The Application of Mechanical Surface Treatment in the Passenger Car Industry

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1 Introduction

At the beginning of automobile manufacturing, about 100 years ago, customer expectations concerning performance and quality were relatively low. People drove cars for the purpose of getting quickly and reliably from point A to point B. Cars were built from conventional engineering materials at that time. Iron and steel constituted 80% of vehicle weight. Synthetic materials did not exist then.

Nowadays, this situation has completely changed. Modern cars must meet a large variety of additional requirements. Among these, the most important are safety, environmental effect, resource preservation, climate comfort and favorable cost of ownership.

Ultimate driving performance can be achieved by fulfilling these requirements and, in addition, by providing an individualized driving experience, i.e. superior agility, engine power, elasticity in speed changes and corner handling. These high demands on automotive engineering can only be met through the appropriate use of advanced materials in combination with light-weight design.

As a result, the composition of materials in passenger cars has changed significantly during the last decades. Fig. 1 shows a typical distribution of the materials of a modern passenger car, in this case the current BMW 5 series. Iron and steel only make up 51% of the weight, whereas light metals and plastics make up 15% and 12% of the weight, respectively.

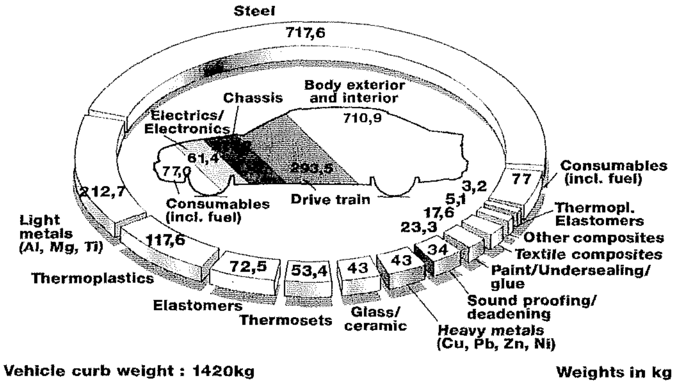

Figure 1: Materials in the BMW 520i

2 The Role of Materials Technologies in Automotive Engineering

Most materials in modern vehicles have been specially developed for the new automotive requirements. The main objective of the development of advanced materials technologies for automotive applications is to promote the desired properties of a vehicle.

This is usually achieved by:

- technologies improving material properties (e.g. mechanical surface treatment of metal components)
- technologies where the material has an additional function (e.g. combination of reduced machining costs and enhanced strength of fracture-splitting materials for conrods or crankcases)
- technologies reducing the number of processing steps (e.g. bake hardening effect during the painting process of body panels which subsequently reduces the number of forming steps)
- technologies preparing a material for a new application and enabling it to substitute other materials (e.g. replacing cast iron by aluminum alloys for crankcases)

Neither the complexity nor the novelty of these technologies is the key factor. Of prime importance is the contribution to enhanced driving performance achieved by advanced materials technologies. In addition to the manufacturing processes, economical and ecological aspects must also be considered.

In this respect, notable achievements made by advanced material technologies include:

- reduction of fuel consumption through light-weight material design
- improvement of comfort and handling performance through light-weight material design for unsprung masses
- increased power output through light-weight material design for oscillating masses
- improvement of crash energy management through optimized deformation behavior
- reduction of cost of ownership through wear resistant material systems
- maintenance of the original appearance and function throughout the lifetime of the vehicle through corrosion resistant material systems

Many of the above mentioned requirements can only be achieved by increasing the fatigue strength of highly loaded car components.

The optimal development of the strength of metals requires mechanical surface layer hardening.

3 Concept of Mechanical Surface Treatment

The mechanical surface treatment is based on the elastic-plastic cold-working of the surface. The surface layers are work-hardened and residual compressive stresses are generated. The surface resistance against fatigue crack initiation and propagation, corrosion fatigue or friction fatigue increases significantly and therefore, improves the structural performance under cyclic loading. In addition to that, a reduced surface roughness due to the flattening of roughness peaks can be expected.

