Prestressing Technology as Strategic Design Parameter

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Abstract

Optimal prestressing can significantly reduce the negative stresses in the forging die and consequently improve both the performance and life of the forging tool. The paper addresses the concept and importance of prestressing and compares different prestressing tool systems. At the end, the paper illustrates the objective of optimal prestressing by means of an example taken from industry. The initial analysis of the tool system could be performed by analytical calculations but numerical analysis (FEM) was required to obtain the proper understanding of the stresses in the forging tool. The result was the adoption of an optimized tool design based on a stripwound container solution with high stiffness and adjustable prestressing of the forging die. The tolerance improvement of the gear parts was moved to a new level.

1. Introduction

The globalization of the automotive industry as well as many other industries have significantly changed the business environment. Today's competition requires technical advanced and cost-effective development, production and delivery systems, and the supplier base to these global industries has been following the customers for ensuring local supplies and services whenever and wherever needed. The forging industry is no exception from this trend. Initially, the move out was motivated by cost reduction of simple high-volume parts; but today these markets have their own demand and needs to serve. The interest for advanced technology has grown as well including the tooling business for various forging operations. From our own business activities, we see a strategic interest in tooling solutions for complex components and forging processes.

The tendencies in precision forging such as net shape forging of increasing complex parts [1, 2], ecological manufacturing, cold forging of stainless steel and light-weight materials lead to steadily increasing tool loads. At the same time, economic requirements necessitate the optimisation of the life and performance of the forging tools. Among the various measures to improve the tool performance, service life [3] and the demand for super precision parts, the prestressing of the forging dies is one key design parameter. This paper addresses the importance of optimal prestressing of the forging dies with a view to different prestressing tool systems.

2. The Concept of Prestressing

The concept of prestressing of forging dies is recognized in the forging industry and shall in this context be understood as the compressive stress (typical radial) intentionally being devoted to the forging die. The purpose of prestressing the forging die is to reduce the level of critical tensile stresses, which the die will see under full loaded conditions in the forging process. The higher the prestressing, the deeper the forging die will be pushed into a compressive state as illustrated in Figure 1. The left-side graphical illustration shows a forging die with no prestressing. Typically, the level of interference fit is expressed as an oversize of the forging die, for example 0,5% interference fit would mean an actual OD ø50,25 mm of an ø50,00 mm outer die diameter.

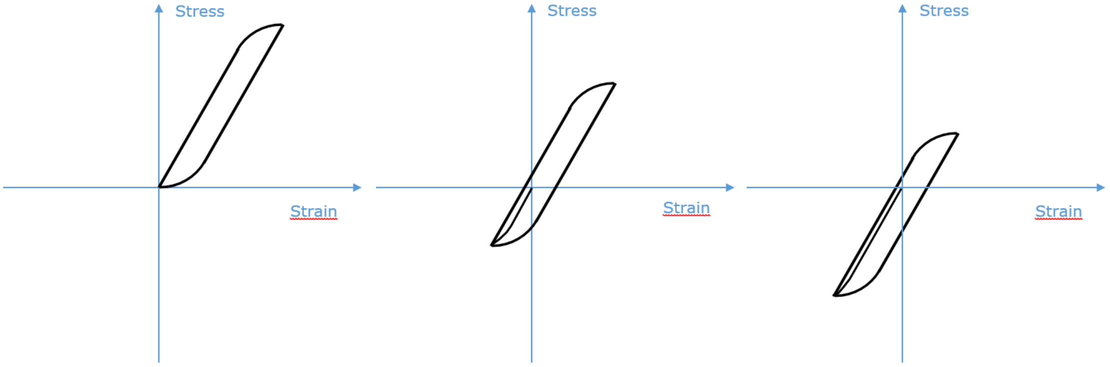

Figure 1. Principal Stress-Strain Amplitude for Three Levels of Prestressing of the Forging Die

The importance of prestressing increases with the tool load. The higher the forming load, the higher the level of tensile stresses in the forging die. As mentioned above, there is a general trend with increased forming loads of the forging dies, which is a derived consequence of a higher degree of part finishing in the forging process, relatively larger parts in small tools, increasingly more difficult part materials to form, higher degree of part deformation, etc. Consequently, the relative importance of prestressing is increasing in the forging industry [4].

