Innovations in Cold Forging Die Design

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Industrial summary

The demand of the market to the major industrial cold forgers for development and production of complicated net shape parts at fairly low unit costs requires innovative new die designs for optimisation of die life and reduction of die deflections. The high-stiffness STRECON® E+ containers influence the stresses, strains, and deflections in critical dies so that die lives can be improved by factors of 3 to 10 and die deflections reduced by 30 to 50%. Application examples for bevel gear dies, planetary gear wheel dies, and spline dies show how the STRECON® E+ containers can be applied to such critical dies in an innovative way.

1. Introduction

STRECON® Technology, a section within the Danfoss Group, is the worldwide manufacturer and distributor of strip-wound prestressed containers. The strip-wound containers are unique tool elements replacing conventional multiple stress ring sets in tools for cold forging, manufacture of synthetic, industrial diamonds, and other high-pressure applications [1].

The strip-wound containers are manufactured by winding a thin strip of high-strength steel around a core of tool steel or tungsten carbide. During the winding process, the steel strip is preloaded with a controlled winding tension, as illustrated in Fig. 1. The core material has a structure and a hardness that can withstand high prestress and cyclic working load. The strip steel is especially developed for optimum combination of the physical and mechanical properties. Optimum stress distribution is obtained by varying the winding tension from layer to layer. The prestressed condition in the coiled strip is equal to that of a conventional construction with "several hundred" stress rings. Consequently, the strip-wound containers can be loaded with a higher internal pressure than a conventional multiple stress ring set before the material will deform plastically. Thus, it is possible to obtain a higher interference when fitting a die into a strip-wound container than into a conventional multiple stress ring set.

2. Requirements to die life optimisation and net shape manufacturing

Today's cold forging production is characterised by two partly opposed trends within manufacturing development. The first trend, which has been known for decades, is production of parts at steadily lower unit costs forced mainly by the automotive industry. The second trend is the development of more and more complicated parts with narrower tolerances formed in net shape cold forging processes with the purpose of eliminating subsequent machining operations.

As tooling costs is one of the major variable cost parameters in cold forging, and, as the tooling costs to a great extend depend on the tool life, great efforts are often made to optimise the tool performance.

Tool optimisation involves material selection, heat treatment, design, manufacture, surface treatment, etc. When ensuring high quality for each parameter, satisfactory tool lives can be obtained. An important parameter for tool life optimisation in high-pressure applications is the compressive prestressing. The quality of compressive prestressing depends on the strength of the tool usually consisting of a die and a reinforcing ring. As regards reinforcing rings, a conventional design consists of a single ring or a multiple ring set with a strength that is often too low to provide a sufficient compressive prestress of the mounted die. The alternative to stress rings are strip-wound containers as shown in Fig. 2.

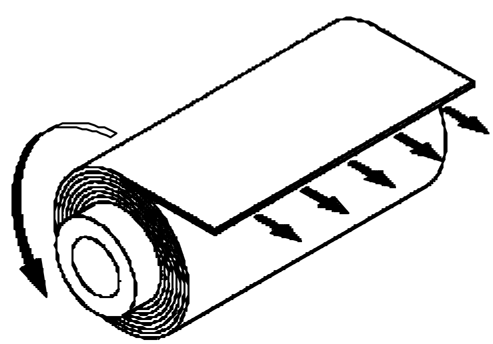

Fig. 1 Winding principle of STRECON® prestressed container

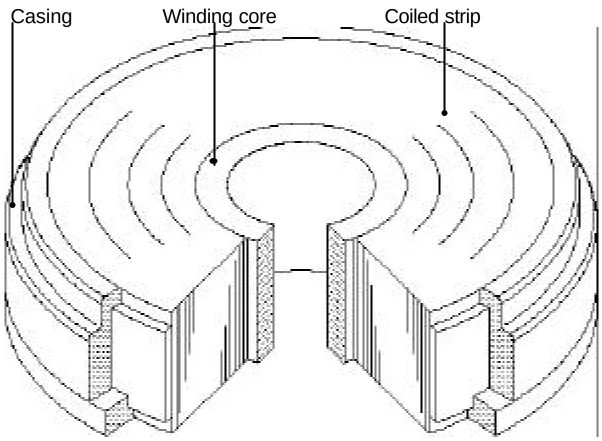

Fig. 2 Layout of STRECON® prestressed container

Strip-wound containers are characterised by a strength that is twice or three times as high as that of conventional stress rings. The high strength makes it possible to provide an optimum prestress of the die leading to die life improvements of 2 to 10 times depending on the application.

