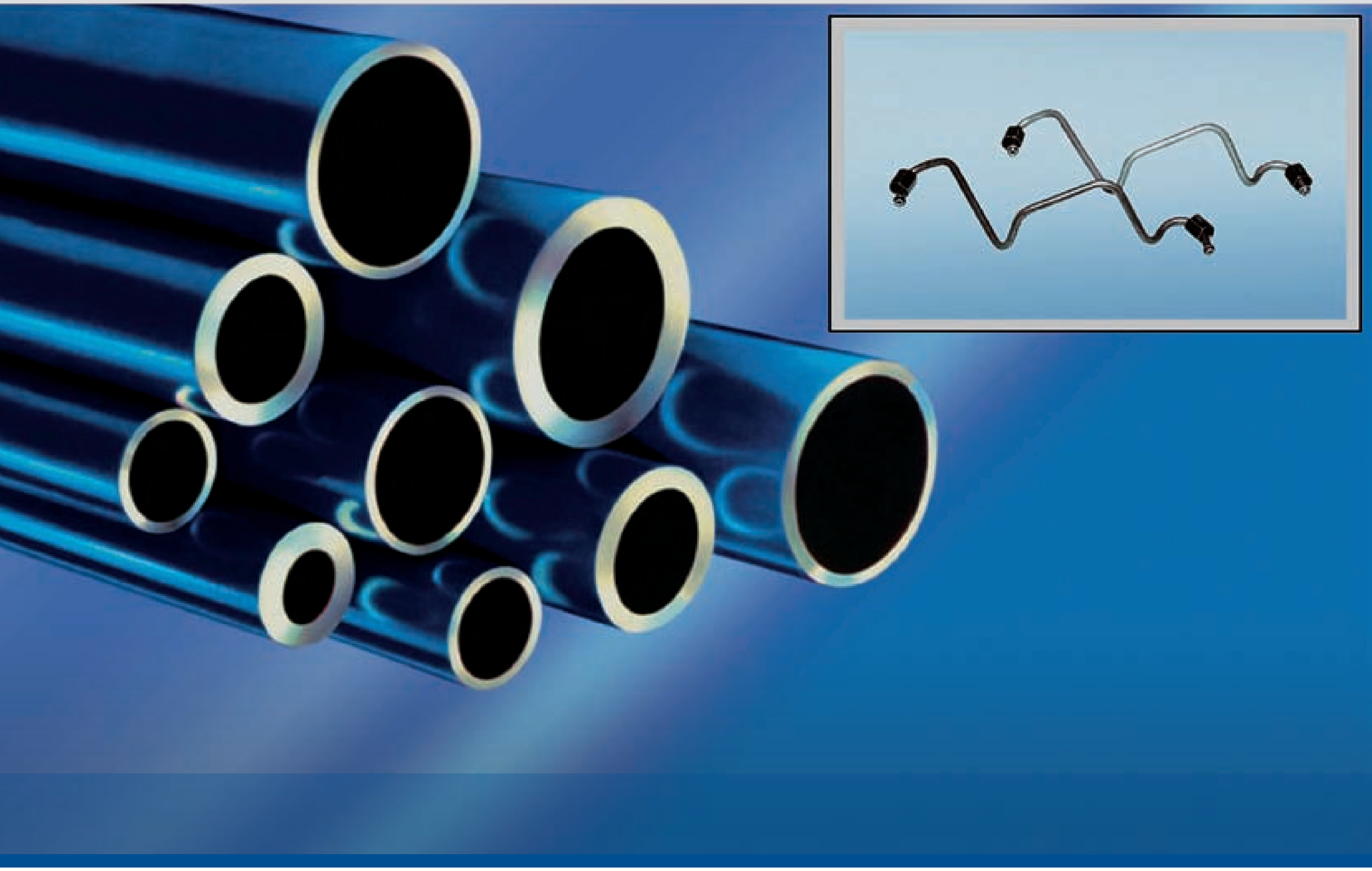

Precision Tubes for High-Pressure Diesel Injection Lines

The requirements on diesel injection lines raise because of increasing customers demands and more rigid environmental laws. In this context higher injection pressures effect both aspects positively. One important condition for increasing pressure levels is the economical provision of suitable injection lines. To reach this aim, Mannesmann Präzisrohr GmbH developed precision tubes for injection lines, which are fulfilling these increasing requirements.

