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1. Introduction.

The purpose of this report is to outline the design processing, manufacturing, material selection, and testing procedures of a high-pressure fuel injector, used in diesel and DI – petrol internal combustion engines. The injector used in these style systems requires rigorous detailing because they're easily considered one of the key components for maintaining safe operation during a process that is inherently treacherous, controlled combustion. Failure of such component could cause fires within the engine bay or lead to detonation within the cylinder that could cause catastrophic internal component failure potentially leading to fatal traffic collisions. Despite the safety aspects of these components, the performance of them is fundamental and not only from the power prospective, but the environmental impacts because if there is a defective sealing or poor operation, the introduction of poor combustion will generate more dangerous exhaust emissions and given the current fight against global warming and greenhouse emissions is evidently now of more importance. With all these design and operation importance's understood the development of materials and testing of these components is of the utmost importance, and through this report the historical development of materials, operation and manufacturing process testing will be discussed and critically analysed.

Objectives –

- Provide an overview of the general operating requirements and historical development of a high-pressure fuel injector and its system.
- Detail all aspects of the design factors, material selections and the processing routes taken by most manufacturers.
- Compare and contrast the different manners in which mechanical failure can happen within this component and explore the procedures and/or techniques used to gather data that allows analysis of said failure mechanism.
- Determine the effectiveness of the procedures and compile the previously collected data published to potentially outline any defects that'll occur during the processing route used.

2. Selected Component.



Figure 1 A standard gasoline direct injection (GDI) injector (Bosch USA, 2021).

The selected component for this study is a gasoline direct injection engines injector. This style of internal combustion engine is usually abbreviated to GDI or GTDI, gasoline direct injection and gasoline turbo direct injection, respectively. The latter of which is the most common application because the performance enhancements of using forced induction far outweigh that of naturally aspirated engines.

Direct injection was first introduced into gasoline (petrol) engines around 1925 by a Swedish engineer Jonas Hesselman for the Germans during the second world war to help stop their aircraft stalling during difficult aerial manoeuvres (Goms, 2012). After which many manufactures realised, they were limited by the technology of the times so the concept was arguably forgotten about for several years until around 1955 when Bosch introduced the first GDI system onto a Mercedes-Benz 300SL. This technology however was still operated under fully mechanical principles and remained relatively low pressure right up till around the late 1990's where electronic control of the systems became a viable option because of the technological advancements and the drop in cost of components, pioneered by Mitsubishi (RENAULT F5R Team, 2021). Between 1990 – 2005 is considered as the first generation of these electronic, high pressure GDI systems because after this in 2006 the first of the spray guided combustion systems were introduced (IU.Spicher, 2010) and with this introduction the industry began to move away from PFI because using GDI enabled manufactures to achieve better specific fuel consumption whilst reducing the CO₂ emissions produced which is the target for all industries, not only automotive (F.Leach, 2013).

Using direct injection in a gasoline internal combustion engine (ICE) introduced an important design consideration for where to place the injector in the cylinder to help aid the style of combustion for the different operating points under load. The simple definition

of these positions are to have the injector placed in the cylinder wall and use either; the tumbling air coming into the cylinder to mix the fuel and air or use the shape of the piston to cause an interaction between the air and fuel, these are the wall guided techniques. The other type, which is the second generation of GDI combustion, is to have the injector placed right next to the spark plug and this technique led to much more efficient combustion and even better fuel economy than before (S. P. Chincholkara, 2015).

For this report, an injector used in a spray guided system is to be used, with the sole focus on the nozzle of injector because these are subject to the most extreme conditions and are the main area of failure for these components.

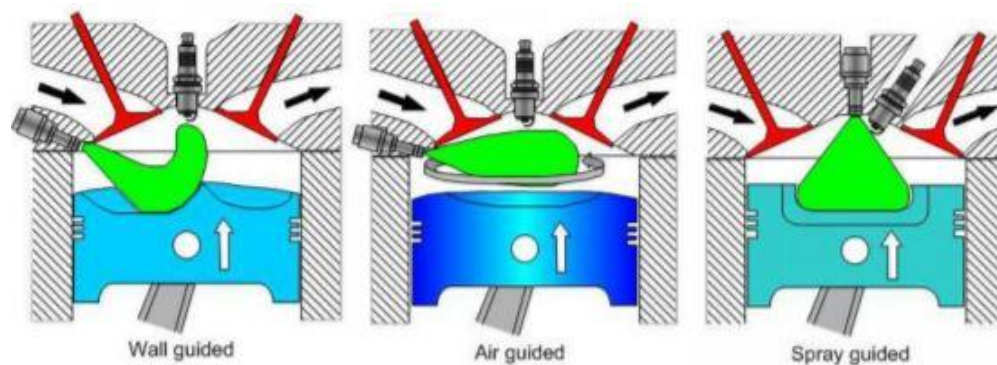
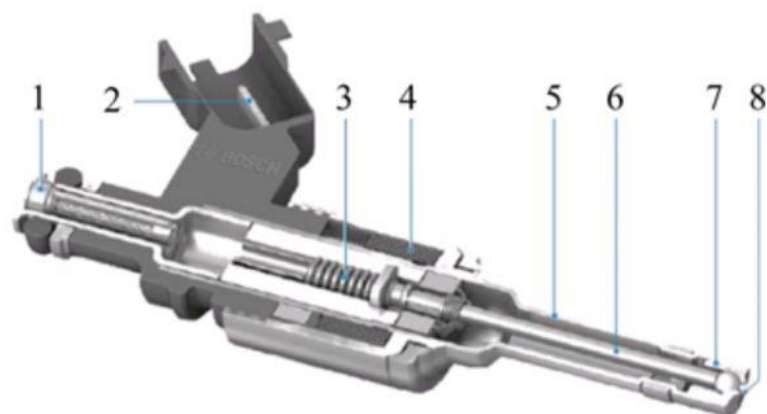


Figure 2 The three traditional techniques for gasoline direct injection combustion based on injector position (Tejas B Raju, 2014).