The increase in surface hardness depends on the hardening potential of the material as well as on the material condition before cold-working. For instance, in the case of a highly hardened initial condition, no additional increase in surface hardness is achieved by mechanical surface treatment. Moreover, mechanical surface treatment of highly hardened metals might even result in a reduction of the surface hardness.

The following sections present various examples of the advantages and disadvantages of mechanical surface treatment of automotive components.

3.1 Roll Strengthening

We use the example of a stub axle to demonstrate the strengthening potential of rolling.

The bold line in Fig. 2 presents loading sequences for a typical consumer, extrapolated until 300,000 km. The dashed line in the same figure shows the loading sequences under racing conditions on the Nuerburgring, extrapolated until 10,000 km. The loading sequences for the Nuerburgring primarily show intermediate and high load levels and a few low load levels. It must be noted that both sequences were measured from the same car.

In addition to these two loading sequences. Fig. 2 shows the Woehler curves for the stub axle before and after roll strengthening.

It appears that the life span of the untreated stub axle is shortened under racing conditions. The corresponding S-N-curve and the loading sequence intersect. In other words, the load levels that intersect with the Woehler

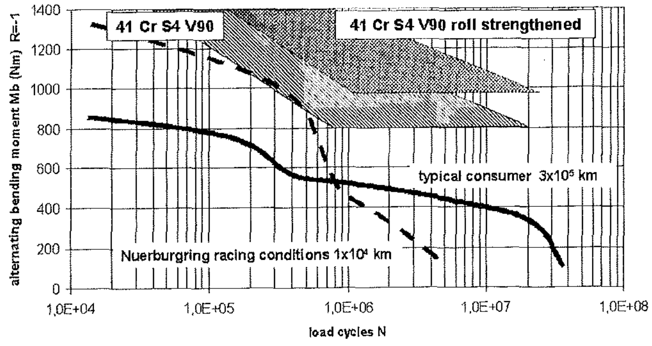

Figure 2: S-N-diagram for a stub axle before and after strengthening as compared to two loading sequences

curve are already high enough to initiate partial failure of the stub axle. However, the S-N-curve of the roll strengthened stub axle is above the loading curves and thus, prevents the stub axle from fatigue failure.

Roll strengthening can be used to induce high residual compressive stresses within critical areas of the stub axle. As a consequence, critical tensile stresses due to the loading sequence are successfully reduced. It is known that the residual compressive stresses increase as the rolling force increases. The optimal rolling pressure can be found from measurements of the residual stresses.

The upper half of Fig. 3 shows a diagram of the lifespan of a stub axle as a function of the rolling force. The lower half of Fig. 3 shows the corresponding measurements of the compressive residual stresses inside the critical radius. The quantitative agreement is good. It appears that the maximum compressive residual stresses are reached over a rolling force range of 12,000 N to 14,000 N. Rolling forces above 14,000 N lower the residual compression. Similarly, the stub axle loses its fatigue strength in this regime.

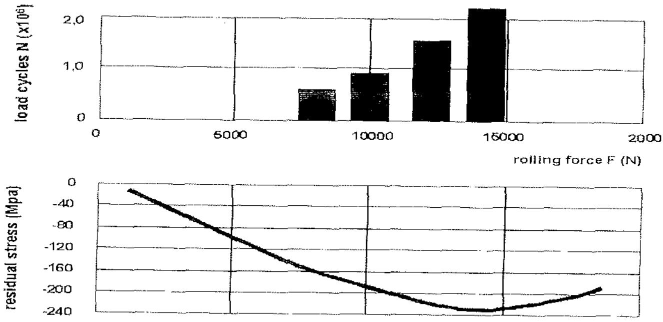

Figure 3: Rolling force optimization based on residual stress measurements

Fig. 4 shows the change in diameter as a function of the rolling force. Again, in close analogy to the residual stresses, the curve attains its maximum at 14,000 N. Further increase of the rolling force results in a reduction of the diameter. As a consequence, the dimensional accuracy and the surface roughness are no longer satisfying. Moreover, the loss of roughness indicates that very high rolling forces destroy the surface layers by means of material separation.

3.2 Thread Grooving

Another possibility to increase the lifespan of car components is the application of chipless forming processes.