In the case of mono-blocks, the forging die is not prestressed at all as the die cavity is machined directly into the die block. Mono-block dies are mostly seen in the hot forging segment and can be explained by the tool size, complexity and/or low forming load. It is our experience, however that many hot forging dies could benefit from prestressing, and even a little compressive die support could take off the top of the most critical tensile stresses in the forging die. The limited use of die prestressing in this segment is also a question about industry practice.

A more developed approach to prestressing is to look at the stress / strain behaviour of the forging die. This approach examines the full load cycle of the forging die including the stress range and the physical movement of the forging die (i.e. strain behaviour). As shown in Figure 2, the pole position of the forging die will be at a certain level of compressive stress, which is determined by the interference fit. The higher the level of prestressing, the higher the resulting compressive stress in the forging die. During the forging process of the part, the forging die would be heavily loaded and normally go from a compressive state of stress into tensile stresses. The endpoint of the load cycle determines the maximum peak stress, which the die will see in the forging process. At push out (i.e. at part ejection) there is principally no load on the forging die, and it would have returned to its pole position defined by its level of prestressing. The distance from the pole position and the maximum stress at full load determines the stress range. The higher the forming load, the larger the stress range.

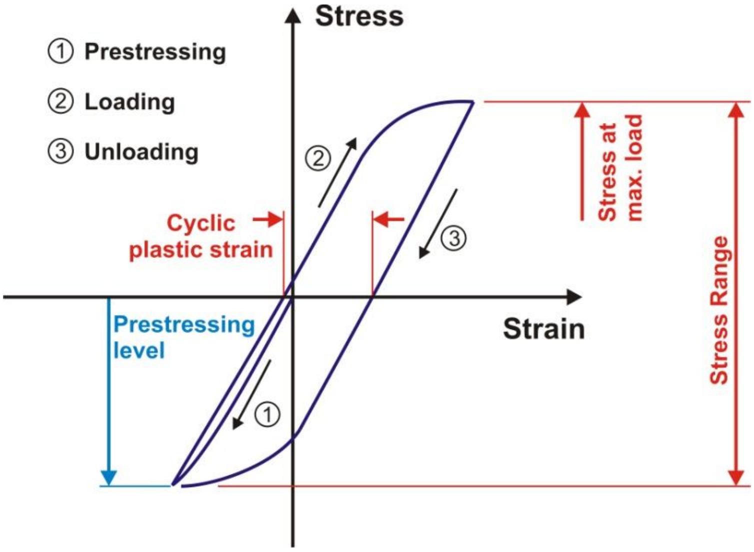

Figure 2. Principal Stress-Strain Response in the Critical Point of a Prestressed Forging Die

Simultaneously with the compression of the forging die, the die does also see a certain amount of physical contraction. The higher the prestressing, the higher the contraction of the forging die. However, the ability to compress the forging die is determined by the material properties of the die itself and the overall tooling system. Tool systems with high stiffness (i.e. Young's Modulus) deflect less than normal steel-based tool systems. For example, the Young's Modulus of a tungsten carbide die is approx. 2,2 higher than a steel die, namely 460 GPa compared to 215 GPa, and consequently a carbide die would deflect approx. 36 % less than a steel die made of same dimensions and cavity. Under full loaded conditions, the forging die would physical move from its pole position (i.e. in contraction determined by the level of prestressing) to its maximum point of expansion, and the distance between the two points determines the strain range. The smaller the strain range, the shorter the stress range due to the reduced physical deflection of the die during the forging process. In Table 1, the principal difference in deflection of a forging die has been calculated for a tool with the following dimensions: The compression ring ø150 x ø50 mm, and the forging die ø50 x ø35 mm. The analytical calculation is made for a forging die of tool steel die and tungsten carbide and assumes an inner process pressure of 1200 MPa.

Compression ring ø150 x 50 mm **Forging die ø50 x 35 mm**	**Difference in die deflection**	
Material of forging die	Tool steel	Tungsten carbide
Loadability of compression ring	1000 MPa	800 MPa
ID die contraction from prestressing	-0,067 mm	-0,045 mm
ID expansion under max process load	0,276 mm	0,177 mm
Reduction in strain	-	36 %

