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OPTIMISATION OF LIFE PERFORMANCE AND NET-SHAPE CAPABILITY OF COLD-FORGING TOOLS THROUGH MINIMISATION OF MICRO-PLASTIC PHENOMENA

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Summary

In the introduction, it is stated that most complex shape dies for net-shape cold forging fail due to low-cycle fatigue and that the crack initiation and crack-merging phases mainly determine the life of the dies.

Advanced material testing methods show that the crack initiation in high-hardness tool materials is mainly controlled by the cyclic plastic strain range and by the level of compressive mean strain. A multi-parameter advanced elastic-plastic material model for application in FEM programmes is developed for analysing and optimising of cold-forging dies where cyclic micro plasticity is a very critical and determining factor for the die life.

A 3-D finite-element analysis of a bevel-gear die insert incorporating an elastic-plastic material model demonstrates how high-stiffness stripwound containers can reduce the critical cyclic stresses and strains. Comparison of the calculated stress-strain cycles with data from low-cycle fatigue tests indicates that life until local crack initiation can be increased from approx. 400 to more than 70,000 cycles.

Keywords: cold forging, stripwound containers, low-cycle fatigue, die life, material model, finite element, bevel gear

Introduction

During the cold-forging production, the forging dies are loaded cyclically with high, alternating surface pressures. The level and distribution of the alternating surface pressures are determined by factors such as the geometry of the product before and after deformation, grade of workpiece material, workpiece temperature, lubrication, etc.

In the optimisation of the performance and life of the cold-forging dies, these alternating pressures can be seen as predetermined boundary conditions that are fixed for all variants of die designs. However, the alternating pressure distribution can be optimised by modification of the geometry of the forging process, the lubrication, the workpiece material, etc.

Modern process simulation by FEM can lead to considerable improvements of the pressure distribution profile, and in modern development of forging parts, it is almost a requirement to optimise the process and the consequent process loads before optimising the die performance [1]. Even with dies optimised by normal FEM simulation methods, cracks are a well-known phenomenon especially in die inserts for parts with complex geometry and sharp corners such as dies for transmission gear wheels, planetary gear wheels, bevel gears, front wheel drives, etc.

In the case of complex high-precision dies for net shape parts, studies of failed dies clearly show that the dies mainly fail due to micro cracks in sharp corners caused by low-cycle fatigue [2]. These micro cracks are seldom causing a significant and critical reduction of the strength of the dies, but the micro cracks cause burrs and tool marks on the surface of the cold-forged parts which is unacceptable in the industrial production of net or near net shape parts.

In the high-volume production of net shape parts, the presence and size of burrs and tool marks at critical quality issues of the parts are monitored so that production can continue until the burrs have reached a critical size [3]. As to net shape cold forging of bevel gears, for instance, initial micro cracks and very small burrs can be detected after approx. 1000 parts, but production can continue until 10-15,000 parts where the micro cracks and burrs reach an unacceptable size. Without microscope or magnification aids, the die may still look totally perfect.

Wear is very seldom seen as a failure reason in the group of complex dies [3]. In the cases where wear phenomena are observed at lower die lives, microscopic and metallographical examination will often reveal that the wear phenomena are initialised and related to low-cycle fatigue mechanisms, for instance microscopic particles, which are torn out from the base material due to low-cycle fatigue mechanisms, acting as seeds for abrasive wear. Therefore, a systematically structured improvement of the life of complex cold-forging dies must be based on studies and understanding about low-cycle fatigue phenomena and mechanisms.

Low-cycle fatigue can be divided into four phases:

- cyclic loading of undamaged structure
- initiation of micro cracks, $a<0.1$ mm
- merging of micro cracks to surface defects and larger cracks, $0.1\leq a\leq 0.5$ mm
- stable crack growth phase $a\geq 0.5$ mm

Most complex cold-forging dies will be taken out of service and registered as failed during the third phase where micro cracks merge to larger surface defects of the die, and burrs become visible, but where the crack growth rate still is extremely low.