The long-term trend of producing cold forged parts with closer tolerances combined with the development of tool designs, tool manufacturing processes, and quality control has made it possible during the last years to produce complicated parts with high tolerance demands. Examples of such parts are transmission gear wheels, planetary gear wheels, and front wheel drive parts. To obtain success with net shape parts, the cold forging process must compete with fine-machining and grinding processes both economically but also, which is of equivalent importance, technologically as regards dimensional accuracy and surface quality. World-wide, even the most advanced cold forging industries are facing the technological challenge of improving the quality of cold forged gear profiles by 1 or 2 tolerance grades to be able to compete with fine-machining and grinding processes. To overcome this challenge of a stable production of transmission gear wheels with very accurate tolerances, it is absolutely necessary to apply new innovative tool designs. A special challenge on the market is that these complicated net shape parts right from the beginning have to be produced at fairly low costs to be competitive with the alternative manufacturing processes.

3. High-stiffness strip-wound containers

An innovative development within die design during the last years is the high-stiffness strip-wound container also known as the STRECON® E^+ container [2,3]. This strip-wound container differs from the usual STRECON® container as the very thick winding core, on which the strip is wound, is made of tungsten carbide, see Fig. 3. As the tungsten carbide has a Young's modulus of 500 to 580 GPa, the total stiffness of the container is increased to 400 GPa or higher depending on the design.

The high stiffness of the STRECON® E^+ container reduces the strains and stresses in the die during the cold forging process. Thus, cold forged parts with complex geometries and small radii, such as bevel gears and planetary gear wheels, can be produced in high and profitable volumes. With dies mounted in conventional stress rings, it is only possible to produce small and unsatisfactory volumes per die.

The use of STRECON® E^+ containers will lead to a considerable reduction of the die costs, and thus, to a reduction of the tool costs per produced part. Another advantage of the high-stiffness STRECON® E^+ container are the reduced deflections in the die during the cold forging process. This leads to improved accuracy of the cold forged part which is very important in the production of high complexity net shape or near net shape parts.

4. New designs for optimisation of die life

For some years, the high-stiffness STRECON® E^+ containers have been used for new die designs which in conventional production suffer from low die lives and critical tool economy. The following examples demonstrate how STRECON® E^+ containers can be used for optimisation of die lives for geometrically simple parts as well as for parts with complicated shapes.

4.1 Die life improvement for hollow shaft die

A major European automotive company is producing hollow shafts for front wheel drives in large quantities. In the process of optimising the properties of the final product, various parameters such as material, geometry, and relative dimensions have been modified in comparison to a similar product of a previous generation.

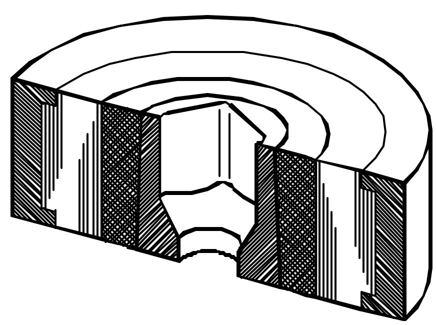

Fig. 3 Layout of STRECON® E^+ prestressed container for manufacture of geometrically complex parts

At production start, it turned out that these changes, each of which seemed to be of minor importance, summarised in a change of the die load that changed the die life remarkably in negative direction. The optimised die set-up is illustrated by the upper cylindrical die in Fig. 4. With the purpose of optimising the die life by use of STRECON® containers, the forming process was first analysed by means of the cold forging simulation programme, DEFORM. The simulation showed that the changes incorporated in the new die design led to a critical increase in the local die load so that the radial pressure locally clearly exceeded the permissible pressure of the tungsten carbide die that was mounted in a double stress ring set. A finite-element analysis showed that even with an optimised conventional die, it would not be possible to obtain a sufficiently high loadability to avoid very early die failures. The analysis also showed that with a die prestressed by a normal STRECON® container, an improved but still low die life had to be expected as the stress and strain ranges and the accumulated plastic work at the most critical point of the die exceeded acceptable values.