Table 1. The Principal Difference in Deflection of the Forging Die

The service life of a forging tool, i.e. the number of forming cycles until its failure by wear or fracture, depends on the interaction between the load on the tool and the loadability of the tool. This concept is shown in Figure 3 and illustrates the complex nature of high performing forging tools [4]. The load on forging dies is determined by several interacting load parameters such as the type of forging process, lubrication, temperature, billet material properties; preform design, part geometry, forging steps. The ever-present task of the forging engineer is to keep the load on the forging tool at a moderate level in order to obtain well performing forging processes including a high and ideally predictable service life of the forging tools. There exist several different approaches for achieving such an operational state, for example advanced process simulation and special process designs. Prestressing is also an effective design parameter in achieving high performing tool systems as this parameter directly addresses the stress / strain behaviour of the forging die [5]. The optimal prestressing of the forging die can be achieved by balancing the stiffness of the forging die and the tool system as such with the nominal level of interference fit. Generally, the lower the tensile stresses at maximum process load, and the smaller the strain behaviour of the forging die (i.e. physical deflection), the better the base condition for achieving high performing forging tools. Furthermore, high-stiffness tool systems reduce considerably the deflections of the forging die in favour of improved part accuracy and reduced dimensional scatter of the forged parts (e.g. a batch production).

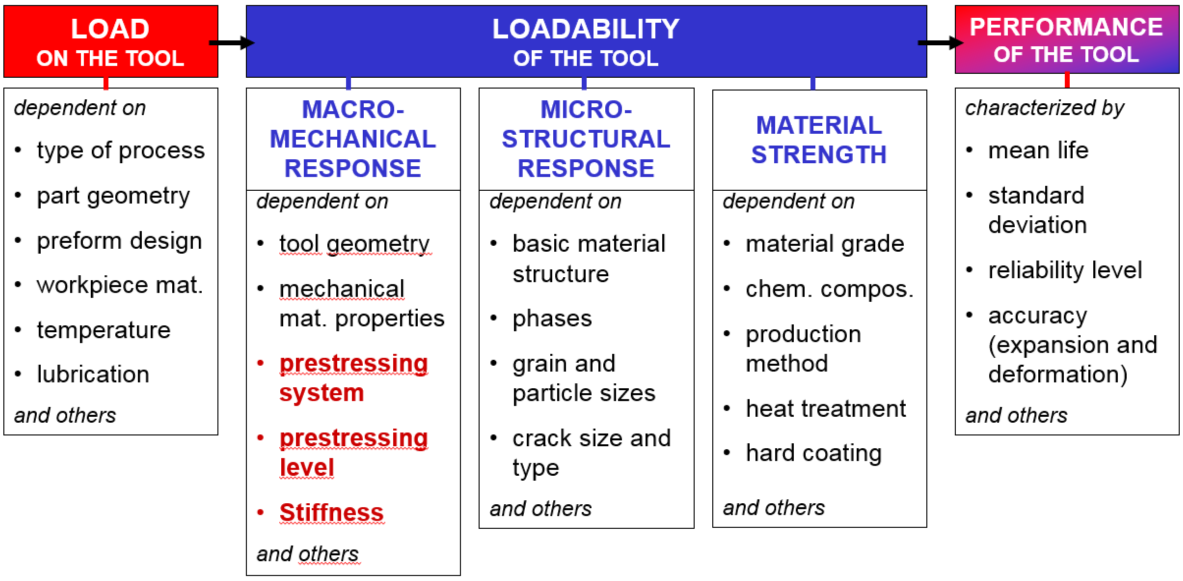

Figure 3. The Load and Loadability Concept regarding the Performance of the Forging Die

3. Prestressing Tools

The prestressing tools are normally referred to as compression rings, stress rings, retainers, die holders, containers etc. These rings are typically designed as single (i.e. 1-ring) and double ring (i.e. 2-ring) systems and made of hardened tool steel of a standard SKD61 or H13 material grade, which is a chrome-molybdenum-vanadium type of tool steel. The strength of the compression ring is given by its size, material yield point and hardness, see the example in Table 2. The single ring is typically hardened to 48 HRc, while the inner ring of the double ring system is hardened in the range of 52-54 HRc, and the outer ring to 46-48 HRc.

A compression ring made by the stripwinding technique offers a prestressing tool system, which is significant stronger than the standard compression rings described above. As can be seen in Table 2, a stripwound container is 2 times stronger than single ring and 1,7 times stronger than the double ring with same tool dimensions. The additional strength allows for higher prestressing of the forging die when needed, but the prestressing system does also remain fully elastic throughout its service life (i.e. its engineered performance). The underlying explanation shall be found in the stripwinding technique, in which the container itself is prestressed to a higher compressive state than possible with standard compression rings. The material yield point of the steel strip material is approx. 2100 MPa (at room temperature) and hardened to 62-64 HRc.