Production may continue into the stable crack-growth phase, but a crack growth to final fracture is undesirable as fracture fragments may cause very costly sequential damages on subsequent dies. Therefore, studies of low-cycle fatigue phenomena in relation to cold-forging dies shall mainly focus on the crack initiation and merging phases rather than on the crack-growth phase, and consequently, a considerable part of a strategy for improvement of the life of complex and high-pressure loaded cold-forging dies must focus on various aspects and activities that can extend the crack initiation and crack-merging phases of the low-cycle fatigue failure mode.

During the 1990s, STRECON® Technology of Danfoss A/S has initiated and completed a series of projects [4-11] in collaboration with institutions such as the Technical University of Denmark and Risoe National Laboratories with the purpose of optimising the life and deformation conditions of cold-forging dies consisting of high-quality die inserts of tool steel or cemented carbide and STRECON® prestressed containers through combination of

- advanced material testing methods
- complex material models
- advanced FEM analysis

Advanced material testing methods

The testing of low-cycle fatigue properties of ductile low-hardness steels has a long tradition [12] whereas the amount of tests of high-hardness materials such as tool materials has been very limited due to the lack of testing equipment with high-speed, high-accuracy strain control systems and to unsatisfactory performance of the experimental set-up and procedures.

In a number of Danish projects [4-7], the necessary experimental procedures have been developed so that test samples of high-hardness tool steels and brittle cemented carbides can be tested in an almost standardised way. Thus, resulting data such as static stress-strain curves, cyclic strain versus fatigue life curves, crack-growth rate and fracture-mechanical data can be established.

In this context, the cyclic compression-tension tests with various compressive mean strains have revealed the most interesting results. For the actual materials, the number of cycles to fracture is extremely dependant on the amount of plastic deformation. If, for instance, a test specimen of tool steel is cycled between $+\sigma_{0.2}$ and $-\sigma_{0.2}$ giving a cyclic plastic strain range of about $\Delta\varepsilon_p \sim 0.4\%$, the number of cycles to failure will not exceed a few hundred cycles.

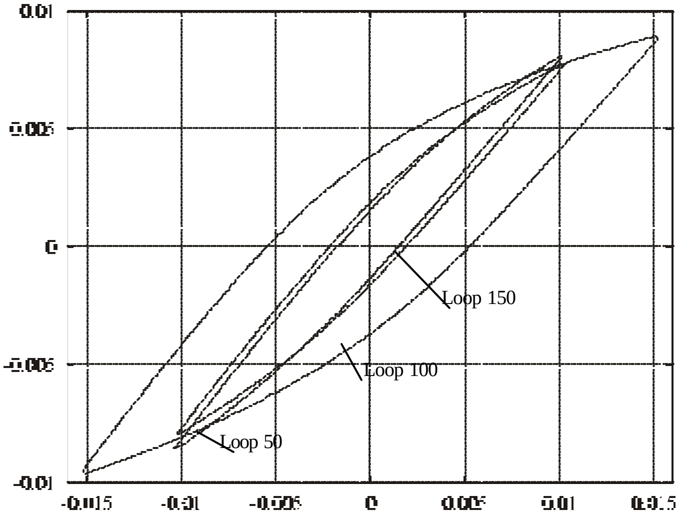

Fig. 1 Cyclic incremental step test of tool steel - Calmax

A target of a cyclic life until crack initiation above one thousand cycles requires a limitation of the plastic strain range approx. to $\Delta\varepsilon_p \leq 0{,}05\%$. Only negligible cyclic plastic strain ranges such as $\Delta\varepsilon_p < 0.01\%$ are found to lead to fatigue lives above 10^4.

It can be concluded that the crack initiation in tool materials is strongly related to the amount of cyclically plastic deformation and that even cyclic plastification on a micro-scale level will lead to crack initiation and fracture at a low number of cycles.

Another important finding of the performed tests is an unexpectedly strong dependency of the level of compressive mean strain on the number of cycles to failure.