1 Introduction

In recent years the market share of diesel driven cars increased rapidly. The main reason for that is the revolutionary evolution of the diesel technology. The development of high-pressure direct injection systems with continuously raising injection pressures lead, in combination with turbo chargers, to a massively increasing performance of the engines along with a reduction of the environmental harming. Thereby the higher energy density of diesel compared to fuel is already used by Audi for example in endurance motorsport races. To transform these developments to serial production, systems have to be developed to process the diesel in the necessary way and to bring it with pressures of more than 1800 bars to the combustion chamber. When using a Common-Rail-System, which has established oneself against the pump-injector-system, this happens by a pressure reservoir, called rail, and going off of it the injection lines, which are extremely subjected to dynamic load, because of the high medium pressure level combined with the high-frequented, with the engines revolution oscillating overall pressure load, **Figure 1**. Material development, a continuously improve of the design of the process chain of tube manufacturing and an optimized autofrettage process brought the Mannesmann Präzisrohr GmbH into the position to produce injection lines for automobiles, which can exceed and fulfil the demands of the pressure level of 2000 bars for raising performance and reducing emissions of future engines.

2 State of the Diesel Technology

Compared to fuel Diesel has with a calorific value of 9.8 kWh/l an about 10 % higher energy density. This advantage is used by modern diesel engines to raise the performance in combination with a reduction of the fuel consumption. The consumer considers these aspects intensively when he makes his decision for a new car especially with respect to the raising oil price, tightened laws and a higher ecological sensibility. Because of this, the market share of new diesel automobiles increased from about 10 % in the 1970s to more than 50 % in the recent years in Europe.

For many years the fuel mixture preparation of diesel engines was realized by pre-chamber or turbulance-chamber processes. In recent times the direct injection process was developed intensively with the result that the performance characteristic has completely changed. Especially modern turbo charging en-