An analysis of a die mounted in a high-stiffness STRECON® E+ container showed that the increase of the stiffness of the supporting system to double the normal value would reduce the critical parameters (stress and strain range, maximum tensile stress, and accumulated plastic work) to an acceptable level where satisfactory die lives could be expected. The FEM calculations showed that even though the STRECON® E+ container was initially foreseen for prestressing of sharply notched dies of tool steel or high-speed steel, it could as well be used in an innovative way for the prestressing of geometrically very simple cylindrical dies loaded with by high local pressures.

With three years of production experience where all three designs (conventional double stress ring set, normal STRECON® container, and optimised STRECON® E+ container) were tested on a large scale with approx. 1,000 dies, the following average die lives were obtained:

Conventional double stress ring set N ≈ 4,200 pieces
Normal STRECON® container N ≈ 10,500 pieces
STRECON® E+ container N ≈ 19,300 pieces

The 4.6 times increase in die life resulted in an equal size of reduction of the direct tooling costs and additional saving due to fewer stops, die changes, and quality checks. From the point of view of tool management, it is of course important to obtain high die lives, but another important result of the analysis of die life statistics is that the variation in die life has been considerably reduced from more than a factor of 10 between maximum and minimum die life to a factor of 4. This makes long-term planning of die manufacture, purchase, and stock much more reliable.

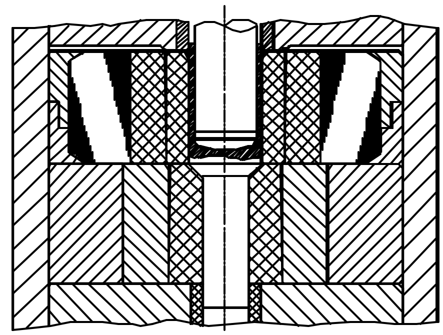

Fig. 4 Tool for manufacture of hollow shaft

4.2 Die life optimisation for bevel gear die

Another illustrative example deals with the analysis and optimisation of a cold forging die for industrial mass production of bevel gears for differentials in automobiles. Further details of the analysis can be seen in [3,4]. Three different tools are analysed. In the first analysis, the die is mounted in a conventional double stress ring. The second and third analyses are both made with dies mounted in STRECON® containers. In the second analysis, the STRECON® container has a winding core of hardened tool steel, whereas in the third analysis, a STRECON® E+ container with a winding core of tungsten carbide is used.

The geometries of the bevel gear and the STRECON® E+ tool are illustrated in Figs. 5 and 6, respectively. Cracks are initiated due to fatigue in the corners of the die leading to unwanted burrs on the cold forged bevel gears and finally to a total failure of the die. In order to increase the die life, it is essential to reduce or even eliminate the tensile stress concentrations in the critical corners of the die. Furthermore, is it important to reduce the amount of plastic work per load cycle. In some way, the plastic work is depended on the stress 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 improved die life.

Fig. 5 Cold forged bevel gear for differentials in automobiles

An elastic-plastic material behaviour based on a kinematic hardening rule is assumed in the analyses, and the assumed forging load is based on calculations in [5].

Figure 8 illustrates the tangential operational stress distributions for all three analysed 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® assembled die, the maximum tangential stress has been reduced to 680 MPa, and furthermore, the region subjected to tensile stress is significantly reduced. In the STRECON® E+ assembled die, 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 in the STRECON® E+ tool.

The tangential stress-strain relations along the critical edge in the first load cycle of all three designs are illustrated in Fig. 9. 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. 9 until fracture. For a detailed description of the test, please refer to [6].