The average construction of a GDI injector can be seen to contain;



- | | |
|--------------------|---------------------------------|
| 1 Inlet and Filter | 2 Electrical Connection |
| 3 Spring | 4 Electromagnetic Coil |
| 5 Valve Shell | 6 Pintle with Solenoid Armature |
| 7 Pintle Seat | 8 Orifice Borehole |

Figure 3 Average construction of a GDI injector (Florian Schulz, 2018).

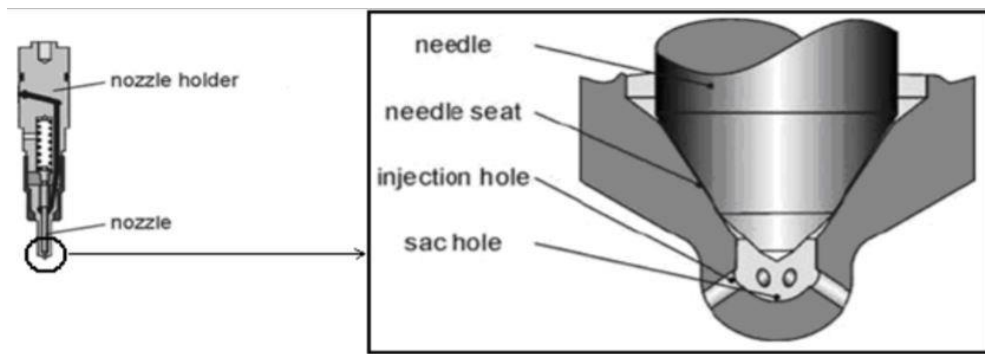


Figure 4 Closer description of the nozzle section of an injector (Semin Semin, 2010).

The standard operating requirements for GDI injectors are as such;

- Operate at pressures between 30 – 210 bar on average.
- Be able to injector fuel at a pulse width of 0.4 ms.
- Have the ability to inject fuel between 1 – 3 times per event.
- Handle in-cylinder temperatures more than 2500k from the flame front.
- Withstand in-cylinder pressures on average of 100 bar.

(KRIEGER, 2016), (Sara McAllister, 2011).

1. Design Changes.

Historically the design changes made to injector nozzles have seemed to be more towards increasing the efficiency of the injector in terms or being able to control the spray pattern of the liquid fuel and facilitate the system to handle higher pressure systems, more than 2000 bar. Not to stop the failure of the part due to mechanisms a like fatigue or corrosion, because these changes were more of the materials used and processing routes that enabled the manufactures to increase the capabilities.

The focus area for structural design changes of the injector nozzles are for achieving more effective combustion due to a better spread of fuel across the cylinder and its interaction with the air due to higher turbulence, generating a better mix of the fuel and air leading to higher cylinder pressures and better fuel economy.

The design of the nozzles is purely a personal choice for the manufacturers and there isn't a definitive construction because some patterns and styles will work better for certain ICE internal geometries and therefore it could be argued to be subjective and dependent upon physical testing and/or simulation testing.

It's thought after much investigation that designs that include smaller orifices are the better solution because it's been shown that the air/fuel mixes better because the fuel rich core of the jet is smaller than it would've been with larger orifices. However, with the smaller orifice, the turbulent energy of the injected fuel spray is lower than that of the larger holed nozzles, so the argument contradicts itself because the mixing of the air and fuel is controlled by the turbulence of jet boundary layer (Semin Semin, 2010).

Examples of these nozzle design types can be seen in the following figure;

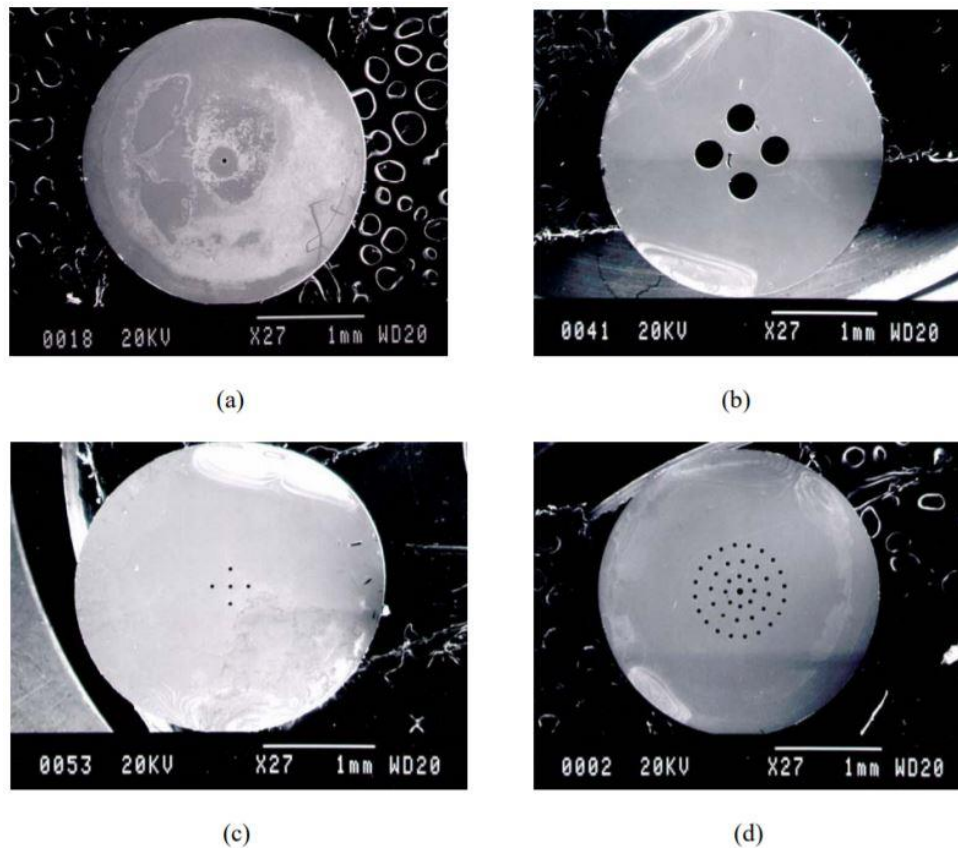


Figure 5 Nozzle design types in terms of hole construction (Seunghyun Baik, 2003).