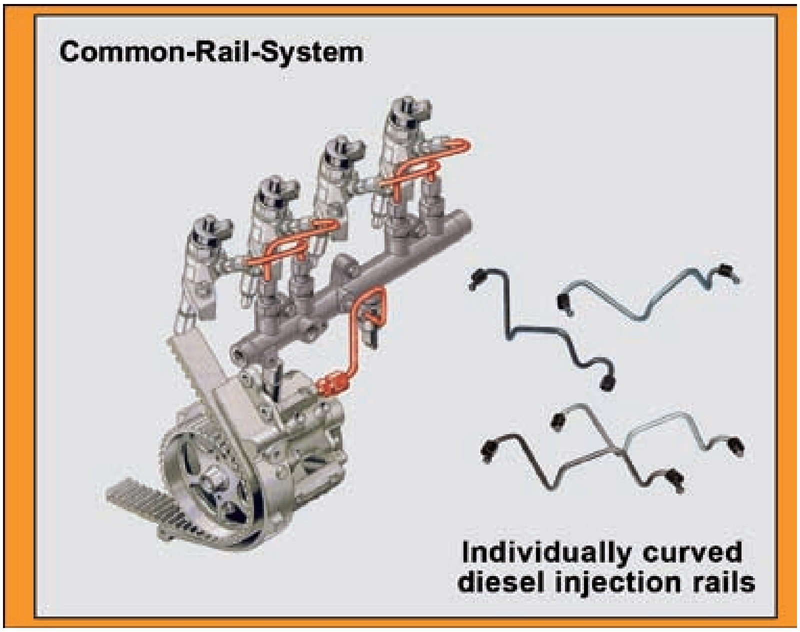

Figure 1: Common-Rail Diesel injection systems

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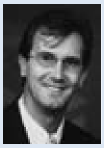
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gines reach high torque levels in very low revolution speeds in combination with a low fuel consumption. This became able on the one hand by the development of the exhaust-driven turbo chargers and on the other hand by very high injection pressures which makes the potentials of the direct injection usable. In this context the common-rail and the pump-injection technology were produced in serial cars, but only the common-rail-technology is established in the next diesel generation. In the common-rail-technology two main systems are distinguished. These are injection system with and without a pressure intensifier. In engines with pressure intensifier there are quite low pressure levels of about 1350 bars in the rails and the injection lines which are transformed by the intensifier on high injection levels. In engines without pressure intensifier the high pressure level affects on the whole system. This leads to high technological requirements for the rail and the injection lines. The advantages of common-rail-engines without pressure intensifier are the simple design of the injection system with respect to the overall size and costs of the components and a higher flexibility regarding pre-injection and the characteristic of the injection process.

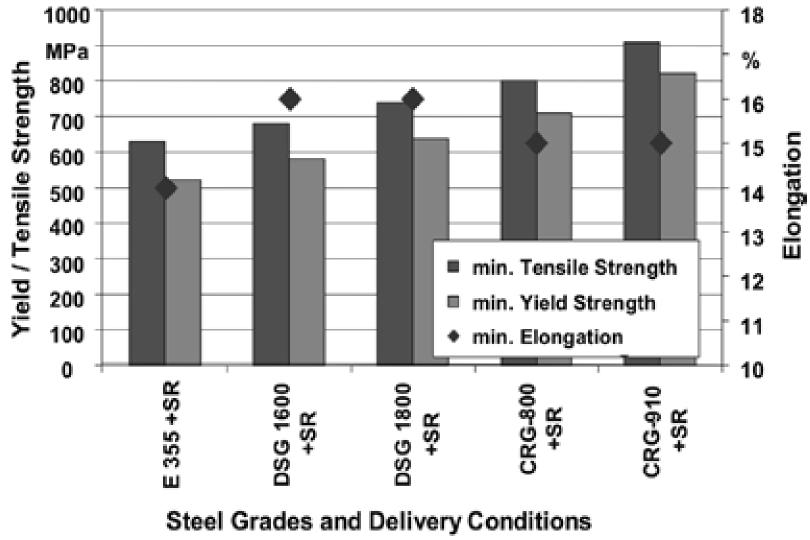

Figure 2: Mechanical properties of the investigated steel grades

3 Demands on Diesel Injection Systems

In common-rail-systems without pressure intensifier the whole system positioned behind the high pressure pump is affected by a high, with the engine revolutions oscillating dynamic load. Compared to the injection lines, the volume of the rail is quite high to work as a pressure reservoir. This reservoir provides a basic fuel volume with a basic fuel pressure to the system and compensates bigger volume and pressure variations as a result of removing fuel and refilling. That is the reason why the rail is directly linked with the high pressure pump and why the rail is manufactured as a tube of a high wall thickness which is closed on the opposite site to the pump. From this rail the injection lines go off to the injectors of the cylinders. The demands on these lines are higher than the demands on the rail. The wall thicknesses are lower than the rails walls with the result, that the structural resistance against the internal pressure is mechanically lower. The thinner walls are necessary as it is an important demand on the injection line to compensate tolerances in the installation space in the engine as well as to provide good bulge and bending properties. This leads in combination with the rising internal pressures to very high demands on the mechanical properties regarding toughness fatigue durability and the inner surface quality.

Basing on the pressure level of the first direct injection engines with about 1350 bars today pressures of 1600 to 1800 bars are state of the art. Higher injection pressures could not be reached, as there were no suitable high pressure lines in the required dimensions. Using an optimized process chain and new material concepts Mannesmann Präzisrohr GmbH managed to manufacture tubes for injection lines, which are suitable for the 2000 bars pressure level.

4 Tubes for Diesel Injection Line

The production of tubes for diesel injection lines is a long established core competence at Mannesmann Präzisrohr GmbH. In this context, it accompanied the engine Producer along the technological development of modern diesel engines. In the beginning of this technological trend the potential of the direct injection was early identified and the strength against alternating load of the tubes systematically increased by holistic process and material optimization.

