

Shortening the Process Chain in the Ball Pin Production / Chassis Components by Using Stainless Steel

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Summary

By using an affordable stainless ferritic steel, ball pins were able to be cold forged economically, eliminating the relatively cost intensive process steps of annealing, quenching and tempering, and nitriding. The mechanical-technical characteristics of these ball pins are comparable to parts made of quenched and tempered steels manufactured conventionally (e.g. 41Cr4). We demonstrate that the properties of the finished part are able to be influenced specifically by modifying the process parameters. In particular, the variation in cold working makes it possible to change the strength of the part, depending on the requirements for the ball pins to be produced.

While lightweight construction means savings on energy and CO₂ emissions in the useful phase of an automobile, the use of stainless steel contributes to the improvement of the ecological and economic balance in the manufacture of vehicle components.

Key words: ball joint, ferritic stainless steel, cold forging, static and dynamic strength.

1. Introduction and Aim

Due to rising cost pressure and increasing demands in conjunction with conservative use of resources, energy efficiency and CO₂ reduction, the automotive supply industry is being forced to utilize every opportunity to reduce the cost of parts manufactured. The resulting aim is to cut or save on cost-intensive processing steps while maintaining at least the same technical product properties.

The following discussion of a project between ZF Friedrichshafen AG, Swiss Steel AG and Fuchs Schraubenwerk GmbH is an example of how this aim can be achieved by using the stainless steel X1CrNi12 (designation according to an internal ZF standard) and how both technical as well as ecological benefits can be obtained in ball pin manufacture.

Ball pins are used in the car in many places as a central component in the chassis such as e.g. in transverse arms, track rods, suspension/wheel joints, angle joints and in stabilizer coupling rods. Ball joints consist of a ball pin that runs in a permanently lubricated bearing in a plastic socket which in turn rests in a housing. In order to be able to mount the pin and the socket, the casing is open on one side and is closed after assembly by a holding ring or cover.

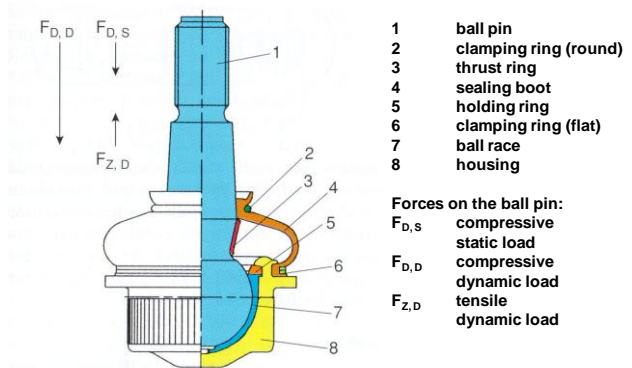


Figure 1: Ball joint (carrier joint), side view and half section [1]

The joint is protected from environmental influences by means of a sealing boot that is fastened by two clamping rings. The holding ring prevents the boot from slipping from the tapered part of the pin [1] (**Figure 1**).

In the conventional manufacture of ball pins, quenched and tempered steel – e.g. material 41Cr(S)4 or 42CrMo(S)4 – in the form of hot-rolled rods is used as the input stock. In the process, hot-rolled rods are annealed (GKZ annealing) to a state structure with spheroidite prior to cold working according to the requirements for cold forming. After annealing, the required surface quality and dimensional accuracy is determined by pickling, phosphatizing and a skin-pass. The ball pin is then subjected to cold forging in several stages. The necessary strength and toughness of the part is determined by

subsequent quenching and tempering treatment. Finally, the pin is machined by turning and (thread) rolling, wherein sulfur additives of 0.02 percent in weight to 0.04 percent in weight clearly improves the machining process.

In India and Asia, ball pins frequently have a cross hole in the thread which secures the nut against lost. 42CrMo(S)4 quenched and tempered to over 1200 MPa is also primarily in use in these regions [2].

Since the mid 1990's, it has become standard practice particularly in premium vehicles to protect the ball pin from corrosion by coating it completely. Ball pins made of worked annealed steels are carbonitrided at an external electroplater after the diameter of the net shape has been turned. In addition to nitriding in a salt bath, gas carbonitriding (GCN) is also available with and without plasma support. The layers deposited or added during nitriding are characterized by very good resistance to corrosion in addition to good wear resistance. Depending on the surface quality, the time of exposure in neutral salt spray testing [3] is 96 h to 240 h. The waste produced during nitriding in a salt bath contains cyanide and must be disposed of. This waste has a negative impact on the life cycle assessment. A disadvantage of gas carbonitriding of ball pins is the embrittlement caused by the process temperature during slow quenching. By reducing the phosphorous content of the steels used, brittleness measured as notch impact energy can be reduced (**Figure 2**).