For the high-speed steel M2, for instance, with a strain range of $\Delta\varepsilon = 2 \text{x} 0.75\%$ equal to a total stress range of approx. $\Delta\sigma = 3000$ N/mm^2, the number of cycles to failure will be $N_f \approx 200$ at a mean strain of $\varepsilon_m = -0.3\%$. A shift in mean strain to $\varepsilon_m = -0.5\%$ and $\varepsilon_m = -0.7\%$ results in an increase in the number of cycles to failure of $N_f \approx 2000$ and 20,000 cycles, respectively.

These results that are typical for most of the tested tool materials show that a 0.2% shift in mean strain results in a change of the number of cycles to failure by an order of magnitude. It can be concluded that a shift in the compressive mean strain will lead to dramatic changes in cyclic life and that a numerically higher compressive mean strain is very beneficial for postponing the crack initiation.

Complex material models

The results of the experimental low-cycle fatigue tests show that crack initiation and fatigue life is strongly related to the elastic-plastic material behaviour close to the yield point.

For analysing and optimising structures such as cold forging dies where stresses and strains are cycling with peak values exactly in these critical areas, a new material model capable of describing the elastic-plastic behaviour under cyclic loading has been developed [8-11,13]

The model is capable of describing phenomena as cyclic hardening and softening, mean stress relaxation, ratchetting and damage development and combines non-linear isotropic and kinematic hardening with continuum damage mechanics. In the full version of the model, twenty-two parameters are used to describe the various phenomena, but a reduced number can, for instance, be used in cases where only one load cycle is analysed. The parameters for a specific material with a given hardness have to be determined in uni-axial static, incremental and cyclic fatigue tests. Due to the number of parameters, it is a very comprehensive work to obtain a satisfactory material database for the large number of materials used in cold-forging tools.

The material model was originally incorporated in a separate FEM programme and has later been implemented in the general-purpose programmes ANSYS and MARC as user-programmable subroutines to analyse real production applications such as cold-forging dies. Figs. 2 and 3 show an analysis of the cyclic stresses and strains in the transition radius of a forward-extrusion die during the first 50 load cycles. The circumferential stress shows a very limited cyclic plasticity whereas the stress parallel to the surface denoted the tangential stress in the figure is strongly deformed plastically during the first load cycle and also has a high cyclic plasticity during every subsequent load cycle. This explains the well-known phenomenon of a very low number of cycles to crack initiation for dies with small transition radii. An increase of the corner radius will decrease the cyclic plasticity and increase life to crack initiation.

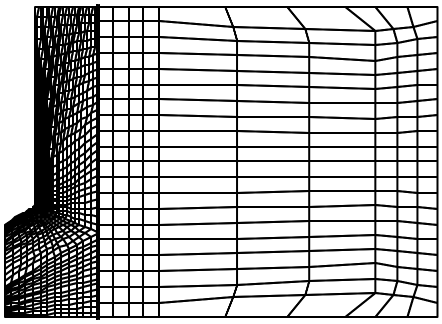

Fig. 2 FEM structure of forward-extrusion die

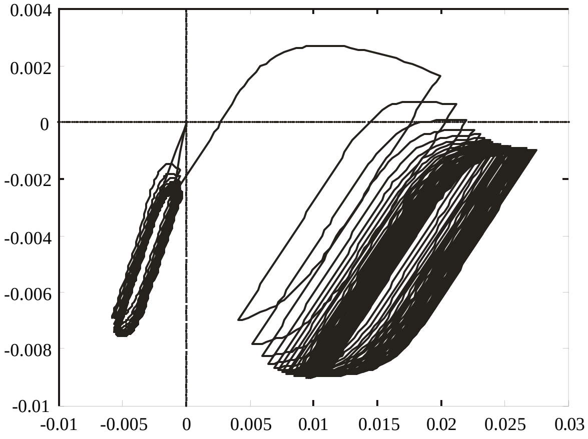

Fig. 3 Cyclic stresses and strains in the transition radius of a forward-extrusion die. Transition radius R=1 mm

Advanced FEM analysis of cold-forging dies

In the introduction, it was stated that by optimisation of the life of complex cold-forging dies, a main focus must be put on the crack-initiation phase as it determines the main part of the die life.

Furthermore, it has been concluded that the number of cycles to crack initiation and fracture is mainly determined by the amount of cyclic plastic strain and also by the compressive mean strain and that the amount of cyclic plastic strain is a very critical determining factor for die life even if the plastic strains only are on the micro scale.