2. Materials.

From preliminary investigations the material selection process of gasoline high pressure direct injection injectors owes itself more to the corrosion property differences between gasoline and diesel. With diesel injectors the material selection is based on the operating principles of dealing with consistently high temperatures and pressures during operation, while not being affected by the build-up of combustion products, a like soot and oil. The metals used for the nozzles of such injectors are comprised of carburized steels such as; Ferrium C61 (ASM 6517), Alloy 53 and AISI 9310 (QuesTek

Innovations LLC, 2020). Or maraging steels; C300, C350 or C362 where these maraging steels can deal rather sudden changes in either speed, but more importantly temperature because of the aging process involved in its manufacture. These steels are capable of dealing with atmospheres that would otherwise destroy most other steel compounds, hence their uses throughout the aerospace industry (All Metals & Forge Group, 2020). Another material type is an alloy known as AerMet100, and despite its class leading properties for hardness, FTT, tensile strength and ductility, the alloy doesn't have good corrosion resistance and therefore requires some form of surface sealing (Service Steel Aerospace Corp., 2018). According to the patent for the "materials for fuel injector components", published in the United States the most effective method is to nitride the outer surface in a nitriding furnace via a nitrogen containing material, like ammonia. Or using plasma-nitriding with ionised nitrogen gas and it's suggested that these procedures are done at a temperature close to 480°C for 24 hours (Michael J. Pollard, 2010).

However, considering the nitride process as an additional form of surface sealing and not a process to simply place the surface of the component into compression, increasing its tensile performance, there is a series of additional procedures required, such as; grinding, polishing, oxidation and impregnation, all of which can significantly increase the cost of manufacture (P Wach, 2017).

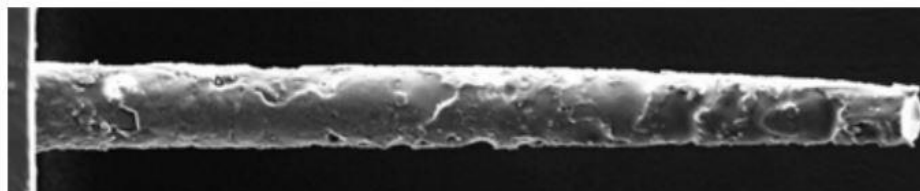


Figure 3: SEM image of a plastic impression of a laser drilled pre-hole. Ø 80 µm drilled in 1-2 seconds.

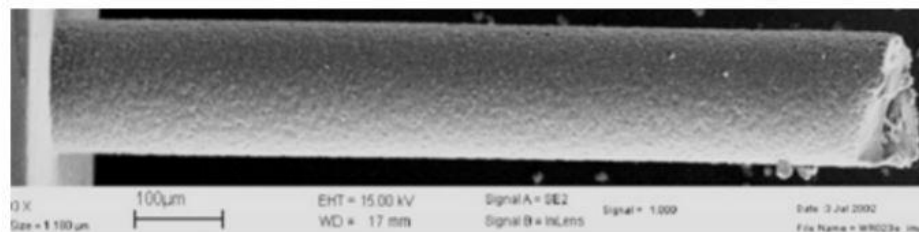


Figure 4: SEM image of a plastic impression of a laser-EDM hole following EDM drilling. Ø 140 µm drilled by EDM in 9 seconds.

Figure 6 Comparison of the use of only laser drilling technique and the introduction of laser drilling followed by EDM drilling, named Laser-EDM (Lin Li, 2006).

3. Process route.

Considering the process route for a high-pressure fuel injector nozzle, the standard steps through the manufacture starting with the design, it's not an overly complex shape but the tolerances for these must be identified early on. For example, considering the holes in the nozzle, in previous years there could've been a tolerance of 0.025mm but in recent years with the combustion process necessitating perfection, these tolerances are now in the region of 0.00051mm deviation in diameter (Jablons, 2020). To put into perspective the level of accuracy required during manufacture, the orifice sizes commonly used in GDI injectors is between 0.08 – 0.2mm (Mitroglou, 2006), so the way in which these holes can be machined is clearly reduced to niche techniques. For example, pulsed laser drilling or electrical discharge machining. The latter of the two was commonly used for larger injector orifice sizes $>200\mu\text{m}$, but with the introduction of Microhole EDM, this machining procedure can now achieve sizes from 75 - 400 μm burr free (MacGregor, 2012).

With these sorts of manufacturing tasks, it would be expected that the procedure would take a 'considerable' amount of time respectively, however, manufactures like Bosch GMBH can produce "around 25,000 a month" using the EDM technique. Therefore, the factor of time for manufacture can be considered as minimal and it's clear than mass manufacture is possible with the machinery of today.

The other important part of the process is the machining of the nozzle itself from the high-hardness metals such as the maraging steels, carburised steels or martensitic steels, the tooling requirements are of the utmost importance. As is the shape of the nozzle, because to more complex the shape, the harder the machining will be, and more cost is induced from more expensive methods and a longer time allotment.