A general disadvantage of the coating process is that the basic material can continue to corrode, e.g. after the coating has been damaged. In addition, the nitrided layer produced by the nitriding process is extremely hard / tough (600 HV_{0,3}) and the Young's modulus of the outer layer is very high (approx. 450 GPa). The nitride outer layer can be damaged, for example by minimal plastic deformation of the substrate material and thus the corrosion resistance of the part is considerably reduced. The chain of damage in the vehicle, however, is structured in such a way that no surface damage is sustained even during special driving maneuvers.

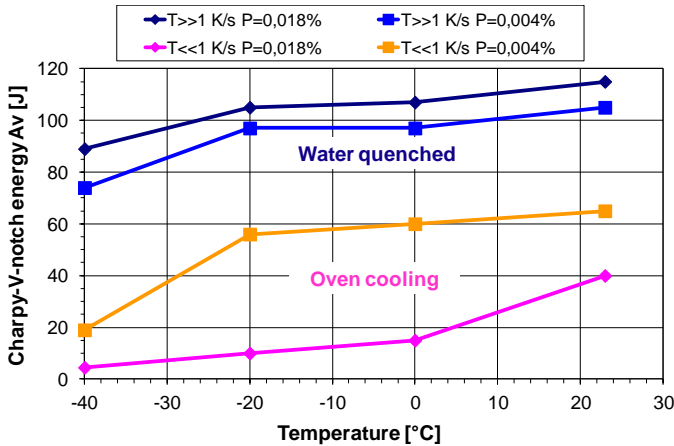


Figure 2: Charpy test (ISO-V samples) subject to the test temperature for slow and rapid cooling from nitride process temperature and for lower and higher P content

Ball pins are typically nitrided by external surface coating companies. Ball pins must often be transported over vast distances. The nitriding process itself also takes approx. 2 weeks, which ties up material and capital.

Given the circumstances described, it becomes apparent that there is an urgent desire for alternative solutions. One option is the use of ball pins made of stainless steels, wherein these pins must meet the existing mechanical and physical requirements and may not be priced much higher than nitrided pins.

The basic manufacturing process for ball pins made of quenched and tempered steel and the intended manufacturing process for ball pins made of stainless steel are shown in **Figure 3**. By using stainless steel as an alternative to nitriding, annealing and quenching can be eliminated, in addition to nitriding itself and the transport – subject to the selection of suitable steels. This not only makes the manufacturing process leaner and more flexible, but also faster.

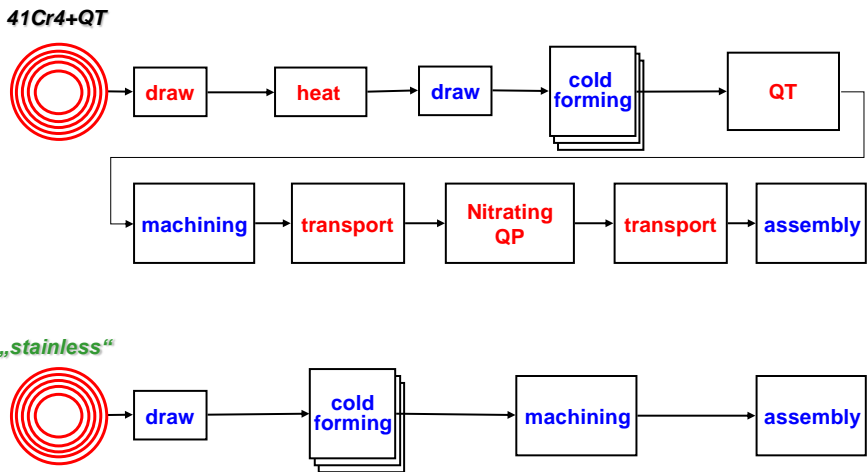


Figure 3: Elimination of process steps by using stainless steels as an alternative to nitrated quenched and tempered steels

2. Saving process steps in ball pin manufacturing

2.1. Material selection

The requirements profile for ball pins is shown in **Figure 4**. In addition to adequate strength, toughness and corrosion resistance, the slugs must also be able to be machined and the ball joint must permanently retain the required joint properties; and this must all

