a system that can be considered mature, we will focus on the transition from state III to IV, as shown in Fig. 45.

Inventing strategies

The proposed inventing strategies are derived from the analysis of the evolution of the engine cylinder heads. Therefore, even though they intent to be generic, they might result to be more suitable for engineering systems that hold similarities with the system under study.

We have defined since the beginning of this analysis that there are two fundamental categories of robust design strategies, considering the system under question as a component of a larger system:

1. Intents to reduce system sensitivity to noise

2. Intents to reduce component's sensitivity to noise

Considering the robustness inventions applied to cylinder heads, the changes in the design of the combustion chamber, analyzed in the first section of Chapter 3, correspond to robustness inventions falling under the first category while the ones related to enhancements of the overall structure, analyzed in the second section of Chapter 3, fit into the second category.

Consequently, the inventing strategies derived from the cylinder head's evolution analysis are as well classified under these categories.

All strategies consider that the source of variation and the nature of the noise (range of variation and causes) are considerably identified.

Intents to reduce system sensitivity to noise

Counteract variation

This strategy consists in aggregate characteristics in the design that will provide the component with the ability to counteract or annul the variation. Examples of this strategy among the analyzed inventions are those where the combustion chamber is intended to create tumble-flow, swirl-flow or turbulence.

One can say that, from the design standpoint, a new function is being assigned to the component in the context of the system. In the specific case of the cylinder head, the portion correspondent to the combustion chamber delivers the function of air/gas mixer to the engine.

These inventions are effective in the way that the system does not receive the noise, since this is eliminated by the component, thus the performance of the system is not affected.

Limit range of variation

This strategy consists in diminishing the noise effects by reducing the range of variation. Examples of the application of this strategy are those robustness inventions oriented to manipulate the gases to concentrate them in a particular area of the combustion chamber. These inventions imply the reduction of the available volume in the combustion chamber at the compression stroke.

Another set of inventions that falls into this category are those related to positioning the valves and the spark plug(s) in determined locations in the combustion chamber enhancing the combustion velocity thus limiting the time available for noise to be present and increase.

These inventions are effective in the sense that they reduce the actual variation, hence the noise is weaker and so it is the effect of it in the performance of the system.

Change source of variation

This strategy is not to be confused with eliminating the source of variation, as robust design focuses on the elimination of the *effects* of variation without eliminating the *sources* of variation.

It is true that whenever possible, a reasonable thing to do is to eliminate the sources of noise that affect the system's performance. Nevertheless, robust design usually deals with uncontrollable sources of variation which are external to the system but affect it. In that sense, this robustness invention strategy consists in manipulating the source, so as to reduce the noise produced by it.

That is the case of the introduction of direct injection systems and other patents concerning enhancements in combustion chamber filling. The source of variation – the fuel injection – and its characteristics are not changed, but by changing its point of actuation – the injector location – the variation can be reduced thus reducing the effect of the noise in the system's performance.

Intents to reduce component sensitivity to noise

Physical protection against variation

This strategy consists in adding physical barriers that receive the effects of variation instead of the component. These barriers usually are more resistant to the effects of variation that the component itself – a case where the barrier has the same characteristics than the component would be to add thickness to the characteristic, which is called "brute-force" robustness.

The conventional valve seats in the combustion chambers fall into this category. Of the inventions analyzed, the ones related to adding physical inserts in the combustion chamber face, and the ones recommending the addition of a ceramic valve seat inserts are perfect examples of this robustness strategy.

The effectiveness of this strategy relies in the increased resistance (or decreased sensitivity) provided by the protection. A particular drawback is the usual implication of additional parts thus increasing manufacturing complexity (usually additional assembly operations).

Increase resistance against variation

This strategy implies to change the nature of the component in order to make it more resistant (less sensitive) to the variation. It usually involves chemical alteration but it may also involve only structural (geometrical) reconfiguration. It is often a more radical change than the previous strategy, but when successful, it is also more effective. Examples of this strategy are the valve seat surface transplant, and the magnesium alloy.