With the common procedure for manufacture being turning, using cubic boron nitride (CBN) tools. The procedures does take a considerable amount of time because the materials aren't commonly good conductors of heat. This is disadvantageous during manufacture because when machining at high speed and feed rate, the heat generated on the tools changed the material properties meaning the machining is no longer possible. So, cooling during this process is key, but this will require testing because the rate of cooling and amount can have a negative effect on the material itself (S.Thamizhmanii, 2011).

3. Engineering Principles.

One type of material used for GDI injector nozzles is made by a company named 'Aubert & Duval' which they name as X15TN. The properties of which can be seen in the following tables;

	C	Si	Mn	Cr	Mo	V	N	Ni
min.	0.37	-	-	15.00	1.50	0.20	0.16	-
max.	0.45	0.60	0.60	16.50	1.90	0.40	0.25	0.30

Table 1 Chemical composition of material X15TN (AUBERT & DUVAL, 2021).

Class	Type	Severity
1	Freckles	A
2	White spots	A
3	Radial segregation	B
4	Ring pattern	B

Macrostructure according to ASTM A 604

Table 2 Macrostructure of material X15TN (AUBERT & DUVAL, 2021).

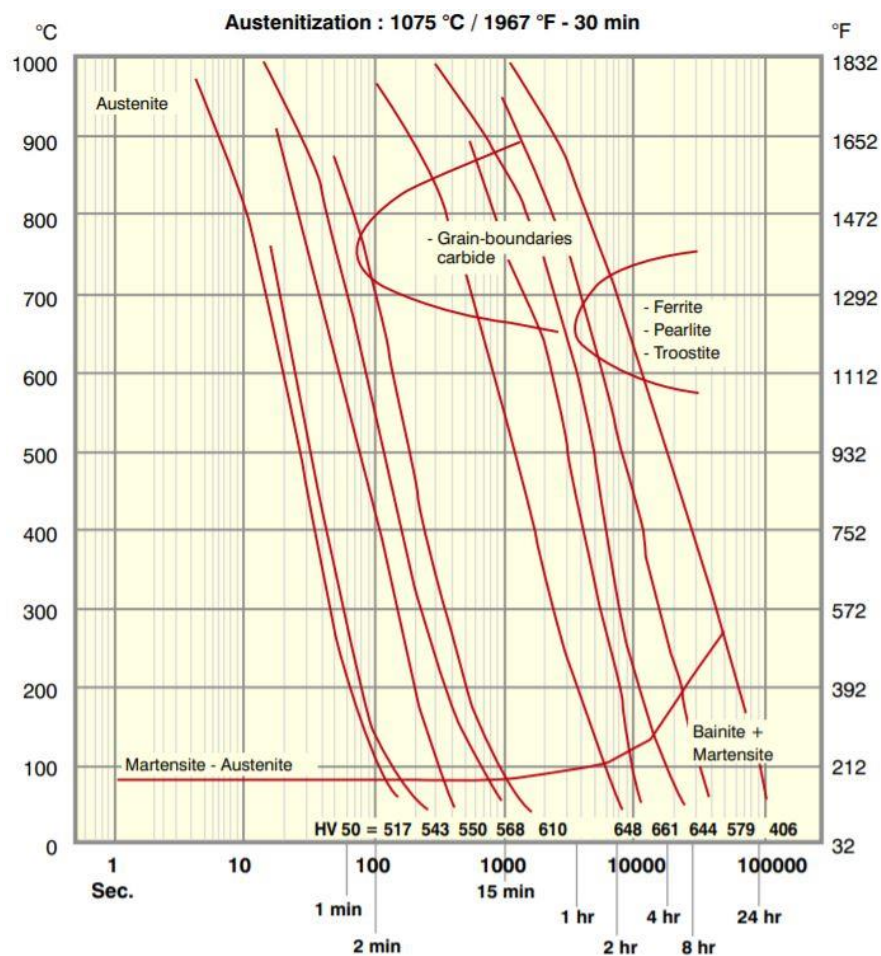


Figure 7 CCT Diagram for the material X15TN showing the effects of heat treating (AUBERT & DUVAL, 2021).

Fatigue occurring from the changes of temperature in GDI injector nozzles isn't commonly a point of failure because of the properties of materials used gives them phenomenal ability to deal with the temperatures in-cylinder and the pressures of fuel being injected. And with the manufacturing processes resulting is such high levels of accuracy, low surface roughness and having minimal effect of the surrounding area during machining, it's no surprise that the material is more than capable of lasting a lifetime. For example, in a study that measured the hole-to-hole spray abnormalities after a 100-hour fatigue test of three different injector nozzles, the reason for differences in spray pattern was owed to build up of combustion products, not material fatigue.

This leads to the next point of cavitation corrosion, joint with the type of surface finish available on the nozzles. They are dependent of each other because poor surface finish will invite residues of fuel bind to the injector meaning it can become an auto-ignition point potentially ensuing cracks to fracture the material, but it also leads to soot and other corrosive products building up on the nozzle which can then introduce cavitation to occur on the nozzle orifices and external face.

For example, from a study conducted to test deposit on injector seat and orifice, they found that with an injector that has; straight drilled holes, had no amorphous silicon coating and no hydro-erosive grinding showed less material build than that of the worst studied; 3° taper, an amorphous silicon coating and used hydro-erosive grinding to change the surface finish.