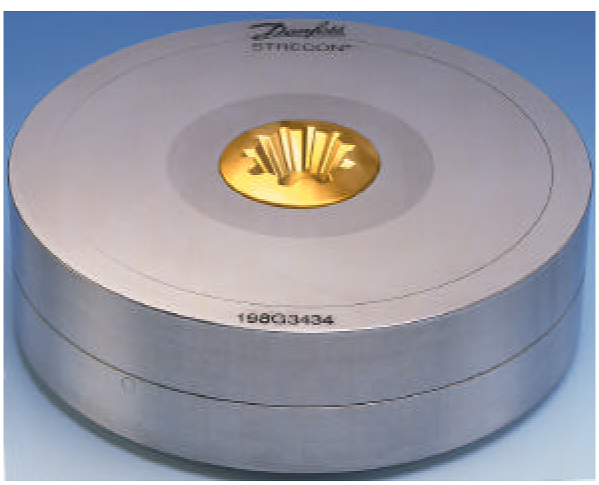

Fig. 6 STRECON® E+ tool for manufacture of bevel gear

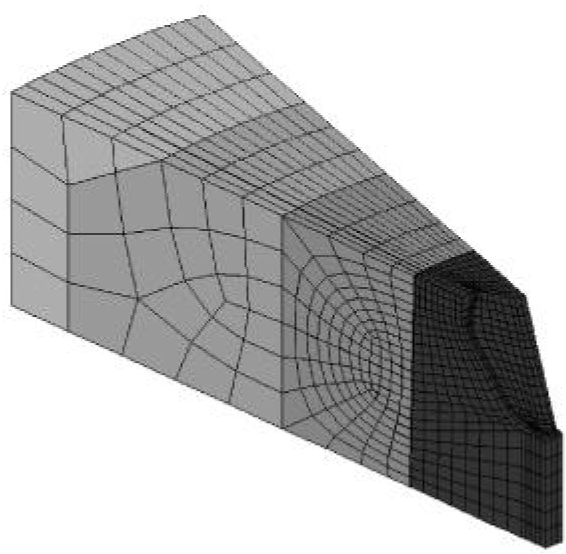

Fig. 7 Finite-element model of STRECON® E+ tool for bevel gear

The test specimen loaded according to the stress-strain condition in the conventional assembled die failed after 440 cycles. It shall be mentioned that the stress-strain condition in the uni-axial test specimen cannot be compared directly with the three-dimensional stress-strain condition of the die. However, as the tangential stresses are the major stresses in the die, the approximation is valid. The test specimen loaded according to the stress-strain condition in the STRECON® assembled die failed after 4700 cycles which is an improvement by a factor of 10 compared with the conventional tool. The test specimen loaded according to the stress-strain condition of the STRECON® E+ assembled die had not failed after 70,000 cycles, and the test was stopped. This is a die life improvement of more than a factor of 160 in comparison to the conventional tool. The lives found in the cyclic fatigue tests can probably not be transferred directly to real-life bevel gear dies, but still, the relative difference in the number of cycles to failure fully justifies the advantage of using STRECON® containers and especially STRECON® E+ containers for production of bevel gears.

Also the die deflection for the different prestressing systems was analysed. Figure 10 shows the results from the FEM calculation of the radial die deflection for the conventionally assembled die, the die mounted in a normal STRECON® container, and the die mounted in a high-stiffness STRECON® E+ container. The calculation clearly demonstrates that the STRECON® E+ container considerably contributes to the reduction of the radial part tolerance. This has been proved in high-volume production of all three types of dies.

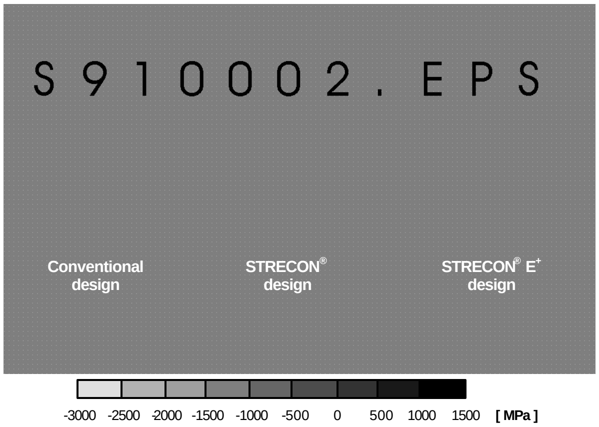

Fig. 8 Tangential operational stress distribution in the die for different designs

The results of the finite-element analyses and the die life predictions of the low-cycle fatigue tests were presented to a customer producing net shape cold forged bevel gears to convince him of the advantage of using STRECON® pre-stressed containers.