The determination of critical parameters as cyclic plasticity on a micro-scale level, mean strain level and stress and strain level ranges requires FEM programmes with advanced elastic-plastic material models like the earlier described model or advanced use of the built-in models in commercial programmes.

By analysis and optimisation of cold-forging dies using FEM programmes with advanced features, the influence of the applied prestressing, the stiffness of the prestressing system, and the die geometry on resulting parameters as stresses, strains, micro plasticity, and deformation in critical regions of the dies can be analysed.

As illustrated in several publications [7-8, 13-16], the application of stripwound containers can reduce the large deformations and critical stresses in the critical small-corner radii of complex cold-forging dies.

Analysis of cold-forging tool for manufacture of bevel gear

This illustrative example taken from advanced net-shape cold forging of bevel gears is used to demonstrate the combined application of stripwound containers and the previously described methods for the optimisation of complex dies. The example deals with a 3-D analysis of a cold-forging die insert for industrial mass production of bevel-gears used for differentials in automobiles. Three different tools are analysed. In the first analysis, the die insert is mounted in a conventional double stress ring. The second and third analyses are both made with die inserts mounted in strip-wound containers. In the second analysis, the container has a winding-core of hardened tool steel, whereas in the third analysis, a winding-core of tungsten carbide is used. The tungsten carbide has a Young's modulus of 500 to 580 GPa, and thus the total stiffness of the container is increased and is higher than 400 GPa. The high stiffness of the container reduces the strains and stresses in the die insert during the cold-forging process. Thus, cold-forged parts with complex geometries and sharp corners, such as bevel gears, can be produced in high and profitable volumes. Another advan-

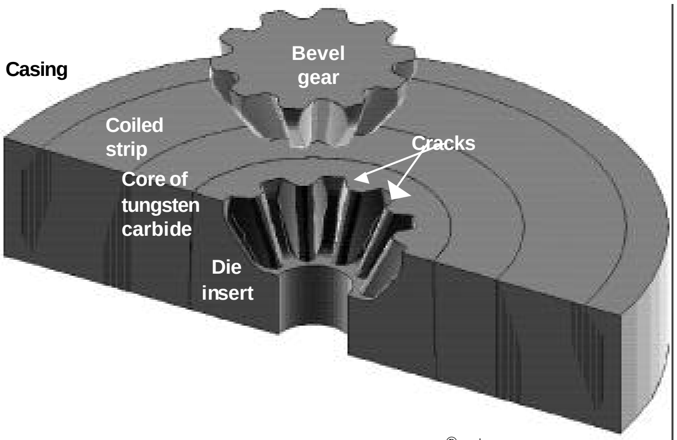

Fig. 4 Bevel gear and section of STRECON® E^+ prestressed container with die insert for production of bevel gears

tage of the high stiffness strip-wound container are the reduced deflections in the die insert during the cold-forging process. This leads to an improved accuracy of the cold-forged part which is very important as bevel gears are often produced as net shape parts, i.e. parts where the surfaces are not machined after the cold-forging. In the following, the analysed tools will be denoted conventional, STRECON® and STRECON® E+ tools.

The geometry of the bevel gear and a section of the STRECON® E+ tool is shown in Fig. 4. As illustrated, cracks are initiated due to fatigue in the corners of the die insert leading to unwanted burrs on the cold-forged bevel gears, and finally, to rejection of the die inserts when the burrs become too large, or to a total failure of the die insert. In order to increase the life of the die insert, it is essential to reduce or even eliminate tensile stress concentrations in the critical corners of the die insert. Furthermore, is it important to reduce the amount of plastic work per load cycle. As shown previously, the plastic work is depended on the stress and strain range, i.e. the difference between the loaded and prestressed conditions. Thus, a reduction of both the tensile stresses and the stress range will lead to an improved die life.

Due to the complex geometry of the bevel gear, it is necessary to make a three-dimensional analysis of the tool. The finite-element model of the STRECON® E+ tool is shown in Fig. 5. As the bevel gear has teen teeth, due to symmetry, it is only necessary to analyse 1/20 of the tool. The model consists of five regions with different material properties.