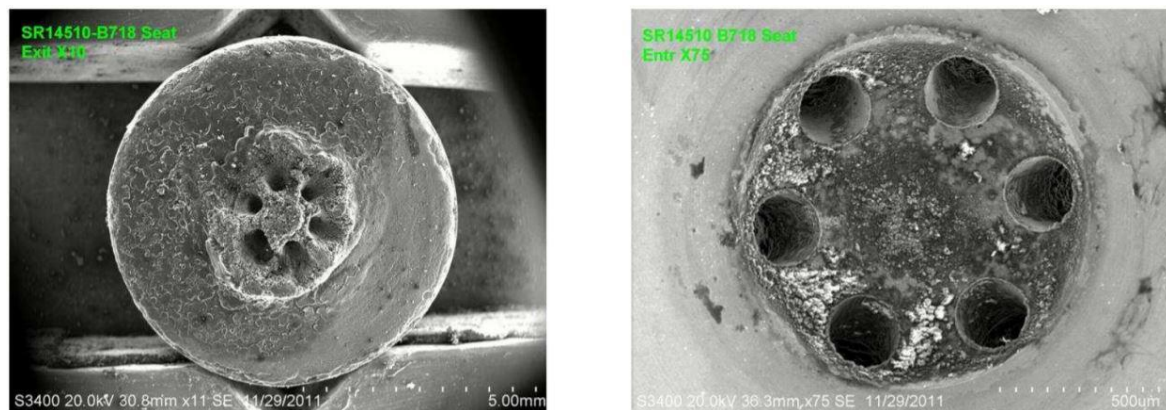


Figure 8 Exit side (left) and internal face (right) of the injector orifices for the study with; straight drilled holes, no amorphous coating, and no hydro-erosive grinding (Imoehl W., 2012).

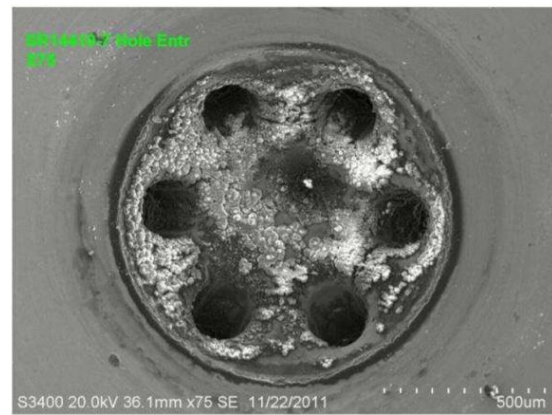
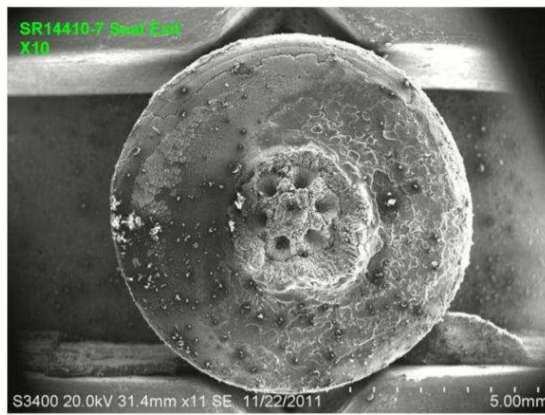


Figure 9 Exit side (left) and internal face (right) of the injector orifices for the study with; 3° tapered holes, amorphous coating, and hydro-erosive grinding (Imoehl W., 2012).

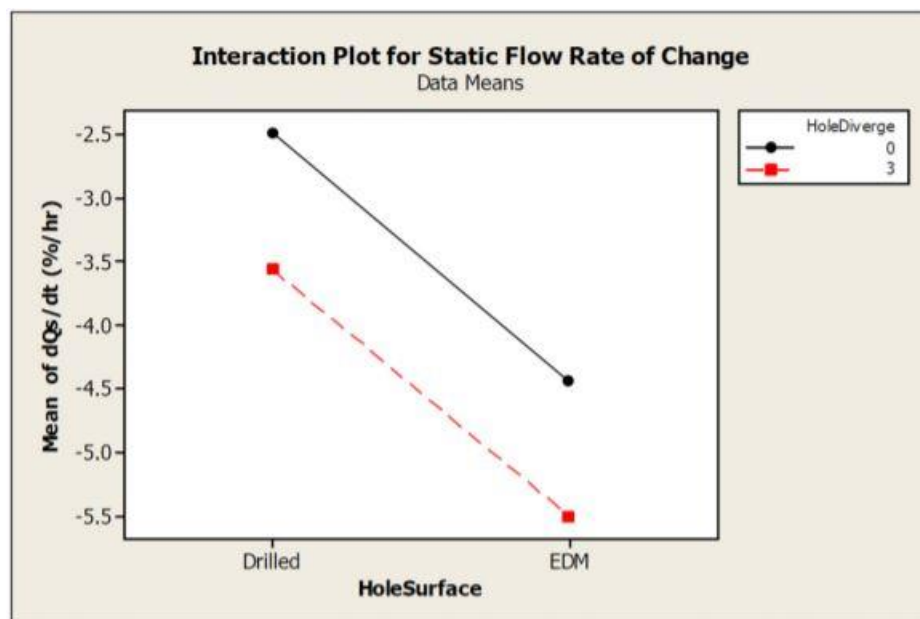


Figure 10 Average change of static flow rate due to surface finish and the difference between machining methods (Imoehl W., 2012).

With the build-up of these substances due to surface finish, cavitation corrosion can be induced because of the “formation and instantaneous collapse of innumerable tiny vapor bubbles that result in pits on the metal surface” (WebCorr CORROSION CONSULTING SERVICES, 2020).

During a study conducted on the effects of E100 fuel, which is a common fuel used in Brazil, it has been found that after a test of 400 million injection cycles can have serious impacts on the internal face of the nozzle, seen below.