Internal process pressure 1200 MPa	Prestressing tool ø140 x ø65 mm Forging die of tool steel ø65 x ø35 mm Radial load on ID prestressing tool Interference level in brackets		
	Radial load from prestressing	Max radial loadability of prestressing tool	Max load index
Single ring	515 MPa (0,37%)	515 MPa	1,00
Double ring	595 MPa (0,5%/0,2%)	595 MPa	1,15
STRECON container	925 MPa (1,0%)	1025 MPa	1,99

Table 2. Comparison of Loadability of Different Prestressing Tools, Size ø140 mm

As addressed earlier in this paper, the stress/strain behaviour of the tool system can be influenced by increasing the mass, and more effectively by changing the material properties of the tool system. The use of tungsten carbide material for the forging die is the single most effective way of increasing the overall stiffness of the tool system due to the high level of Young’s Modulus. However, in many cases it won’t be advantageous – or even possible – to use carbide material for the forging dies due to excess heat, high stress concentration factor and/or high deflection of the forging die under maximum process pressure. The tungsten carbide die is the “perfect” solution when applied for high volume production at moderate stress/strain levels.

An alternative approach to obtain high-stiffness forging tools would be to integrate the tungsten carbide material as part of the prestressing system, for example by having the inner ring of the double ring system made of tungsten carbide, or to use the STRECON® E^+ container. Table 4 illustrates the effect of a high stiffness tool system on the strain behaviour of the forging die, which in this example is made of tool steel.

Internal process pressure 1200 MPa Interference fit of forging die 0,3 %	Prestressing tool ø140 x ø65 mm Steel forging die ø65 x ø35 mm	
	Double ring with carbide inner ring	STRECON E^+ Container
Max allowable radial load on the ID of the prestressing tool	400 MPa	750 MPa
ID die contraction from prestressing	- 0,112 mm	-0,115 mm
ID expansion under max process load	0,233 mm	0,227 mm

Table 4: Comparison of Loadability and Stiffness of Prestressing Systems with Tungsten Carbide.

The effect from the double ring system and the STRECON E$^+$ container is principally the same when it comes to stiffness, but the STRECON E$^+$ container is significantly stronger than the "carbide based" double ring, which in this example has about twice the level of loadability. This means that the possibility of the double ring to provide optimal prestressing of the forging die would be very limited or even not feasible. Furthermore, the risk of overloading the double ring is much higher, which would lead to plastic expansion of the ring (which again would lead to a direct loss of effective prestressing of the forging die), or a fatal crack of the carbide inner ring. The consistency in performance and reusability of the stripwound prestressing tool system would be much higher than achievable with a double ring.

4. Dimensional Adjustment of High Precision Forging Dies

Cold forging of high precision parts such as inner races, spur gears, helical gears and spline shaped shafts and axles, puts high demands on the tool performance. The dimensional tolerances of the forging die are very tight and sensitive to both the die manufacturing itself, the forging process, and small but critical differences of the billet material between batches. In such cases it would be very effective to adopt a tooling system that allows for final dimensional adjustment of the forging die.

It is a known problem that some forging dies are scrapped already in the manufacturing process due to very tight tolerances. For instance, in spark erosion of forging dies the control and consideration of the electrode's wear is limited to a certain extent. In many cases, these problems are not evident until the forging die has been mounted into the prestressing tool or the first set of parts have been forged in the press. Furthermore, the high tool loads in precision forging leads to critical wear and/or plastic deformation. Sooner or later, the resulting dimensional changes of the forging die cause the parts to be outside the defined tolerances. In most cases, this failure requires disposal of the forging die since a reworking of the die shape is no longer possible.

4.1 Compensation of Tolerance Problems

The tooling system STRECON® VARI-FIT offers an effective measure for compensating the above-mentioned tolerance problems in the forging die. The die diameter can be adjusted to the required dimensions repeatedly in small, precise steps., and this is done by an easy tool setting procedure. Thus, the STRECON® VARI-FIT ensures that the parts can be forged within the given tolerance limits.