As mentioned previously, an elastic-plastic material behaviour is assumed in the analyses. As the strip-wound container to a great extend behaves linear-elastically in these analyses, only the die insert is considered elastic-plastic. The three different designs are analysed in three load cases:

Load case 1: Prestressing of the die insert, i.e. assembled condition. The radial interference between the die insert and the double stress ring used in the conventional tool is the highest possible of 0.7%. The radial interferences in the STRECON® and STRECON® E+ tools are 1.0% and 0.7%, respectively. However, the actual interference of the STRECON® E+ tool is much higher due to the high stiffness of the container, so that the interference of 0.7% corresponds to an interference of more than 1.0% for a conventional double stress ring.

Load case 2: Prestressing + loading with internal process load. The pressure distribution is according to the investigation in [12].

Load case 3: Unloading, i.e. removal of internal process load.

The tangential prestress distributions in the die insert for the three different designs are as follows: For the conventionally assembled die insert, the maximum value amounts to -2000 MPa along the critical edge. With the die insert material used, the degree of prestress is not optimal as the material behaves almost linear-elastic at this value. In comparison, an optimum tangential

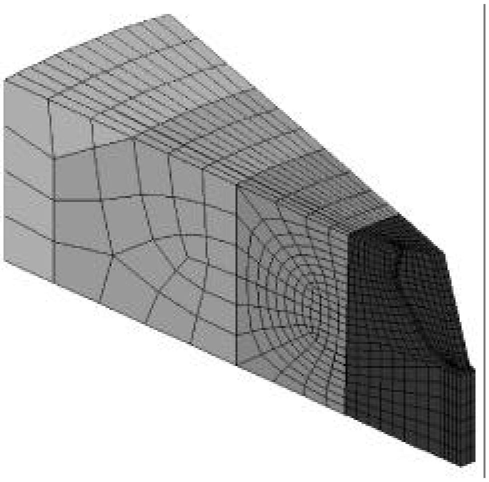

Fig. 5 Finite element model of the STRECON® E+ tool. Due to symmetry, it is only necessary to analyse 1/20 of the model

prestress distribution of -2800 MPa is obtained along the critical edge by mounting the die insert in the STRECON® and STRECON® E$^+$ containers. If nothing else changes in the tools, a 800 MPa higher value in prestressed condition will result in a similar reduction of the critical tensile stresses in operational condition.