The following example demonstrates the increased fatigue resistance of components with internal threads within heavily loaded areas. For functionality reasons, internal threads within critical areas of the part can hardly be avoided. In the case of internal combustion engines, the positioning of the crankshaft bearing is subjected to various constraints. On the one hand, a slender design of the bearing area is highly desirable. In addition to that, due to stiffness requirements, the taphole of the main bearing screw joint should be in the close vicinity of the main bearing boring. On the other hand, the component design must guarantee sufficient fatigue strength. In particular, the taphole of the screw joint between the main bearing and the crankcase is critical. From a mechanical point of view, such a cut thread can be seen as a deep notch in a highly stressed material.

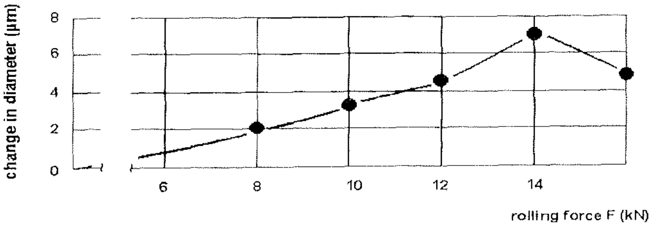

Figure 4: Dimensional change as a function of the rolling force

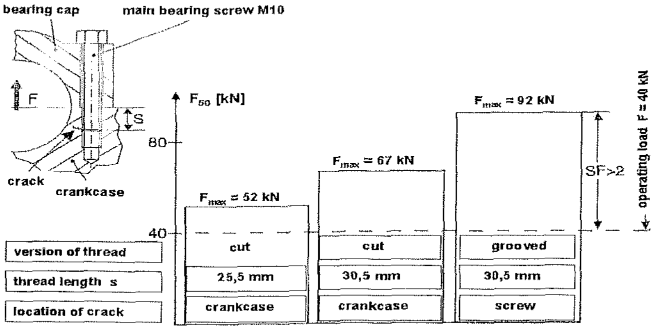

Figure 5: Dynamic experiments on aluminum crankcases; comparison of cut and grooved thread

During dynamic experiments on a light metal crankcase, fatigue cracks initiated within the thread (Fig. 5). The following factors contribute to the likely initiation of fatigue cracks at the lower end of the thread:

- small wall thickness between the thread and the main bearing boring
- stiffness discontinuity due to the lower end of the screw
- significant notch effect due to the thread
- high stresses due to the mean bearing loading and the pre-stressing of the screw

A first step to improve the design was to increase the length of the critical screw by 5 mm (depth now 30.5 mm instead of 25.5 mm). Thus, the most critical spot moved to a region of thicker cross-sections. The fatigue strength increased from 52 kN to 67 kN. However, the minimum design requirement was still not reached.

A significant improvement was achieved by changing the tapping method from cutting to grooving. The resulting fatigue strength of 92 kN was twice as high as the work load of the engine. It must be noted that the thread in the crankcase was no longer critical. The fatigue strength was now limited by the screw.

By contrast to conventional threading, thread grooving does not imply any cutting. Instead, the material is pushed away from the thread valleys. Thus, residual compressive stresses are present in the thread valleys. In the case of dynamic loading, the acting tensile stresses are reduced by the residual compressive stresses. The load level is shifted into a less critical regime, which results in a significant increase of the fatigue strength of the design.

Throughout thread cutting, chips are produced. However, in the case of thread grooving, no chips are formed. Especially for blind holes, a chip-free method is advantageous.

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3.3 Shot Peening

The mostly used mechanical surface treatment method is shot-peening.

Some major advantages of this method are:

- adjustability of the strengthening effect
- high processing quality
- easy surface cleaning
- being well established in the industry

It must be noted that shot-peening is not applied in order to compensate for deficiencies in other steps of the manufacturing process.

The following examples demonstrate the use of shot-peening by the automotive industry.

The design of the chassis suspension is usually based on fatigue strength. Fig. 6 shows the fatigue strength of barrel springs before and after shot-peening.