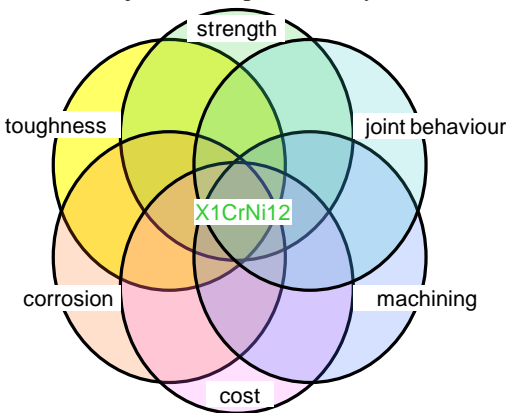


Figure 4: Ball pin requirements

be possible at a competitive cost. Naturally, there are, e.g. austenitic stainless steels with very good corrosion resistant properties and very high toughness. These steel grades, however, are on the one hand fairly expensive and difficult to machine, and on the other, they do not have the desired joint properties.

Free cutting steels are also known that are easy to machine, but do not have the desired toughness. In selecting a material, the focus cannot simply be on one property, but rather the canon of all properties must be taken into consideration. The very low carbon ferritic stainless steel with the ZF internal standard designation X1CrNi12 selected in this case is excellently suited to all of these requirements.

The aim of eliminating cost-intensive process steps such as annealing, quenching and tempering and nitriding by using suitable input stock assumes both sufficient cold formability of the steel in a hot rolled state as well as a corresponding strain hardening during forming so that the mechanical properties required are given to the part. Naturally, this should ideally be done without raising the price of the product by using a high alloy content. The ball pins tested in the framework of this study should have a strength rating of 800-1000 MPa.

For sufficient corrosion protection, a minimum of 11 percent in weight of Cr is required. If the alloying surcharges are compared in an initial approximation for stainless steels, the steels with material numbers 1.40xx are the best. In this group, the heat treatable ($R_m > 800$ MPa) and hardenable ($HRC > 58$) steels have unfavorable corrosion properties due to the relatively high carbon content (greater than 0.2 weight in percent) or they cannot be hardened and tempered to the desired level of strength. In Cr steels with higher carbon contents, an enrichment of the grain boundaries and phase limits with Cr carbides in the form of $M_{23}Cr_6$ (approx. 60 percentage weight Cr) takes place during tempering by means of which the Cr concentration decreases close to the grain boundary to below 11 percentage weight and the steels are thus no longer corrosion resistant. If ferritic stainless Cr steels corrode due to rust film or foreign particles, the corrosion takes the form of pitting.

For the large-scale testing, wire (hot-rolled) rods made of standard Cr steel with material number 1.4003 was used to manufacture the ball pins whose chemical composition in conjunction with an adapted rolling process was designed to meet the requirements. To keep the modified steel from being confused with the standard steel, it was given the ZF internal standard designation X1CrNi12.

Corrosion testing of turned rods made of this material which has historically been conducted in a neutral salt spray test [3] revealed slight contact corrosion only on the ends on the lower side of the rods even after 720 hours. This is produced by the corrosion products of the other parts still located in the chamber. Stainless steels should

consequently always be machined with new lathe tools so that transfer of material from the normal steel is ruled out. The quenched and tempered steel 41Cr4+QT without corrosion protection already has multiple rust corrosion spots after just one hour. But there are also traces of corrosion after nitriding, e.g. on the thread after 96 hours and on the polished ball after 480 hours.

If the contact rust is removed by means of pickling after the corrosion test, it is possible to see small, flat depressions, so called pitting where the contact rust was located. This type of corrosion is typical of Cr steels. Whether pitting occurs also depends on the temperature in addition to the chemical composition. If it is to be prevented from forming, e.g. at 30°C, the steel would have to have a 30 percentage weight of Cr. This type of steel is neither attractive in price, nor can it be adequately formed.

The typical structure of the modified steel X1CrNi12 (largely ferritic / martensitic) is shown in **Figure 5**. This structure is the result of a chemical composition specified more exactly than the standard, particularly in regard to the elements carbon, chromium, manganese, and nickel.



Figure 5: Microstructure of the X1CrNi12 stainless steel in as-rolled condition

In the section prepared with Kalling etching, the ferritic areas are light in color, the martensitic structural elements dark.