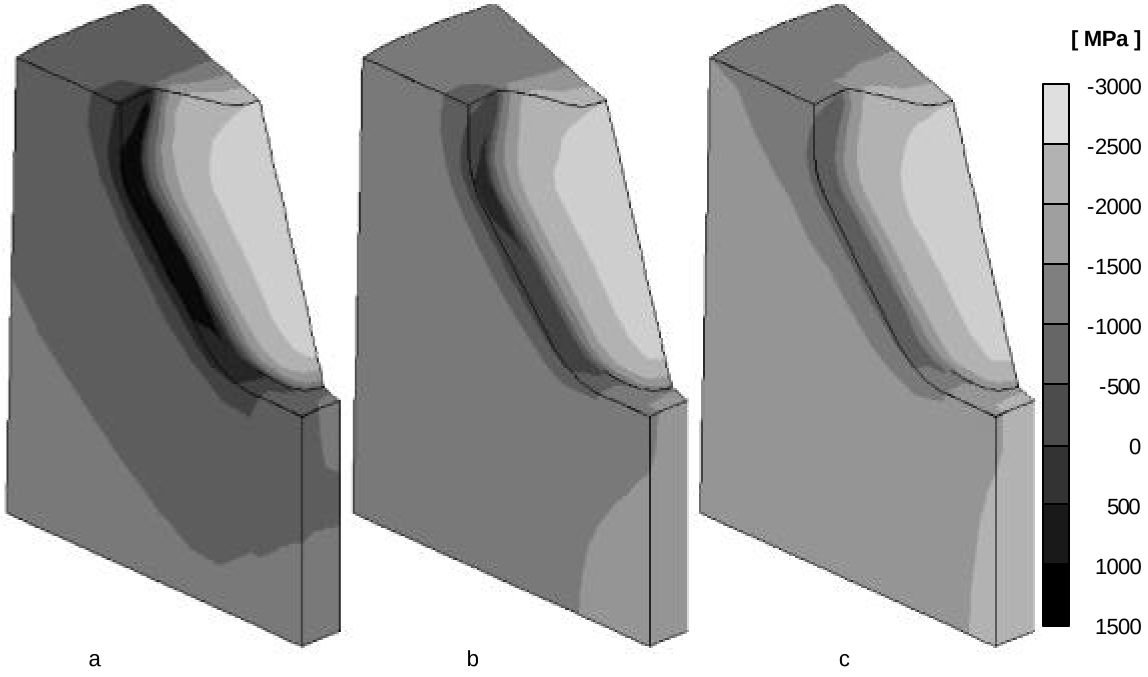

Fig. 6 Tangential operational stress distribution in die insert for (a) conventional tool, (b) STRECON® tool and (c) STRECON® E$^+$ tool

Fig. 6 illustrates the tangential operational stress distributions (load case 2) in the die inserts for each of the three designs. The maximum tangential tensile stress in the conventional tool is 1500 MPa which is a very critical value near the tensile strength of the applied tool steel. For the STRECON® tool, the maximum tangential stress has been reduced to 680 MPa, and furthermore, the region subjected to tensile stresses is significantly reduced. In the STRECON® E$^+$ tool, the region subjected to tangential tensile stresses has been completely removed as the maximum tangential stress amounts to 0 MPa. The removal of the tensile stresses in the STRECON® E$^+$ tool is mainly due to the high stiffness of the container which reduces the tangential stress range. The tangential stress range is identical for the conventional and STRECON® tools, as both tools only consist of steel materials with maximum values amounting to 3500 MPa. This value is reduced by 20% to 2800 MPa for the STRECON® E$^+$ tool, mainly due to the increased stiffness of the container.

The tangential stress-strain relations along the critical edge in the first load cycle for all three designs are illustrated in Fig. 7. The curves clearly illustrate the fracture-mechanical advantages of the STRECON® tool and especially of the STRECON® E$^+$ tool. These stress-strain curves were used to predict the die life of the three analysed designs by means of cyclic fatigue tests. The test specimens were loaded uni-axially in cyclic strain control according to the hysteresis loops in Fig. 7 until fracture. For a detailed description of the test, please refer to [6].

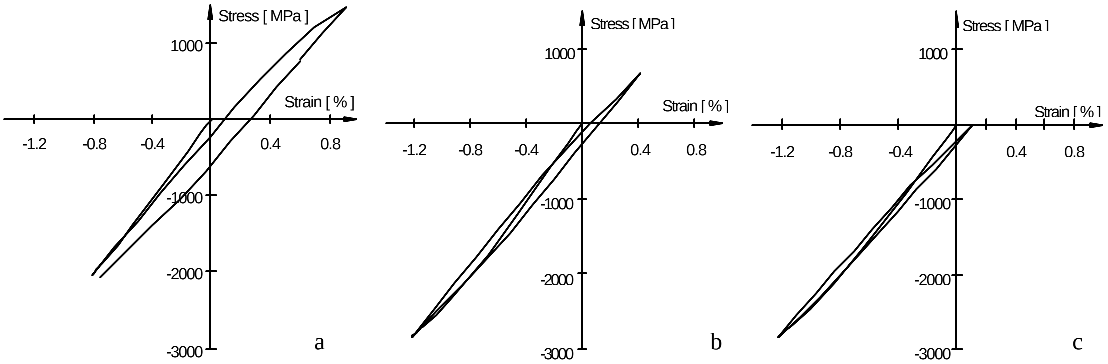

Fig.7 Stress-strain relation along the critical edge in (a) conventional tool, (b) STRECON® tool and (c) STRECON® E^{+} tool