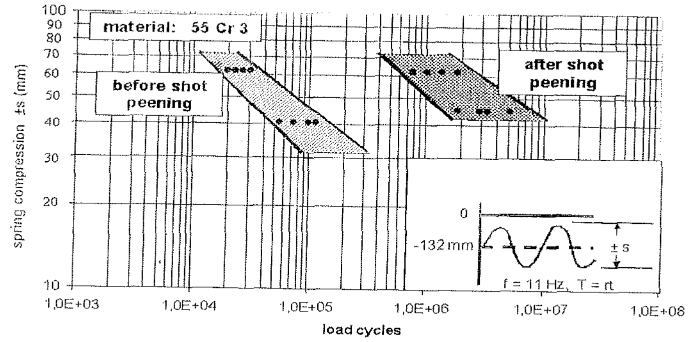

Figure 6: Woehler curves for barrel springs (before and after shot-peening)

For this case, shot-peening lengthens the lifespan by a factor approximately equal to 70. The springs were tested under cyclic compressive loading at a constant pre-stressing. However, it must be noted that these results were found under lab conditions, i.e. no other effects that might have reduced the lifespan were present.

Corrosion has a strong impact on the lifespan of barrel springs (Fig. 7). A salt-spray test was performed (DIN 50021SS, 240 hours). After an optical observation, the barrel springs seemed to fulfill all surface requirements. But the springs did not perform well under fatigue loading. The lifespan was reduced by approximately 40%.

The surface protection had to be improved. The standard surface protection is achieved by a layer of paint. The properties of the paint depend on the baking temperature that usually ranges front 170 to 190°C. But tempering of mechanically strengthened components reduces the residual stresses and thus, the durability.

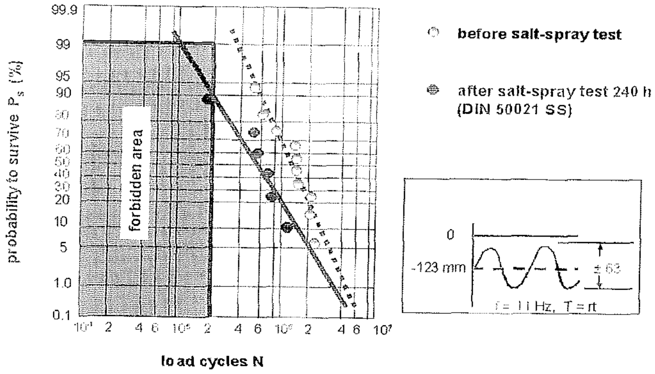

Figure 7: Impact of corrosion on the lifespan of barrel springs

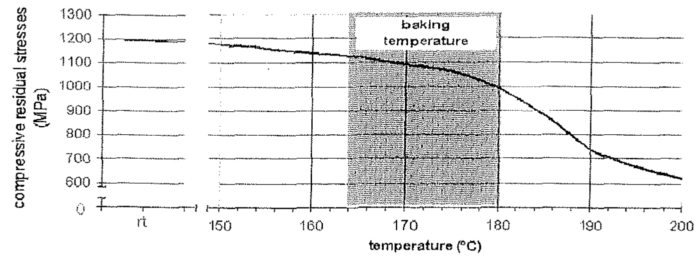

Figure 8: Influence of the baking temperature on the residual stresses in barrel springs

Fig. 8 presents the reduction in compressive residual stresses as a function of the baking temperature after painting. The duration of the baking process was 30 minutes. It appears that the stress reduction increases dramatically for temperatures higher than 180°C. Therefore, temperatures above 180°C must be avoided.

During vehicle operation, the temperature in the barrel springs is about 60 to 80°C. A significant impact on the compressive residual stresses is not expected.

3.4 Shot Peening under Pre-Stressing

An additional increase in strength due to shot-peening may be achieved by the pre-stressing of selected components. We will use the example of a connecting rod.

The general design objective for a connecting rod is to keep the oscillating masses as low as possible. This requires very high fatigue strength of the connecting rod shank whereas the scattering must be as low as possible. This is the only way to achieve both high fatigue strength and cost efficiency.

In the case of engines that are running within a high revolution range, tensile stresses are primarily due to inertia forces. The fatigue-critical sections of the connecting rod surface have to be optimized along the loading direction. An increased performance due to the use of high strength materials with a tensile strength above 1200 MPa is not possible. Without any additional surface treatment, the notch sensitivity of such alloys limits the fatigue strength.