The following three criteria in addition to the corrosion behavior were decisive in selecting the material:

- **Fine-grained and uniform structure as rolled:**

With a grain size number greater than 8 according to ASTM E 112, the steel X1CrNi12 as rolled has an adequately fine-grained structure. This is advantageous since a small grain size as per the Hall-Petch relationship increases hardness and

ductility without reducing toughness. It also has a positive impact on workability and improves fatigue strength. In the steel C45E, for example, it can increase to 295 MPa due to a normalized structure while the steel with a coarse-grained ferritic-perlitic structure has a typical fatigue strength of only 225 MPa [4].

The steel X1CrNi12 is characterized as rolled also by a homogeneous, primarily ferritic-martensitic structure throughout the entire wire cross section with lines of ferrite and martensite caused by the rolling process in the grain (**Figure 5**) which does not however interfere sustainably with cold forming. In conventional quenched and tempered steel 41Cr4, a workable structure is produced by GKZ annealing.

- Sufficient hardness and adequate strain hardening behavior:

The strength of a ball pin is a result of the basic hardness of the starting material as rolled and the strength is improved by strain hardening during drawing and cold forging. **Figure 6** shows the mechanical properties of the steel X1CrNi12 versus drawing reduction.

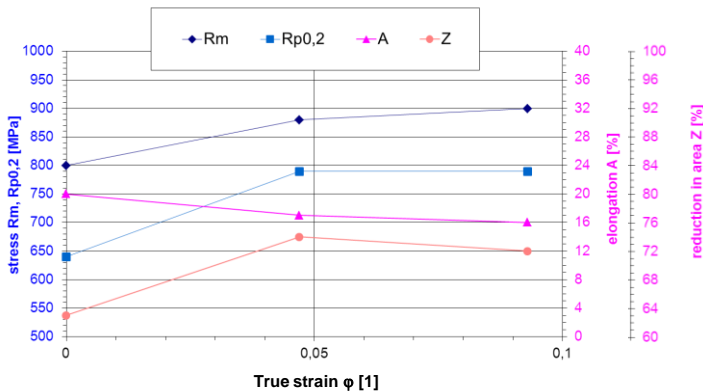


Figure 6: Mechanical properties of drawn wire X1CrNi12

Due to the fine-grained ferritic-martensitic structure, the X1CrNi12 as rolled already has a relatively high yield stress of approx. 650 MPa. The rolled wire at a tensile strength of 800 MPa has a 20% elongation at failure and an over 60% area reduction at fracture. After minimal deformation of $\phi = 0.1$, yield stress increases to 790 MPa wherein elongation is only slightly reduced to 16% min.

- Satisfactory deformability:

Since deformability is easiest to set in relation to the percent of area reduction at fracture, suitable steels must have at least a $Z \geq 50\%$ reduction of area for cold heading either directly as rolled or at least after an annealing on spheroidite. This criterion is already fulfilled as rolled for X1CrNi12.

Figure 7 is an example of the yield stresses of steel X1CrNi12 determined in a upsetting test at different strain rates. Specifically in the starting range of limited elongation, the steel exhibits a fairly strong strain hardening and as of $\phi = 0.3$ a relatively large plateau begins for yield stress. In the flow curves established through experimentation, the dilatometer samples at RT were deformed up to a true strain ϕ of at least 1.1 without visible cracks.

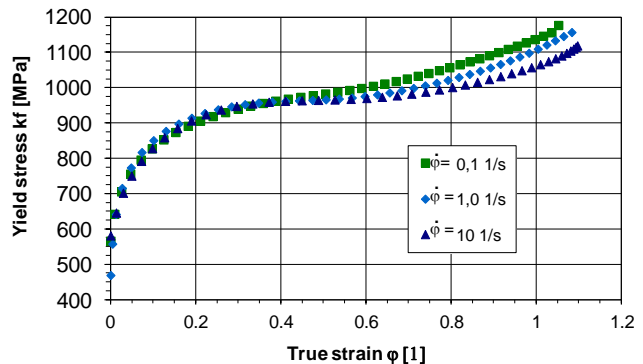


Figure 7: Flow curves at RT for X1CrNi12 steel

2.2 Production steel mill, rolling mill, pickling, drawing

The material X1CrNi12 is smelted based on scrap raw material first in the steel mill's electric furnace. After alloying and VOD treatment (decarburization under vacuum using oxygen), the molten steel is cast on the continuous casting machine into billets measuring 138mm x 138mm.

In the mill, the billets are heated to a temperature between 900°C and 1140°C prior to rolling. In this temperature range, a portion of the ferrite is converted into austenite and precipitates are completely removed (2 phase range $\alpha+\gamma$ in the phase diagram Fe-Cr). The X1CrNi12 steel is then rolled in such a way that the required material properties are achieved directly after the forming process for the final dimensions and a controlled cooling process. Precise matching of the chemical composition with the process parameters during rolling is decisive in this case.