There are two main research and development strategies to increase the pressure level. This is on the one hand the material development and on the other hand the reduction of surface discontinuities or their effects as potential crack starters. The target of the material development is to get a low cost steel grade with a high mechanical strength as well as a high toughness to be resistant against the static pressures and the dynamic alternating load. The basis for the development was an E 355 in stress released condition, **Figure 2**. Diesel lines of this material are suitable for pressure levels lower than 1600 bars.

The next generation of materials for diesel injection lines was the development of the grade DSG 1600 for pressures of more than 1600 bars, basing on the E 355 with optimizations in the production process along with tightened tolerances for the alloy composition with the result of a higher toughness. This leads to a higher ductility as well as to a higher tensile strength.

With the next step of development the pressure level of 1800 bars was reached by the grade DSG 1800. This material has a significant higher mechanical strength compared to the DSG 1600 with a similar toughness. This aim was reached by the use of microalloying elements, which are raising the strength as well as the toughness by creating a very fine sized grain. Furthermore the autofrettage process was adapted on the higher mechanical properties.

The current material developments CRG-800 and CRG-910 are targeting on pressure levels of more than 2000 bar and which are offering the opportunity to maintain the demands of the EU emission laws. In this context the CRG-910 has as a higher mechanical strength than the CRG-800 with a similar toughness.

Figure 3 shows a lifecycle chart with the result of oscillating pressure tests of CRG-910 in the dimension of D_A x D_i = 6.35 x 3 mm. In the context of these investigations pressure expansion tests with different pressure oscillatory widths are accomplished and the number of load changes is documented. Starting at very high pressure levels the testing level converges to an asymptotic value, which is defined as the fatigue endurance limit. To avoid an extreme testing volume a value is chosen which is defined as fatigue endurable.

Basing on these results a variance of the failures is identified, which is used as the basis for the 1 ppm conditional probability of failure. With respect to the customers demands, relating to the dimensions and design of the injection lines an individual pressure level is approved. In this context the medium fatigue endurance limit and the variance of the failure T effect the testing results to make a guaranteed statement for the lifetime and to minimize early failures.

Figure 4 shows testing results for the individual steed grades. It has to be considered that depending on the case of operation different tube dimensions were investigated. The development step from the E 355 to the DSG 1600 enabled a higher pressure oscillatory width but also the variance of the failures increased. That was the reason for the development of the DSG 1800 for pressure levels higher than 1800 bars. Testing the DSG 1800 the pressure oscillatory width was nearly equal to the width of the DSG 1600 but the variance of failure decreased on a level lower than T = 1,07. The wall thicknesses of both specimens were comparable. The next specimen in the figure is also a DSG 1800 with a higher wall thickness in the dimension D_a x D_i = 8 x 3 mm. Because of the highest wall thickness these lines reach higher pressure oscillatory widths with a slightly reduced variance of failure. With the new steel grade CRG 800 the variance of failures could be reduced additionally. This leads to a higher accepted pressure level for the tubes. Testing the CRG-910 the results show an increasing pressure oscillatory width compared to the CRG-800, but the variance also was slightly raising.

A second main influence on the life time of diesel injection lines is represented by the mode and the dimension of imperfections on the inner tube surface, which can be served as a crack starter under oscillating fatigue load. These imperfections result from the hot rolling process, so they are unavoidable. But it is the aim of the production process to reduce these imperfections by using different mechanical or chemical treatments of the surface with respect to economical reason. The DIN ISO 8535-1 devides the modes of imperfections in different failure levels in which the diesel injection lines were classified depended on the mode and depth of the surface imperfections, **Figure 5**. For the quantification of the lines usually the levels S, Q and P (highest level) are used.