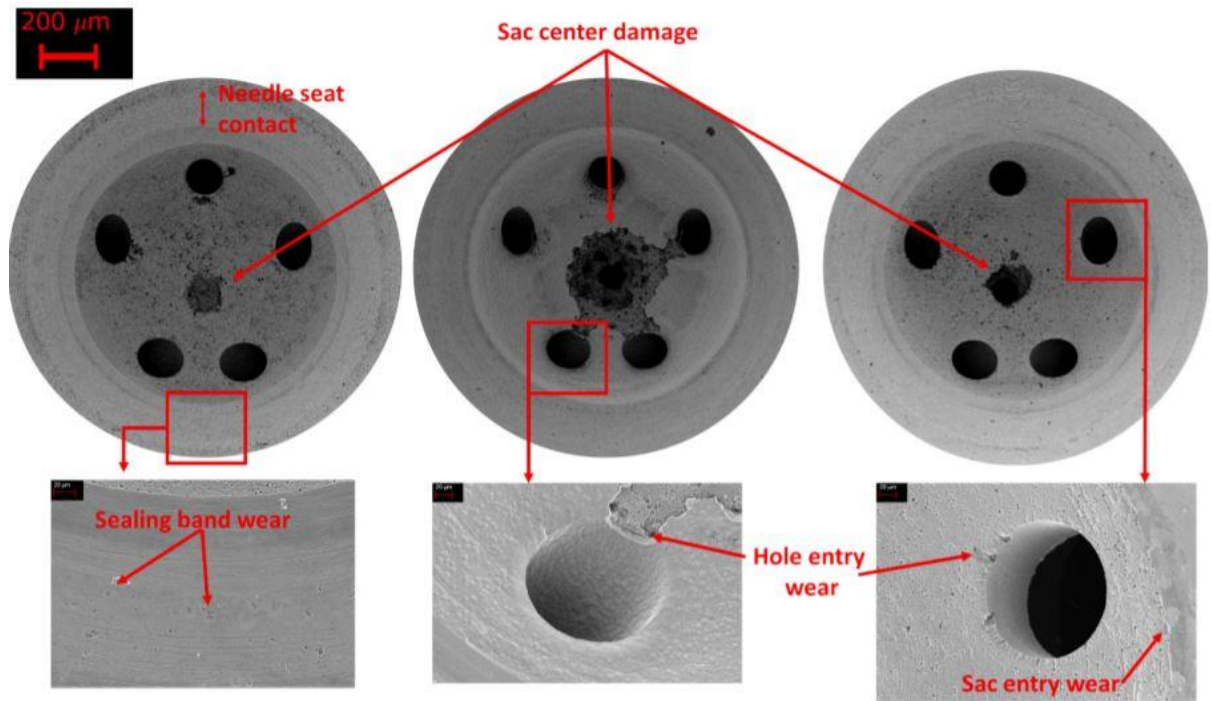


Figure 11 Patterns of damage on GDI injectors after 400 M injection cycles (Eduardo Gomez Santosa, 2020).

As is evident from this investigation the degradation of the injectors can be significant, and this can lead to a removal of protective surface finishes, like nitriding, and dependent upon the material used for actual construction it could lead to failure of the component because of corrosion of the metal underneath, like AerMet 100 that is known to have poor corrosion resistance.

However, despite the chemical deposition of the material, cavitation occurring in the material can also be attributed to sharp corners, because it has been previously found by Andriotis et al. that cavitation structures originated from already existing sites that formed at these sharp corner areas inside the nozzle where the pressure had fallen below that of the vapour of the flowing liquid (Mathis Bode, 2017).

4. Experimental Procedures.

Regarding the experimental procedures used to investigate the initiation and effects of cavitation, commonly used is laser or spark induced bubbles. This is because it's readily understood that when the bubble reaches maximum radius, the dynamics of the bubble are no longer influenced by the hot plasma forming inside the bubble and they behave like hydrodynamic bubbles (Eduardo Gomez Santosa, 2020). However, this method isn't necessarily applicable to high pressure injectors because the conditions of operation if vastly different to the standard experimental setup of still water used and a bubble induced by a laser.

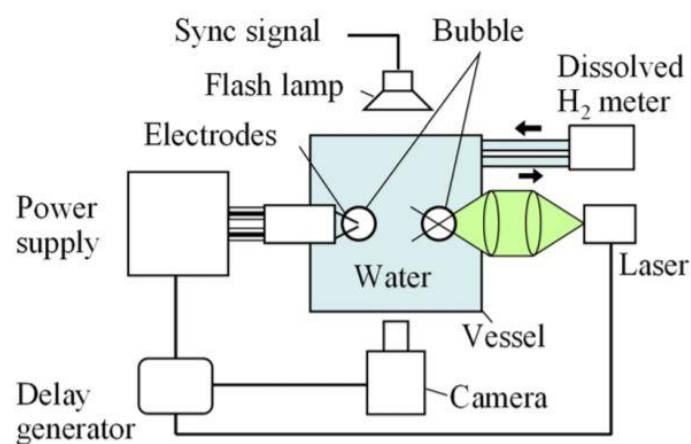


Figure 12 Schematic of setup for the observation of bubble dynamics and measurement of dissolved hydrogen (Takehiko Sato, 2013).

With the experiment conducted by Santosa, E. G. et al., they choose to subject the injector to a cycle of 400 million operations with a 1ms cycle period and a gap of 6ms between operation. This test procedure is also rather niche in respect to using E100 fuel (100% ethanol), this fuel is only really commercially available for use in Brazil and isn't exclusively used. So, for comparative studies to purely gasoline injectors it's difficult to say there will be a correlation, but it is known the fuels in the UK and globally are beginning to contain higher amounts of ethanol blended in for emissions reduction, hence the definite pertinence of this study.