The wire rod is then pickled, coated and drawn to the desired dimensions as preparation for the cold forming – without additional annealing required.

2.3 Cold Forming

Ball pin blanks are pressed from the X1CrNi12 wire drawn to the desired original strength in a 5 to 6 stage cold forging process. By selecting the drawing reduction prior to cold forging and the layout of the individual forming stages, the local mechanical-technical properties of the part can be achieved. In the process, depending on the application, the wire drawing reduction can be varied between $\varphi = 0.05$ und $\varphi = 0.3$.

Since the initial strength of the wires in each case is higher than usual, the shearing system, cold forging tools and the cold forging press will be loaded higher. Consequently, it will be necessary to manufacture the product from this ferritic steel – unlike the previous version – on another stronger press with higher ram force and a more stable shearing system. The unfavorable tribological behavior of the coated wire/part surfaces made of stainless steel compared to the generally forged quenched and tempered steels require additional measures. The use of an adapted tool coating will have great impact on the tool life of live tools.

This additional effort for cold forging compared to the previous series production of ball pin blanks can be compensated for in downstream work processes and result in cost savings.

2.4 Subsequent processing of the blanks

The pressed blanks are partially or completely stripped in the automatic lathe. Machining is done without coolant using standard lathe tools and machining programs with standard cutting speed, feed motion and chip thickness. To prevent impurities in the ball pins in the form of foreign particles, new unused tools must be used for machining. Thread rolling as well as the polishing of the balls is then also done on standard roller-burnishing machines.

3. Manufactured ball pin made of X1CrNi12

Figure 8 is an example of a sophisticated ball pin with undercut neck and pin extruded to the finished size, thread roll diameter, chamfer and hexagon socket. Assuming a rolled wire with a yield stress of approx. 600 MPa and a tensile strength of approx. 800 MPa, high production capacity was able to be pressed without noticeable tool wear or tool/stamp breakage.

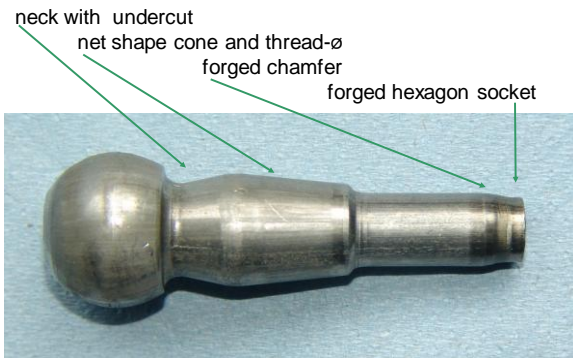


Figure 8: Pressed ball pin blank with undercut neck and hexagon socket

Only those ball pins that were machined on the ball and in the neck as described above were integrated in the joints and tested for their torque behavior. Ball joints must be sufficiently smooth running also after longer standstills. No significant differences were indicated in the tested joints compared to the nitrided standard ball pins.

3.1 Subsequent processing of the blanks

For the threaded section of the ball pin, a minimum strength of 820 MPa is required for nitrided ball pivots to guarantee that the ball pin is securely fastened to the subframe or steering knuckle. In addition to hardness measurements on the longitudinal cross-section, small tensile test pieces were taken from the manufactured ball pins to test the mechanical properties. The hardness values determined are shown in **Figure 9**. It has been shown that the required strength in the threaded section has clearly been met with over 1000 MPa. The tensile strength of the small tensile test pieces (removed from the ball pin) was 825 MPa, the yield stress was 625 MPa.