For a most suitable high pressure diesel injection line, the mode and quantity of imperfections should be as low as possible to avoid the possibility of an early failure. That is the reason why the inner surface is intensively observed. But the extension of the cracks from beginning in the inner surface is not only depending on the surface quality but also on the

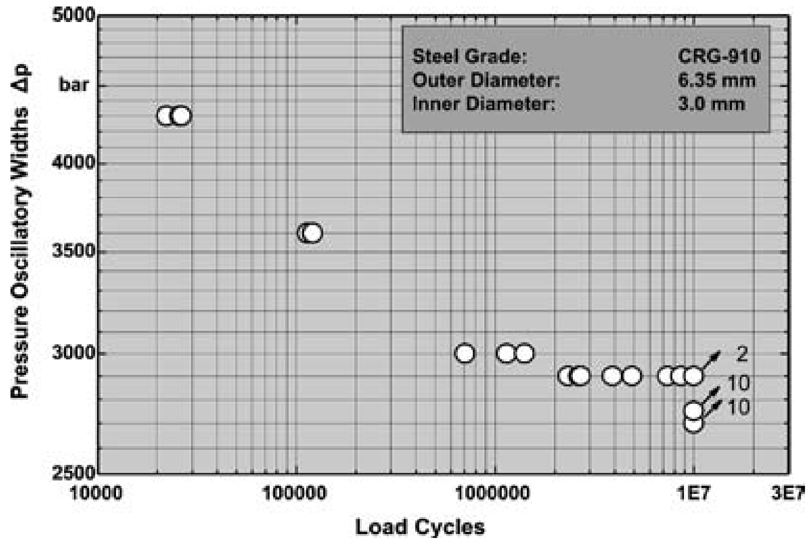

Figure 3: Fatigue diagram of the CRG-910

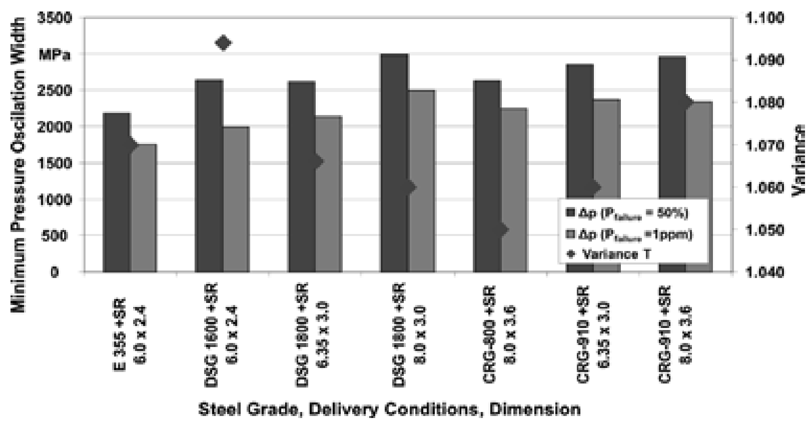

Figure 4: Acceptable pressure levels for different dimensions and materials

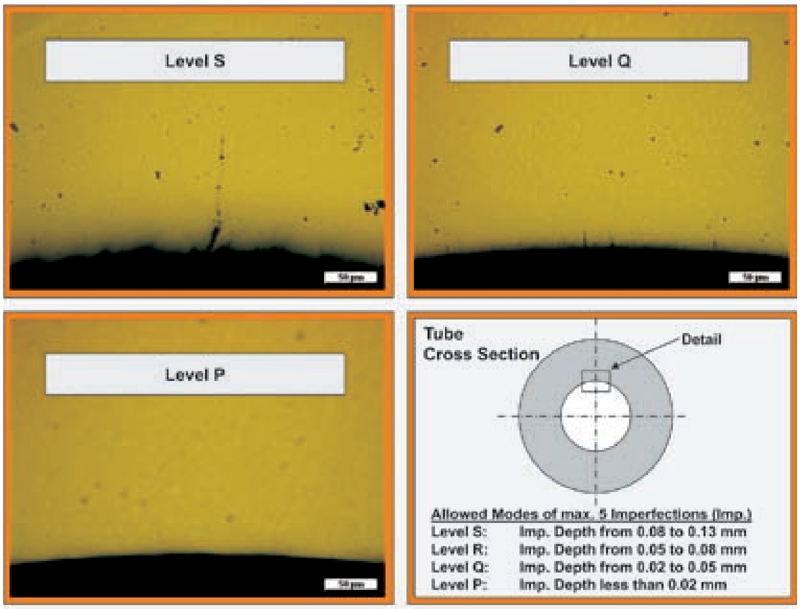

Figure 5: Surface imperfection of Diesel injection lines according to DIN ISO 8535

local tension profile. To get such a suitable residual stress profile diesel injection lines were optimized in their properties by using autofrettage processes.