The three investigated bevel-gear designs were tested by the customer in mass production. In the conventional die, cracks occurred in the critical corners after only 500 to 1,000 parts. The cracks led to production stop after 3,500 to 10,000 parts with an average of 7,000 parts. In the STRECON® assembled die, cracks were observed after 10,000 to 12,000 parts, but it was possible to produce parts 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 the STRECON® E+ assembled die, 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.

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 by 90% compared with the conventional tool for bevel-gear production.

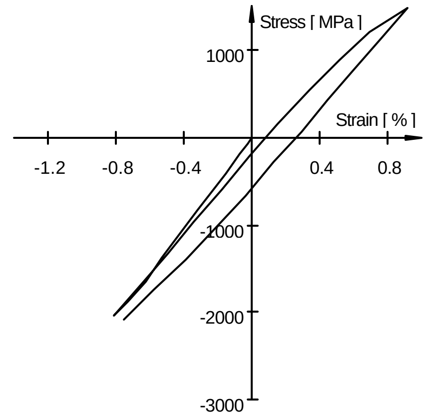

Fig. 9a Tangential stress-strain relation along the critical edge of conventional tool

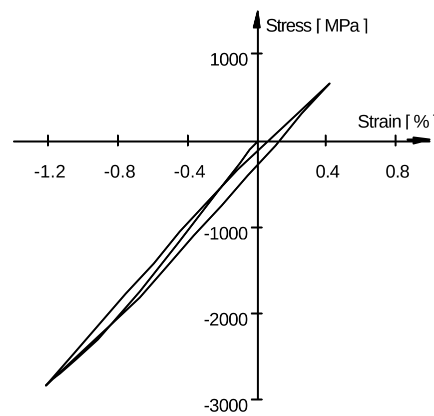

Fig. 9b Tangential stress-strain relation along the critical edge of STRECON® tool

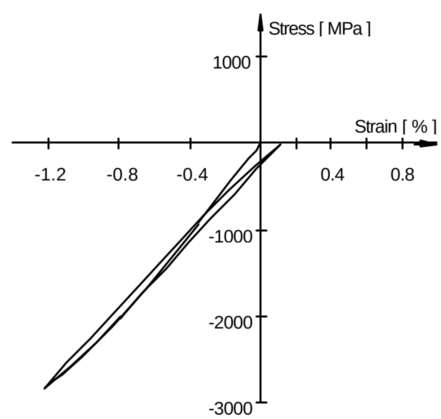

Fig. 9c Tangential stress-strain relation along the critical edge of STRECON® E+ tool

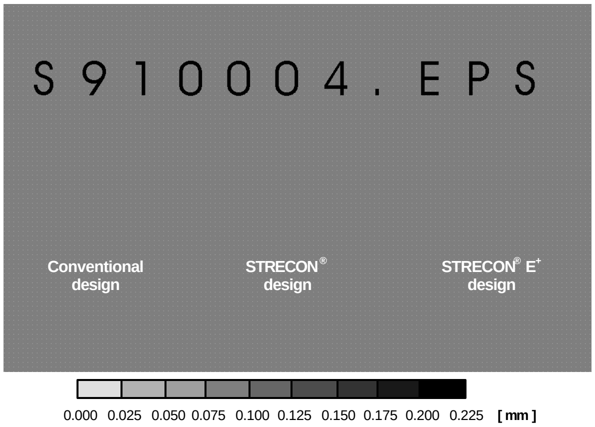

Fig. 10 Radial deflection in the die during the cold forging process

5. New designs for optimisation of net shape manufacturing capability

The manufacture of net shape parts by metal forming processes is especially complicated in cases where the net shape surfaces to be obtained are geometrically complex and where close dimensional tolerances must be obtained. This is due to the fact that sufficiently accurate shapes and tolerances can only be obtained by more or less complicated corrections of the die shape and die dimensions in relation to the part dimensions as dies deflect elastically under forming pressure. This should be compared to net shape manufacturing by machining where the final shape and accurate dimensions are obtained by less and less material removal as the dimensions approach the final value.