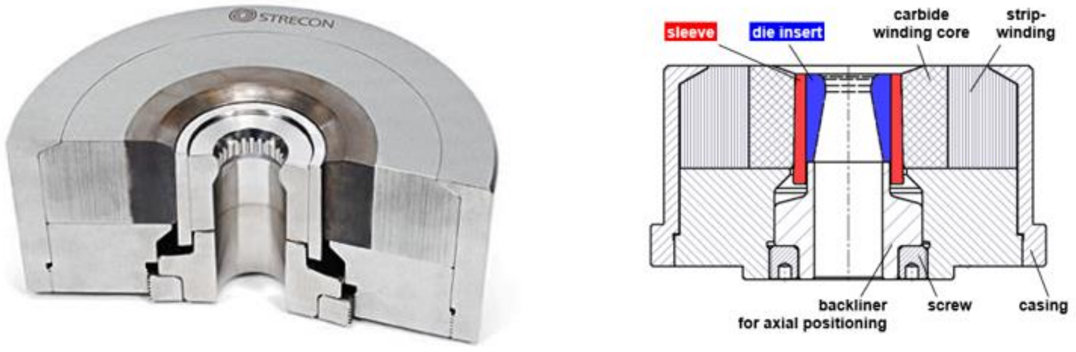

Figure 4. STRECON VARI-FIT Tooling System

Specifically, the dimensional adjustment of the forging die is performed by varying the radial prestressing. Higher prestressing leads to smaller dimensions, and the opposite with reduced prestressing. This die adjustment is performed with a die sleeve, which is mounted between the forging die and the prestressing tool system. When changing the axial position of the sleeve, and thanks to the conical shrink fit between the sleeve and the prestressing tool system, the level of radial prestressing changes, and consequently the inner diameter of the forging die.

The adjustment of the inner die diameter can be done with very high accuracy by changing the axial position of the intermediate sleeve. In case of a carbide die with an inner diameter of Ø 28 mm, for instance, an axial displacement of 0.1 mm leads to a diameter change of 2 µm. In case of a die made of high-speed steel, the relative change of the inner diameter is higher because of its lower material stiffness.

The advantage of the STRECON® VARI-FIT compared to other tool concepts is that the inner diameter can be both extended and reduced several times, only depending on the direction of the axial displacement.

The tooling system can be applied to various die insert geometries, forging process characteristics, and requirements to the precision in adjustment.