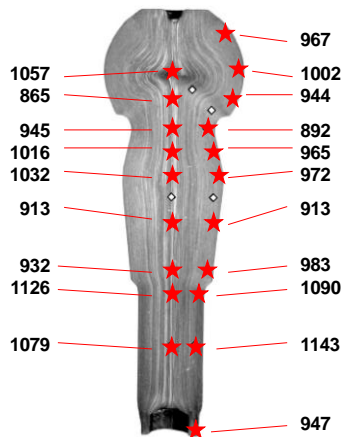
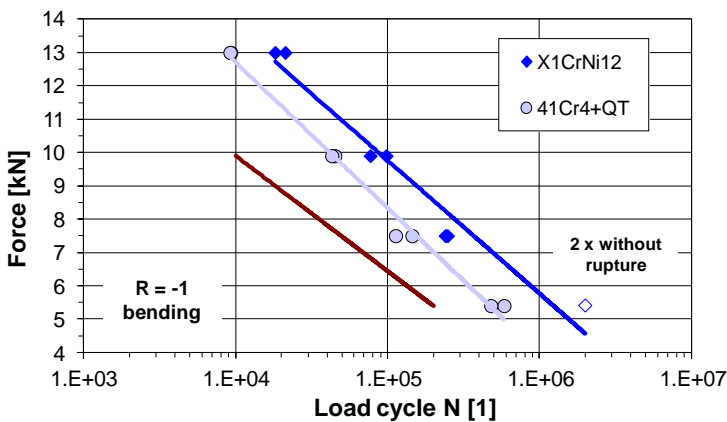


Figure 9: Tensile strengths at various measuring points in longitudinal section calculated from the hardness according to DIN EN ISO 18265 Tab. A1

3.2 Fatigue Limits

In the joints, the ball pins are primarily subjected to stress by reversals of bending. The maximum bending stresses of 780 MPa (static) or 190 MPa (dynamic) for conventional ball pins is a result of the vehicle weight, front axle weight, engine and break performance as well as geometrical dimensions of the vehicle suspension design. These values must at least be met also by the alternative material.

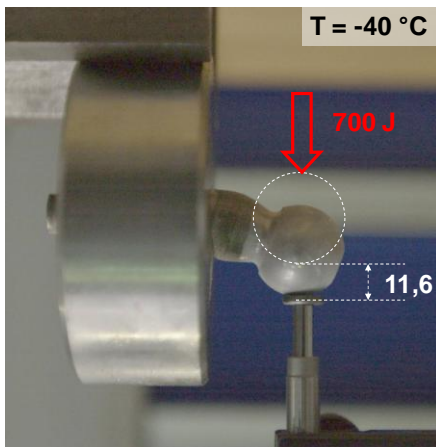
The fatigue limit of the ball pins was determined in a single-stage Wöhler fatigue test using a continuous alternating load wherein the fatigue strength is defined at $2 \cdot 10^6$ load cycles. **Figure 10** compares the 50% component S/N curve for ball pins made of X1CrNi12 and 41CrS4+QT (quenched and tempered to 950 MPa) of the same geometry. The open symbols represent 2 fatigue-tested specimens without rupture. The absolute extent of the fatigue strength was not able to be converted to an amplitude of the stress variation range due to how the test was conducted. Consequently, the ordinates only show the load applied during testing. The breakage in X1CrNi12 primarily occurred in the neck area of the ball pin according to the maximum stress step-up that occurs at that point. The quenched and tempered steel variant also tends to fail at the neck under high loads while at a lower load it breaks where it is fixed.



The fatigue limit of the stainless steel ball pin clearly exceeds that of the ball pin made of quenched and tempered steel by far although its yield stress is 40 MPa lower. However, Stainless steel ball pins are lower than the fatigue limit of the nitrided pins. The ball pins made of X1CrNi12 achieved $1 \cdot 10^5$ stress cycles at 6 kN. The number of cycles endured before rupture is approx. 10 times higher than the number required by the specifications. Given the same grain structure and geometry, the fatigue limit is linearly dependent on the yield stress [5]. The literature [5] also describes that the ferritic perlitic structure of the 30MnVS6 has a higher fatigue limit than quenched and tempered steel 41Cr4 given the same (tensile) strength. This is explained by the optimum globular grain structure and the smaller grain size. The greater fatigue limit of the X1CrNi12 compared to the 41Cr4 despite the lower yield stress is also explained by the better globular structure and the finer grain.

3.3 Behavior in response to sudden, mechanical loading stress

Based on the damage chain, defined parts in the chassis are to be ductile in the event of excessive loading. If the ball pin assumes this task in the damage chain, it may not fail due to low ductility.



To test this criterion, the behavior of the ball pin made of X1CrNi12 was tested at low temperatures under impact stress. Tests were conducted at low temperature since the steels tend to be extremely brittle and fail at low temperatures. Drop-hammer tests (mass 28.5 kg) were conducted at -40°C to test the parts up to an energy of 700 J. The drop-hammer mass falls from a defined height onto the middle of the ball of the ball pin.