Mannesmann Präzisrohr developed in cooperation with the Salzgitter Mannesmann Forschungsinstitut (SZMF) a simulation tool to receive the best autofrettage pressure for the injection lines with regards to the tube dimension and the material. So the pressure can be especially optimized on the individual diesel injection line.

The effects of optimized autofrettage processes can be seen in **Figure 6**. It shows the result of two testing series of two different tubes manufactured by different process chains. The first line reached the quality level P by using a chemical deburring process, while the second line achieved the level Q in the as-drawn condition. Both lines got autofetted in the same way.

Figure 6 shows the endurance chart of the tubes. It becomes evident, that the tube with the higher surface quality does not reach significant longer life times. In these tests the untreated tube had a higher pressure resistance as the chemical treated. This shows, that on the one hand a high surface quality is important for high pressure diesel injection lines. But on the other hand an optimized residual strength profile leads to very long life cycles of the tubes. In this context it can be goal-prominent either to optimize the interior surface at high expenditure or to reduce the effects of the unavoidable surface imperfections by optimized autofrettage processes. So both the life time of the lines can be increased and the manufacturing costs can be reduced by avoidance of the treatment of the inner surface. The selection of the respective strategy has to orient at the individual process costs.

5 Summary

The requirements on diesel injection lines raise because of increasing customers demands and more rigid environmental laws. In this context higher injection pressures effect both aspects positively. One important condition for increasing pressure levels is the economical provision of suitable injection lines. To reach this aim, Mannesmann Präzisrohr GmbH developed precision tubes for injection lines, which are fulfilling these increasing requirements.

To raise the pressure levels up to more than 2000 bars two main development strategies were followed. On the one hand the material got several development steps to reach higher mechanical strength as well as a higher toughness. Along with this the production process was and will besystematically optimized for this product. On the other hand early failures can be prohibited by reducing surface imperfections or the effect of them. It could be shown, that the optimized use of the autofrettage leads to a very suitable residual stress profile in the tubes cross-section. The result is, that for reaching the 2000 bars pressure level the highest surface quality level is not absolutely necessary if the residual stress profile is optimized on the tubes dimension and material. But for the step to the next higher pressure level it can be necessary to combine the autofrettage with the chemically deburred surfaces. ■

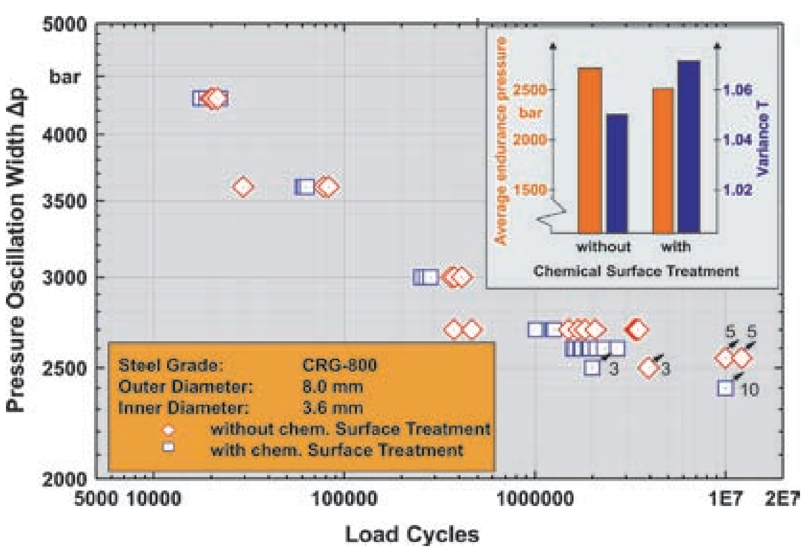

Figure 6: Comparison of load cycles of tubes with and without chemical surface treatment