These kinds of inventions are characterized by being usually difficult to implement, since they require changes in the system architecture and affect several stakeholders.

Eliminate consequence of variation

When the noise cannot be manipulated, a good alternative is to eliminate the consequence of variation, that is, the effect. An invention representative of this robustness strategy is the one disclosed by Mercedes Benz, where the risk for fuel-oil mixing – the consequence of variation, where variation is a possible fuel leak due to injector failure – is eliminated by separating the injector from the oil cavity. Note that the source of variation, in this case the injector, it is not involved in this change, yet the effect of the variation is eliminated.

Another example that falls in this class of robustness invention strategies is disclosed by Porsche. They design a casting structure where some areas susceptible to casting defects are eliminated. They also combine some structural changes that fall in the previous category, by adding ribs to the casting in order to make it more resistant to the noise (mechanical fatigue).

Critical analysis of robustness inventions

This element of the framework is provided to address the uncertainty that characterizes the product development projects. Even in the case of product improvement projects related to systems that are mature and considerably known, there are a number of factors that are not obvious thus need to be conscientiously analyzed in order to properly asses the viability of certain project.

Given a proposed change in design according to a robust design strategy or a combination of two or more, and having already determined the feasibility of implementation of the change in the specific component under question, the following factors must receive attention from the perspective of the whole system:

- **Transfer of weakness.** Is the new design proposed transferring the weakness, that is, the sensitivity to noise, to another component or component in the system? This usually happens when the increase in robustness in one component affects in some way another component, decreasing the robustness of the later.

- **Transfer of effect.** Is the new design proposed transferring the effect of the noise to another component or components in the system?

- **Sustainability.** Is the new design proposed providing sustainable robustness to the component and/or the system? Is the problem going to arise again in a short period of time? Is this an "aspirin" solution?

- **Manufacturability.** Is the new design proposed easy to implement in large scale? Does is affect in a disruptive way the production process of the component and/or the system?

In addition to analyze the above mentioned factors it is also important to have a means to asses the invention from the perspective of the improvement continuity. In that sense, the following should be considered:

- **Favoring further improvement.** Does the new design leaved room for further improvement? If so, what is it needed to execute it?

- **Breaking barriers to improvement.** Is the new design setting new parameters within which new performance goals can be set? That is, is the new design eliminating previously existing limitations to the implementation of other improvements? Is the new design opening possibilities for "rising the bar" of the sate-of-the-art?

- **Relating to current art.** Is the new design an enhancement applied to the current art? If so, could it be transferred to other arts? If not, does it provide an advantage to the current art over other potential arts trying to enter?

- **Related to alternative, potentially future art.** Is the new design an enhancement to an alternative art in order to make it more suitable for adoption?

The conclusion of this critical analysis must be sought in the context of the business strategy and the particular industry dynamics. There are no absolute right answers but only answers that are right under the light of the information at hand.

Chapter 5

Conclusions

Takeaways and future research

The proposed framework for robustness inventions offers a suitable solution to the creativity and control trade-offs that characterize the R&D organizational environment. Taking into account that robustness and reliability are separate characteristics of a system, yet they are intimately correlated, and that robust design leverages such correlation increasing system reliability by minimizing the effects of noise in the system or in a particular component of the system, such framework is based on the conceptualization of robustness as the principle for product evolution.

Considering the perfect design as that which consistently provides maximum performance despite the noise, and recognizing the nature and effects of noise in a particular system, a desired improvement path can be identified. The strategies for robustness inventions suggested provide a means for designing effective product improvement paths. Additionally, the critical analysis proposed helps in the prompt identification of the improvement paths that are most promising in terms of providing sustainable robustness to the system.

The research efforts invested in developing a framework for robustness inventions are far from wasted. It has been demonstrated that the different aspects of robustness are key in the successful application of inventions, as well as that inventions that are oriented to increase the robustness of a system may strongly drive the actual evolution of the system itself.

The author suggests that future research is done regarding the same line of thought. Possible alternatives are to study a variety of components in a system, and diverse systems of different levels of complexity, in order to validate the generalizations derived from this thesis.

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