Figure 11: Measurement of crack-free permanent deformation of the pin (11.6 mm) after drop-hammer-test at -40°C and 700 J

Figure 11 shows the determined deformation of the pin after the drop-hammer test. The ball pins were able to be struck with up to 700 J. With this amount of energy, the ball pins were already so deformed (11mm to 12mm) that further testing with higher energies was no longer possible. No cracks were able to be seen on the the pin and after metallographic longitudinal cross-sections were reviewed.

To guarantee the good toughness properties of the ball pins, the notched bar impact energy of the wire rod was specified and monitored.

3.4 Contact corrosion / electrochemical potential

The materials preferred for use in the chassis are aluminum forged alloys, steels and cast iron. Since the stainless steel ball pins are very different from these materials in the electrochemical series, ball pin blanks made of X1CrNi12 were assembled to disks made of aluminum (AlMgSi1-F40) and gray cast iron (EN GJS-500-7, old GGG40) with electroplated screws and aged up to 10 cycles in the VDA alternating climate test [6] or up to 480 h in neutral salt spray testing [7].

The results of salt spray testing and the alternating climate test did not vary significantly, see **Figure 12**. Ball pins used in connection to aluminum disks as well as uncoated gray cast iron disks are shown after 10 cycles of the alternating climate test from the thread side. The surface of the gray cast iron disks is very corroded. In both variants, the stainless steel ball pins and the nuts belonging to them were only slightly corroded.



assembled to
AlMg1SiCu EN GJS-500-7

Figure 12: Corrosion on the thread side of a pin made of X1CrNi12 after 10 cycles in the VDA alternating climate test. Left assembled in AlMg1SiCu or AA6161, right assembled in GGG40

After the corrosion test, the nuts were unscrewed. The nuts on the stainless steel ball pin were able to be turned out of the pin after being unscrewed using the torque wrench.

To simulate the connection to a wheel carrier, bearing or swivel bearing, the X1CrNi12 pins were assembled to a rod made of gray cast iron by means of a clamping joint (**Figure 13**). These samples were then corroded for 10 cycles in the VDA alternating climate test. The gray cast iron rod was very corroded, while the ball surface of the X1CrNi12 ball pin was still shiny after polishing with a soft cloth.



X1CrNi12 assembled to EN GJS-500-7

Figure 13: Corrosion of a pin made of X1CrNi12 after 10 cycles in a VDA alternating climate test, assembled in GGG40

Another gauge for evaluating contact corrosion is the electrochemical potential. A large potential difference between two metals means a greater tendency of the base metal to dissolve. The electrochemical potential of ball pins made of various steel allows or coatings was tested in

indoor air in vented salt water (250 g NaCl in 1000 g water) against the aluminum alloy AlSiMg1. **Figure 14** shows the measuring results after 16h of testing.

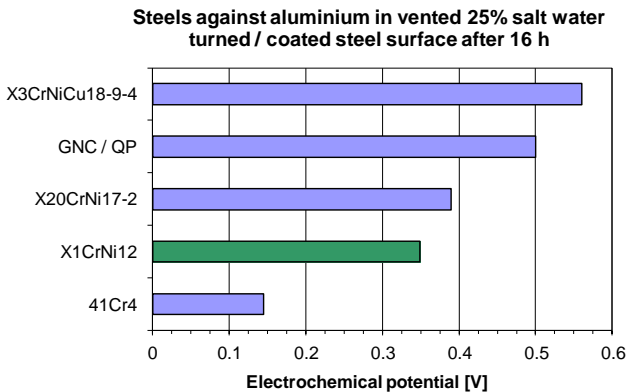


Figure 14: Electrochemical potential of various ball pins measured in a 25% vented salt water solution at room temperature against aluminum

The uncoated points on the pin were covered with tape in order to suppress “fault currents”. An uncoated pin has a potential of 0.15 V compared to the Al alloy.

Pins with GNC or QP coating have a potential that is 0.35 V higher of approx. 0.5 V. The potential of noncorroding steels are greater than higher alloys. Austenitic steel X3CrNiCu18-9-4 are well-suited to cold forging, but in this comparison it has the greatest electrochemical potential. The best corrosion protection or stainless steel in regard to contact corrosion is the X1CrNi12.

3.5 Behavior in the joint

Joints using ball pins made of X1CrNi12 exhibit the same joint properties (pursuant to the specifications of the AK-LH 14 [8]) as joints with nitrided pins. If, however, pins made of austenitic stainless steels are used, basic testing using a ball-prisma-tribometer reveal that scoring develops rapidly between the pin and the ball socket. **Figure 15** shows the coefficient of friction measured over the friction path for balls of both steels. Both the grease as well as the material for the arrangement consist of series material. The coefficient of friction of ferritic steel is constant while the coefficients of friction for austenitic steel fluctuate greatly, which is an indication of scoring of the friction pairing.