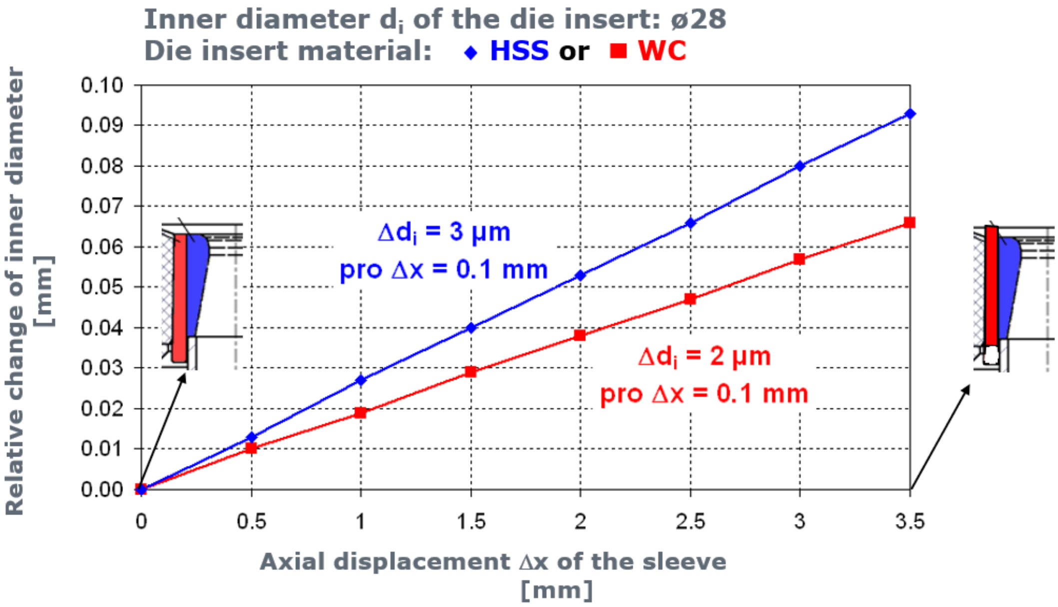

Figure 5. STRECON VARI-FIT - Example of a Die Adjustment Window

4.2 Increased stiffness by the Stripwound Carbide Winding Core

The STRECON® VARI-FIT is an unique prestressing tool system of which the inner core that carries the coiled strip section normally is made of tungsten carbide. The stiffness of the carbide core improves the efficiency when adjusting the inner diameter of the forging die. Furthermore, it confines the expansion of the forging die during the forging process, which increases the accuracy and reduces the risk of fatigue damage. In addition to the highly controlled radial prestressing, the forging die is also prestressed in axial direction. Thus, the STRECON® VARI-FIT system represents a tool design which combines the advantages of various prestressing methods and material properties.

4.3 Precision Forging of Net Shape Parts

Figure 6 illustrates the principal stress / strain behaviour of a conventional ring system and the STRECON container system of which the winding core is made of tool steel and tungsten carbide, respectively. In case of the steel-based prestressing tools, it is only the level of prestressing that differs. The stress range and the strain range are same. In case of the carbide based prestressing tool system, both the stress range and the strain range would be significantly reduced due the above-mentioned effect of limiting the physical deflection of the forging die.

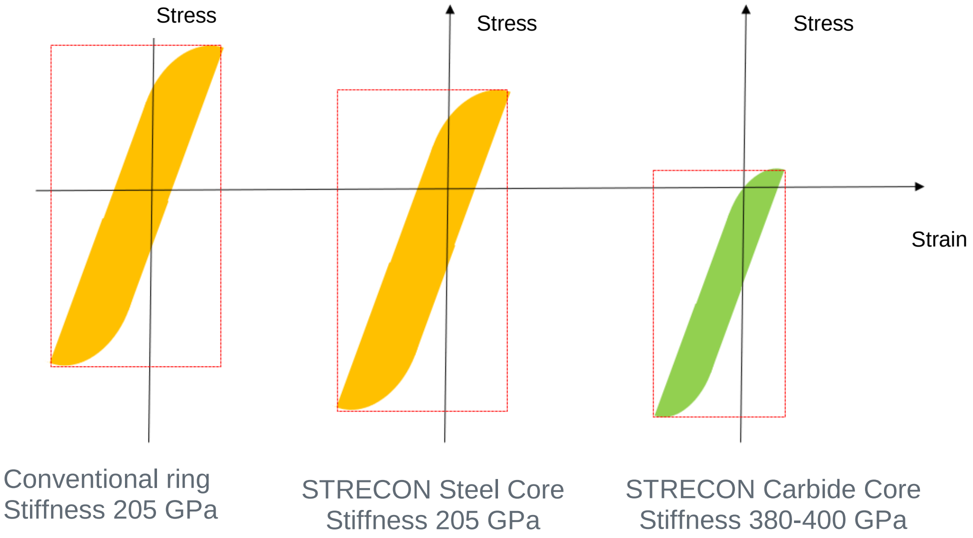

Figure 6. Influence of Stiffness on the Cyclic Stress / Strain Response

The effect on the elastic expansion of the forging die under process pressure is shown in Figure 7. The expansion can be reduced approx. 30% by having a system with a stiffness of 410 GPa.