There is no given reason for the use of this specific experimental procedure but considering the operation of 400 million cycles it's clear the intent would be to operate close to the expected lifetime of the component. Unfortunately given the nature of completely transient operation of a fuel injection system used in an ICE vehicle it's very difficult to quantify the operating temperatures and pressures that should be used for

study; therefore, it's thought that a better approach would be for a continuation of homologation sequence load cycle for a vehicle should be used to understand the effect more appropriately on a specific injector, because of the specificity of ICE's and their components. However, the experiment did find cavitation sites occurring at all expected positions; injection hole inlet, the sac centre, and the sac volume entrance.

Another testing procedure to show the effect of cavitation can be seen in a study conducted by Risi A. D. et al., where the setup was to test various injector nozzles after operation for 100 continuous hours to then measure the changes after. This study once again proved to show that cavitation occurs despite the operating conditions, because it can be seen in the following figures where the spray diameter is larger than that of the orifice exit diameter.

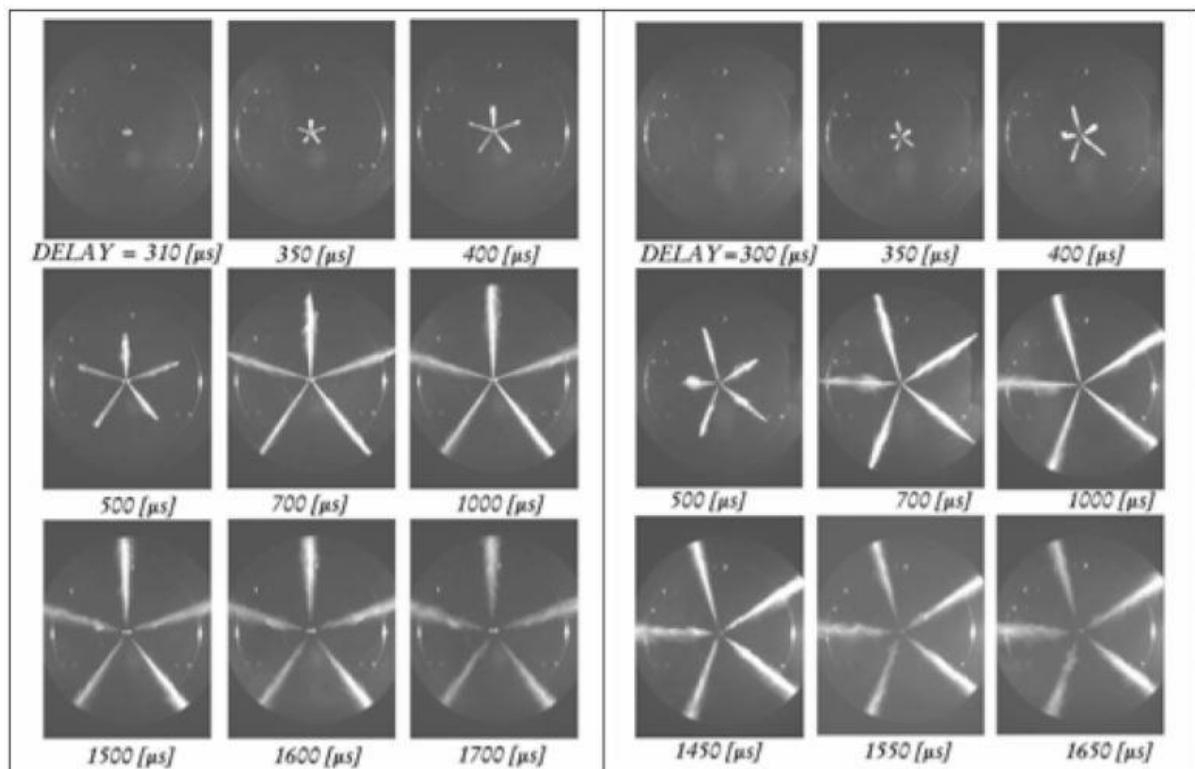


Figure 6: Nozzle MS1-11P=1400 bar, ET=800 μs , Q=27 mm³/shot.

Figure 7: Nozzle MS1-03U P=1400 bar, ET=800 μs , Q=27 mm³/shot.

Figure 13 Spray patterns of two of the tested injectors after 100 hour of in engine operation (Arturo De Risi, 2000).