The test specimen loaded according to the stress-strain condition in the conventional tool showed a considerable cyclic plastic strain range $\Delta\varepsilon_p \approx 0.15\%$ and failed after 440 cycles. It shall be mentioned that the stress-strain condition in the test specimen cannot be compared directly with the stress-strain condition in the die insert. Firstly, the stress condition in the test specimen is uni-axial whereas the stress condition in the die insert is a complex tri-axial stress condition. Secondly, the axial stress in the test specimen is a global stress as the stress value is constant over the entire cross section whereas the stresses in the die insert are local and also affected by stresses in other directions than the tangential direction. The test specimen loaded according to the stress-strain condition in the STRECON® tool failed after 4700 cycles which is an improvement by a factor 10 compared with the conventional tool. The test specimen loaded according to the stress-strain condition of the STRECON® E^{+} tool showed a strongly reduced cyclic plasticity and had not failed after 70,000 cycles where the test was stopped. This is an improvement in life of more than a factor 160 in comparison to the conventional tool. The die lives found in the cyclic fatigue tests can probably not be transferred directly to real-life bevel-gear die inserts, but still, the relative difference in the number of cycles to failure fully justifies the advantage of using STRECON® containers and especially the STRECON® E^{+} containers for production of bevel gears.

The results from the finite-element analyses and die life predictions from the low-cycle fatigue tests were presented to a customer producing net shape cold-forged bevel gears in order to convince about the advantage of using STRECON® prestressed containers. The three investigated bevel-gear designs were tested by the customer in mass production. In the conventional die, micro cracks occurred in the critical corners after only 500 to 1,000 parts. The burrs on the forged parts originating from merged micro cracks led to a production stop after 3,500 to 10,000 parts with an average of 7,000 parts. In the STRECON® assembled die, micro cracks were observed after 10,000 to 12,000 parts, but it was possible to produce parts with an acceptable burr size until a total die life of 15,000 to 20,000 parts. The die life for the STRECON® E^{+} assembled die was significantly increased compared to the two other designs. Based on the results from the low-cycle fatigue tests, this was also expected. In this design, the micro cracks occurred in the critical corners after 74,000 to 77,000 produced parts, and an average die life of 80,000 parts was obtained. Additionally, the variation in die life was reduced which means that it is easier to predict a production stop. In respect to part quality, the long life to initiation of micro cracks results in a high percentage of burr-free components.

By a 7 digit annual production value, the use of the STRECON® E+ container has led to a significant reduction of the tooling costs per part. For the conventional design, the tooling cost per part was US$ 0.37 which was halved to US$ 0.15 by use of the STRECON® design. The cost was further reduced to US$ 0.034 with the STRECON® E+ design which is a saving of 90% compared with the conventional tool for bevel-gear production.

Conclusion

Investigations of failed industrial cold-forging dies show that complex high-precision dies for net-shape cold forging fail due to low-cycle fatigue phenomena in the sharp corners.

The crack initiation and crack-merging phases of low-cycle fatigue mainly determine the life of this group of dies. Wear is seldom a significant problem.

Advanced material-testing methods developed for low-cycle fatigue testing of high-hardness tool materials show that crack initiation in tool materials is mainly controlled by the amount of cyclic plastic strain, even if this is on a micro scale, and by the level of compressive mean strain.

A newly developed multi-parameter advanced elastic-plastic material model for application in FEM programmes makes it possible to analyse and optimise complex cold-forging dies where micro plasticity is a very critical and determining factor for the die life.

A 3-D elastic-plastic finite-element analysis of bevel-gear die inserts mounted in conventional stress rings as well as in two types of stripwound containers show that especially the properties of the high-stiffness stripwound container can influence the cyclic stress-strain situation in the critical corners of the die so that the critical parameter of plastic strain range can be reduced by 75%.

Industrial production tests of bevel-gear dies mounted in the three types of prestressing systems demonstrate that the average life for the bevel-gear die inserts can be increased from 7000 parts for a conventional die to 17,500 parts for a die insert mounted in a normal stripwound container and finally up to more than 75,000 parts for a die insert mounted in a high-stiffness stripwound container.

By the shift from conventional prestressing systems to a high-stiffness stripwound container system, the tooling cost per part is reduced by 90%.

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