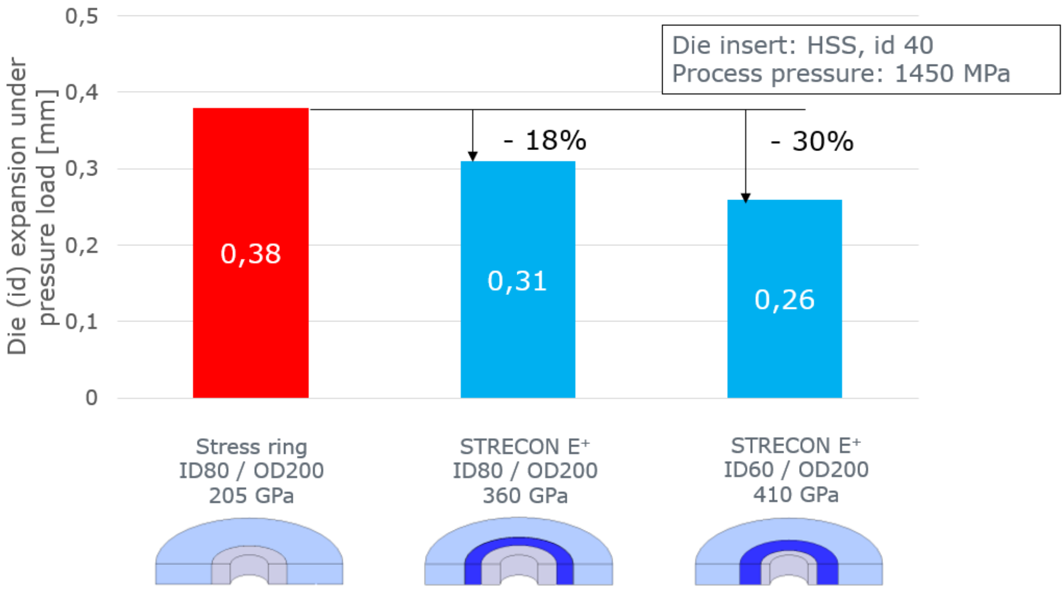

Figure 7. Influence of Stiffness on the Elastic Expansion of the Forging Die

The effect on the stress range in the die insert under process pressure is shown in Figure 8. The reduction of the stress range is approx. 34% having a system with a stiffness of 410 GPa.

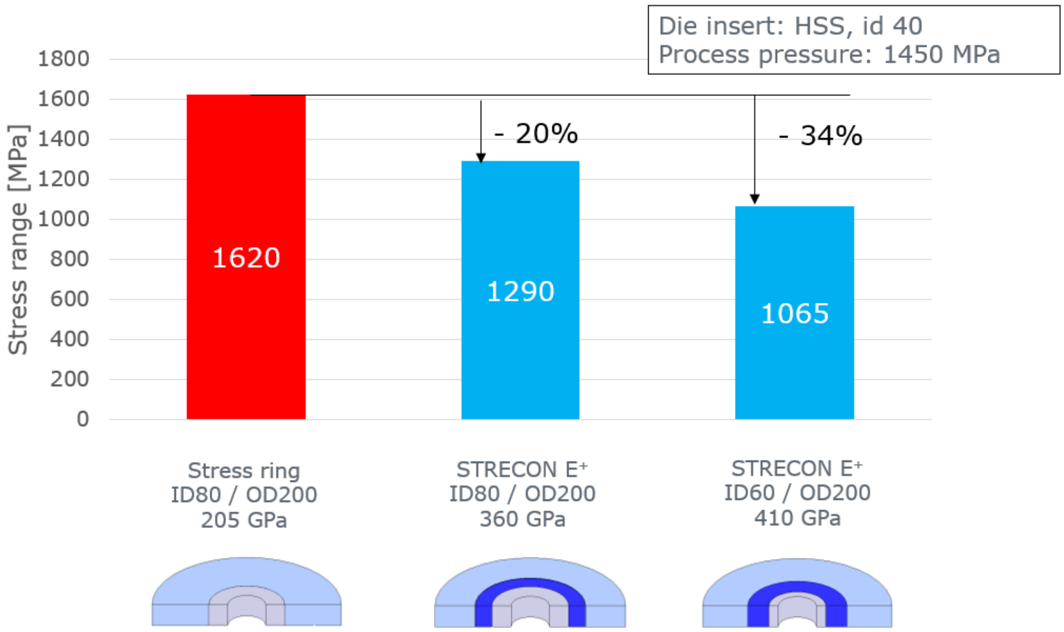

Figure 8. Influence of Stiffness on the Stress Range

5. Examples from the German Forging Industry

The following section is showing examples from the German forging industry. The first part is an axial spline extrusion process (part no. 1 in figure 9) for driveline, and the other part is a closed die forging process of spur- and helical gears (part no. 2 in figure 9) for transmission in EV Cars.

Figure 9. Typical Parts Forged with STRECON High-Stiffness Tooling System

5.1 Spline Forming at CVJ Housing Shaft

Manufacturing of shafts with high precision splines are increasingly being made by a special recursive axial spline forming process, which has been developed by the German company Felss Systems GmbH. For axial spline forming Felss Systems developed the AXIMUS axial spline forming technology and machine system in which the high-stiffness STRECON VARI-FIT container system is an integrated subsystem. The advantage of this machine system is the relatively low forming load, which is approx. 60% lower when compared to a traditional extrusion process. The high-frequency modulated process is just oscillating at 18-25 Hz, and the combination of the special forming process and the high-stiffness tooling system offers an accuracy of the splined part to IT5 in series production.