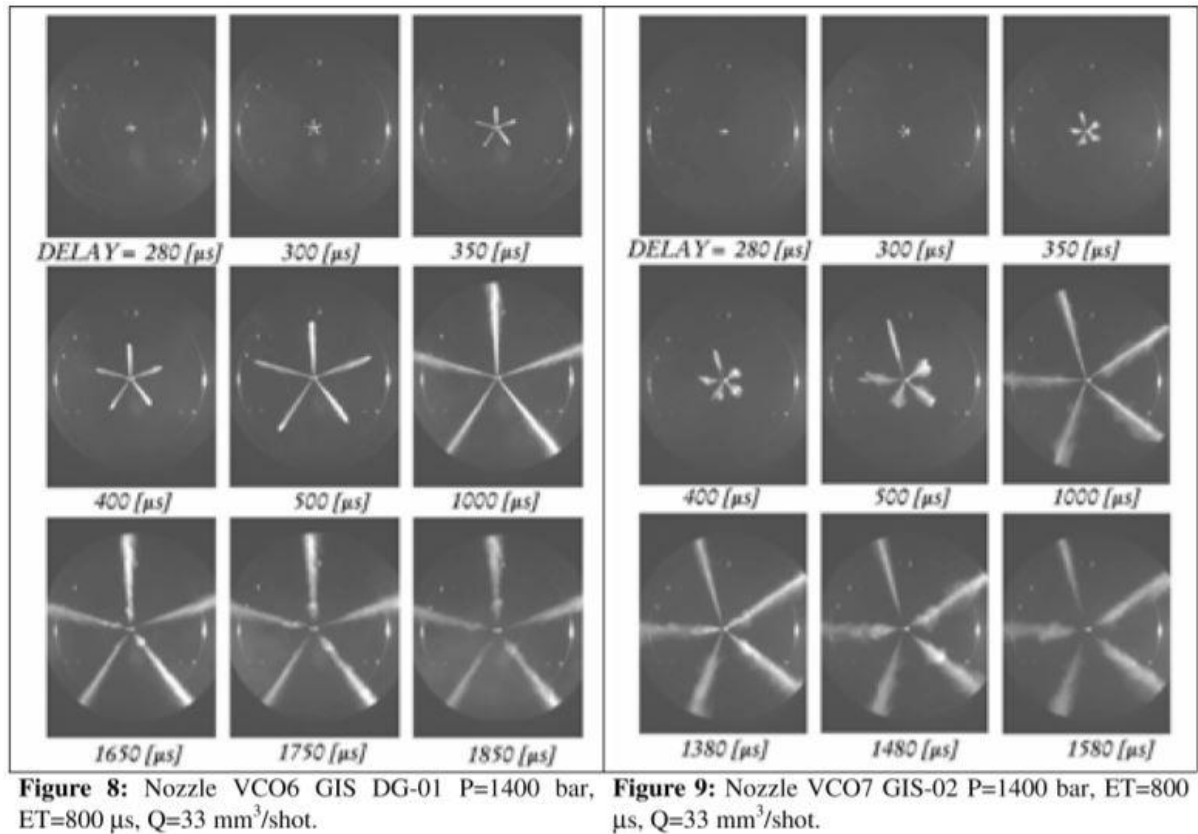


Figure 14 Spray patterns of another two of the tested injectors after 100 hour of in engine operation (Arturo De Risi, 2000).

As can be seen the injectors MS1-03U and VCO7 GIS-02 are both seen to have several of the injector holes experiencing cavitation which is highlighted by the wider than orifice exit diameter and shorter than expected spray patterns occurring. The best representation of the detrimental effect of this is looking at the papers figure 8 & 9, shown above, and the difference between the spray patterns of two different injectors subjected to the same testing and same operational conditions, identifying that manufacturing of the components is the reason for failure and not exclusively the application. So, it's clearly important during manufacture and development of materials to understand how it will react with its surroundings, i.e., this application clearly warrants the need to deal with high pressure, high alcohol content fuel, however it could be argued that with the specificity of the application regarding combustion of E100 fuel, these injectors would only really be used in Brazil, as opposed to the rest of the world. So perhaps during the design process this region wasn't taken into consideration for sales and didn't necessitate this testing procedure, hence they don't perform as well.

5. Conclusion.

In conclusion, it's clear that through the evolution of high-pressure injectors the mechanisms of failure that are key to the detriment of the component are due to primarily cavitation occurring from operation, because of the pressure differentials. This has been found to not always occur however with some types of injector and this is thought to be owed to the manufacturing process and type of material used.

These materials are very hard, have a high fracture toughness and extremely high tensile strength, hence why it isn't common to see an injector fail from a mechanical operation issue in terms of rapid fracture or crack propagation because the structures are commonly "flawless" are demonstrate a good coalescence of carbides within the macrostructure. For example, the X15TN alloy presented by Aubert & Duval can be seen to have a far superior structure to that of the closest similar alloy;

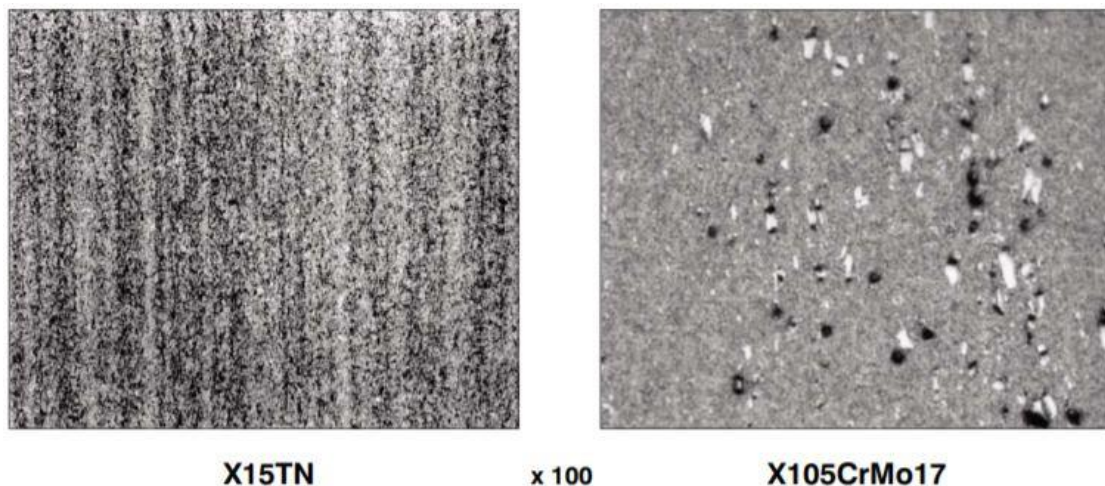


Figure 15 Typical structure of X15TN and X105CrMo17 alloys (AUBERT & DUVAL, 2021).

It's been found that adding a coating to the surface of high-pressure injector nozzles can have a detrimental effect of the component because it increases the surface roughness and therefore increases the residuals attached to the surface, and this can initiate processes like cavitation. Or the residuals can create a point of auto-ignition within the cylinder and this can lead to poor combustion, meaning more soot and other unwanted products to build up in the system and this cycle can rapidly lead to failure.

It is also shown that the use of laser-EDM drilling for the holes in the injector nozzle should be the favoured choice during manufacture because the tolerances can be reduced, with the bonus of a better surface finish. It was also found that the second choice should be laser drilling and the final choice as microhole-EDM.

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