In case of close-tolerance net shape parts, the correction of die dimension and shapes can be very complicated as the dimensional deflection of a die under forming pressure typically is around 10 times larger than the tolerance to be obtained. As the die deflection varies due to variations in the properties of the part material, die temperature, lubricant, and volume of the slugs, compensation can only take place on the basis of an assumed stable mean situation. Unfortunately, it is often so that the variation in die deflection has an equal magnitude as the required part tolerance. Besides overcoming this variation in production and process variables, it is a challenge for the cold forging industry to develop new die designs with reduced die deflection under process or with adjustment or regulation possibilities. As die deflection is almost directly related to the stiffness of the die, the high-stiffness STRECON® E+ container offers valuable features for design of net shape toolings.

As described above, the STRECON® E+ containers have an overall stiffness that is approximately double as high as for steel containers. For the assembled tooling, this means that, depending on the combination of die material and the dimension of the tungsten carbide winding core of the STRECON® E+ container, die deflection can be reduced by 30 to 50% compared to an all-steel tool. In cases where the die is only loaded over a part of the height, the unloaded levels of the STRECON® E+ container will add significantly to reduction of the die deflection compared to stress rings of steel.

5.1 Analysis of die for planetary gear wheel

The net shape cold forging of planetary gear wheels is one of the hottest topics of the cold forging industry at the moment. Already in the mid-seventies, it was demonstrated by Samanta and others, e.g. [7], that planetary gear wheels could be cold forged by mass production methods, but unfortunately, the required accuracy of the final part could not be maintained in volume production. In the meantime, die manufacturing and process control have improved so much that a safe production with accurate tolerances is realistic, and this is the reason why the most innovative cold forging companies have development projects with the aim of penetrating the high-volume market for planetary gear wheels for automatic transmission. But still, almost a quantum leap is necessary before the required tolerances can be maintained without problems in daily high-volume production.

The STRECON® E+ containers give extremely good possibilities for improving the accuracy of planetary gear wheels as the die deflection can be reduced by 30 to 50%. Figure 11 shows a general layout of the active die for planetary gear wheels. Figure 12 shows the results of an analysis of the die deflection when 50% of the total height of the tool is loaded with internal pressure. The figure shows the calculation results for several positions of the pressure zone and combinations of die material and prestressing elements.

It is clear, that the lowest deflection is obtained with high-speed steel or tungsten carbide dies mounted in STRECON® E+ containers and with a centre-placed pressure zone. Besides reducing the deflection, the high-stiffness STRECON® E+ container makes it realistic to apply tungsten carbide for the gear-shaped dies, as the high stiffness reduces the very critical cyclic and tensile stresses in the notches of the die as explained in the bevel gear case.