One method to optimize the strength properties is shot-peening under pre-stressing. This procedure induces residual compressive stresses oriented along the loading direction of the connecting rod. Pre-stressing induces additional elastic deformation energy in the component.

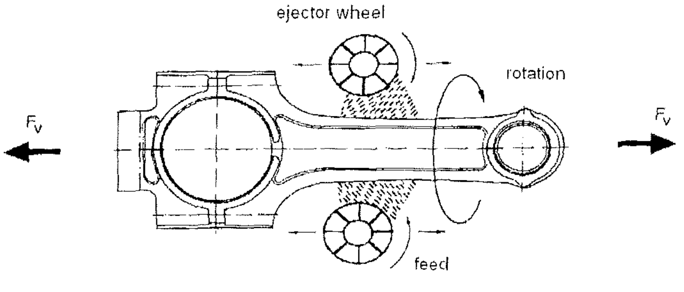

Figure 9: Shot-Peening under Pre-stressing (schematic)

During shot-peening, this energy contributes to an increase of the dislocation density at the surface of the component. The pre-stressing equipment can introduce compressive stresses up to the order of the yield stress of the material.

3.5 Shot Peening - Special Procedures

Challenging engineering tasks often yield innovative solutions. As an example, we will show the engineering benefit of lighter front-axle for rear-wheel driven cars with front engines.

An anti-roll bar is used to limit body roll and thus increase the cornering performance. Typically, it is formed as a torsion bar with a solid cross-section. However, changing the design to a hollow cross-section allows for additional weight savings. A longitudinally welded tube (material 34MnB5) is bent first by cold forming and brought into its desired shape by swaging. Next, to increase the fatigue resistance, shot-peening is applied to the inner surface of the tube. A flexible lance is introduced into the open end of the anti-roll bar. Shot peening media is continuously added to an air flow. The lance tip has a conical deflector so that the steel shot exiting the nozzle is hitting the part at nearly 90 degrees. And finally, after flattening both ends of the antiroll bar, the outer surface of the part is shot peened.

As indicated by torsion tests throughout the procedure development, premature fatigue failure occurred unless shot peening was applied to the inner surfaces of the anti-roll bars. Typically, the fatigue crack started at the inner surface. A required 100% increase of the fatigue life could only be achieved by expensive deflector lance peening. After this treatment, the fatigue cracks initiated at the outer surface, which correspond to the location of the highest stresses.

A permanent monitoring of the relevant process parameters is required to insure high quality standards. Among these, the most important are:

- shot media flow-rate
- peening intensity (air pressure)
- initial positioning of the lance
- velocity of the lance

The technology presented above is currently used for the hollow anti-roll bars of the BMW 3 and 7 series. As compared to the traditional design with a solid section, weight savings of about 45% could be achieved.

4 Summary

The development of light-weight, and thus fuel efficient and environment-friendly cars, is one of the most important challenges facing the automotive industry, Methods to increase the performance and strength of individual components are very important.

Shot peening is competing with various other mechanical and thermo-mechanical methods for surface treatment. Requirements to the component design as well as manufacturing conditions determine the choice of the optimal method. However, shot peening is a well-established method that efficiently increases the fatigue strength of highly stressed automotive components.

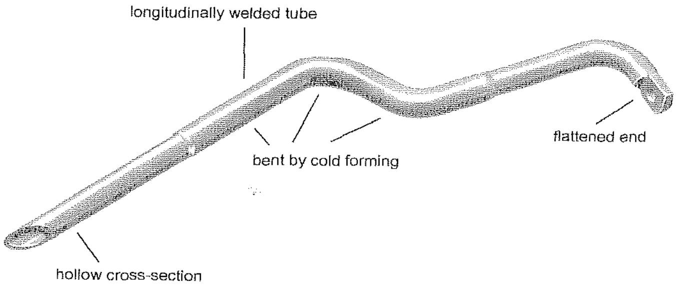

Figure 10: Hollow anti-roll bar of the BMW 3 series with shot peened inner surfaces

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