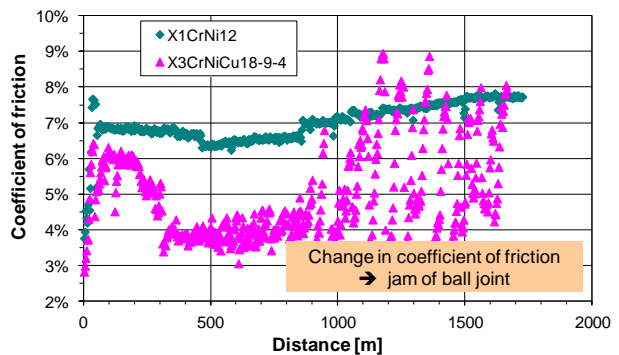


Figure 15: The coefficients of friction in the ball-prisma-tribometer for austenitic steel X3CrNiCu18-9-4 and ferritic steel X1CrNi12 versus greased POM

After the test, the joint lubrication changes into a dark color in the presence of the austenitic pin, while it stays light if the pin is made of X1CrNi12 (**Figure 16**). There are also definite jamming and wear marks on the ball surface of the austenitic stud that is attributable to tribological oxidation. No striking marks were discovered on the ball surface of the ferritic pin. Jamming layers may also form on the ferritic pin under great tribological stress.



Figure 16: Friction behavior of austenitic steel X3CrNiCu18-9-4 and ferritic steel X1CrNi12 in ball-prism-tribometer versus greased POM after a friction path of 1700 mm

3.6 Economic Efficiency and Ecological Advantages

Further non-technical economic and ecological advantages by manufacturing ball pins in X1CRNi12 stainless steel are:

- Elimination of the processes of annealing, quenching, transport, coating
- Shorter processing time and thus an ability to react faster to fluctuations in production (warehousing principle)
- Less tied-up capital
- Lower testing costs (since quenching and coating are eliminated)
- Efficient use of resources and energy, CO₂ reduction

The costs for manufacturing cold forged ball pins and eliminating cost-intensive process steps always depend on the specific part. The economic efficiency of the entire manufacturing chain is a given in view of the described development due to the savings compared to conventionally manufactured parts.

4. Discussion

It has been shown that the process chain in the manufacture of ball pins can be shortened considerably by selecting the right material and considering the complex demands. By using X1CrNi12 stainless steel, the manufacturing steps annealing, quenching and

tempering and coating can be eliminated. The parts themselves can be machined using conventional machines and tools without substantial additional expenditure. Evidence has been provided that the properties of ball pins made of X1CrNi12 are comparable to those of conventionally manufactured parts made of quenched and tempered steels and all requirements for the product are met.

An important requirement for the success of a project such as this is the intensive, interdisciplinary cooperation of all involved over the entire process chain.

Lightweight construction in automotive applications means savings on energy and reductions in CO₂ emissions and can, when in use, contribute to improving both the ecological as well as the economic balance.

If the balance group is expanded and if the manufacturing process of an automobile is included in the overall consideration, then the X1CrNi12 steel provides a comparable qualitative ecological and economic benefit in the production of vehicle components similar to that of lightweight construction.

Literature

- /1/ Fecht, N. Nikolaus Fecht (Herg.); Komponenten für Fahrwerk und Lenkung; Verlag moderne iIndustrie, Landsberg 1997.
- /2/ Kruse, J. Spurstangenkomponenten, Werkstoffe und Herstellung im Wandel der Zeit, 14. Sächsische Fachtagung Umformtechnik, Freiberg, 4.-5.12.2007.
- /3/ N.N. Salzsprühtest nach DIN EN ISO 9227 (ehemals in DIN 50021 genormt).
- /4/ Dahl, W. Verhalten von Stahl bei schwingender Beanspruchung; Verlag Stahl Eisen GmbH, Düsseldorf 1978.
- /5/ N.N. DVM-Bericht 127 „Mit Kerben leben?“, DVM 2000, S. 27.
- /6/ N.N. VDA Wechselclimatest.
- /7/ N.N. Salzsprühtest nach DIN 50021.
- /8/ N.N. Arbeitskreis - Lastenheft Fahrwerksgelenke AK-LH 14; Audi AG, BMW AG, DaimlerChrysler AG, Porsche AG, Volkswagen AG; Dez. 2004.