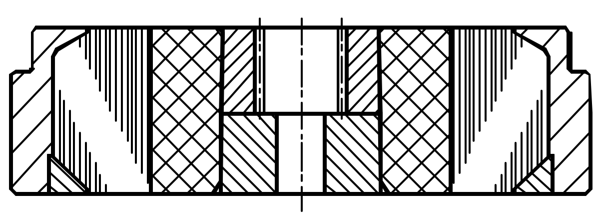

Fig. 11 STRECON® E+ tool for manufacture of planetary gear wheel

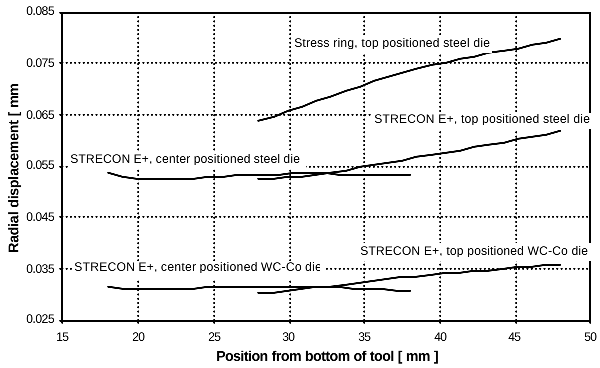

Fig. 12 Die deflections during cold forging of planetary gear wheel

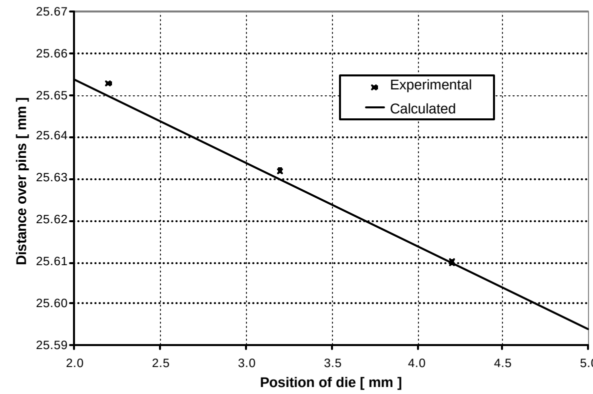

Fig. 14 Results of experimental adjustment test

Laboratory and production tests show that the application of high-stiffness STRECON® E+ containers can reduce the main part of the critical gear profile tolerance to a level comparable to machined gear wheels. For some tolerances, optimisation of tool manufacturing processes and sequences is still needed.

5.2 Design of dies with adjustable internal diameter

For spline-shaped dies as well as for other dies with close tolerances, the required, very accurate die manufacture can be problematic and costly. Often, it is seen that out of a series of equal dies, only a part of the dies are acceptable for production as the rest are slightly outside the dimensional tolerances. With the aim of improving the dimensional quality of the produced part and at the same time reducing the dimensional requirements to the die manufacture, a new patented type of adjustable containers, the STRECON® VARI-FIT, has been developed. Figure 13 shows the general layout of a container mounted with a die for forming of splines at the end of axles for steering or drive applications.

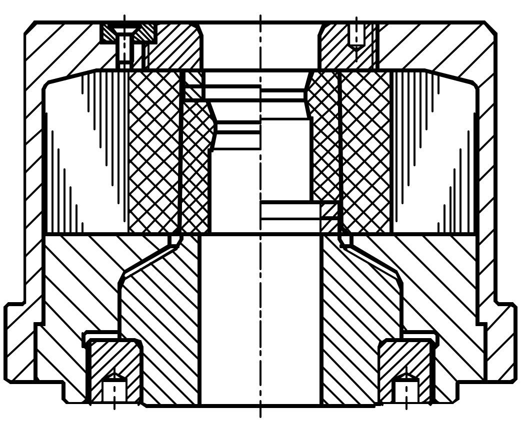

Fig. 13 STRECON® VARI-FIT prestressed container

In the STRECON® VARI-FIT container, the die can be placed and locked in different axial positions, and because of the conical surfaces combined with the high stiffness of the STRECON® container, a high-precision adjustment of the internal diameter of the die takes place. After the first mounting of the die, a test pressing is carried out. Based on the results of a dimensional check of the test piece, an adjustment of the die can be carried out so that parts can be produced as high-quality net shape parts. Figure 14 shows the results of an experimental adjustment test. It is obvious that adjustments in the range of 0.01 mm can easily be performed.

Conclusion

The high stiffness of the strip-wound STRECON® E+ container with winding core of tungsten carbide makes it possible to make new innovative die designs where the high-stiffness feature is utilised for optimisation of die life or for reduction of die deflections.

For dies mounted in high-stiffness containers, the fatigue-life determining factors: stress and strain level, stress and strain range, and accumulated plastic work, can be reduced to a level where die life improvements by factors of 3 to 10 are obtained.

Die deflections due to the working pressure from the part forming, which to a great extend determines the final product tolerances, can be minimised by application of high-stiffness containers. For gear-shaped dies where tolerances are very critical, the die deflection can be reduced by 30 to 50%. The application of high-stiffness STRECON® E+ containers in combination with accurate dies makes it realistic to produce gear-shaped products such as planetary gear wheels in high volumes with tolerances comparable to machined gear wheels but at lower prices.

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