The advantages of the STRECON VARI-FIT system are:

- Optimal prestressing of the high-precision die with tight tolerances
- Controlled dimensional adjustment of the forging die, for example due to workpiece variations from the material suppliers
- Adoption of a high-stiffness and re-useable tool system for optimizing the tool performance and service life

Figure 10. Principal Recursive Forming Process. AXIMUS Machine and splined CVJ Parts for Driveline

	Reached values	Quality DIN3962	Improvement to Rolling Process
Total Profile variation	4,9 µm	5	40 %
Total Flank variation	6,8 µm	5	90 %
Concentricity variation	2,2 µm	1	91%
Pitch variation	8 µm	4	84 %

Table 5: Improvement in Variation of Formed Splines by the Felss AXIMUS machine

"With the recursive axial forming process/machine technology and STRECON VARI-FIT high stiffness system it became possible to produce high accuracy parts, Due to the low press forces and the high stiffness of the tooling system the spline quality was improved by 40% and in IT5 in series production." Mr. Philipp Grupp, Director Business Development, Felss Systems GmbH.

5.2 Closed Die Forging of Spur- and Helical Gears for Transmission

At an early development for a new transmission for EV and Hybrid cars, STRECON was requested to design a high-stiffness tool system for closed die forging of spur- and helical gears. The customer requested a new tooling technology for manufacturing of super precision parts for a new generation of transmissions.

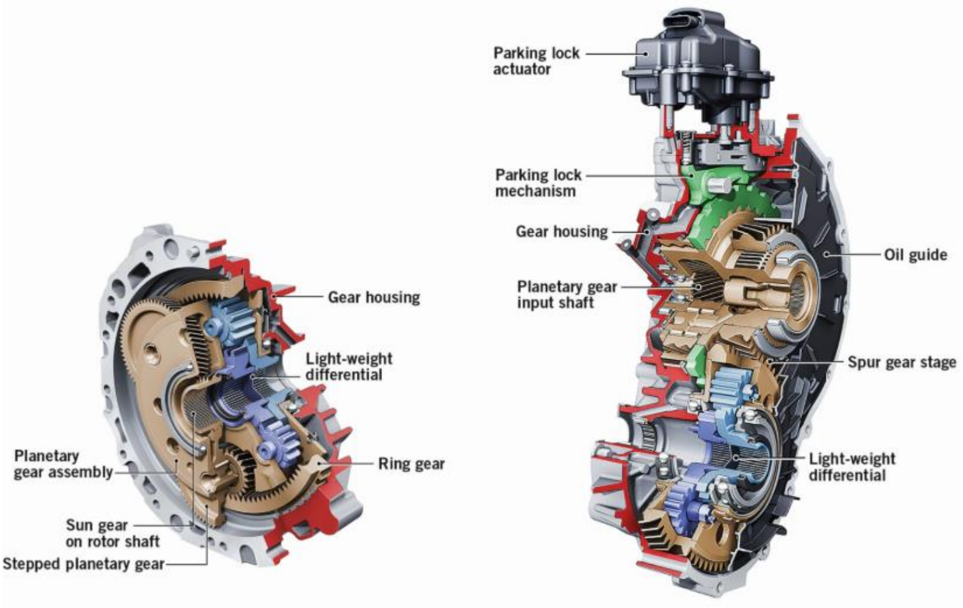

Figure 10. Coaxial and Parallel Transmission.

For speeding up the development time, the STRECON VARI-FIT system was introduced for adjusting the dimensions in the gear die. With the adjustable function the customer was able to fine adjust the gear die already during the first test runs of the forging tool. After finalizing the design work of the forging die, the die adjustment function was removed from the forging tool and replaced with a more cost-effective high-stiffness container system STRECON E+. This container system has been adopted for series production at customer’s production site.

For the gears produced in the high-stiffness STRECON container system the customer succeeded in series production to form gears in the international tolerance grade IT3.

Statement from the customer:

“In addition to the acoustic optimization, the restricted design envelope of the coaxial drive architecture placed particularly high requirements on the developers. The solution to this problem is the highly integrated stepped planetary gear set combined with an innovative spur gear differential. Despite the axial design envelope requirement of 150 millimeters, the transmission concept enables an input torque of 400 Nm with a weight of only 16 kilograms. The planetary gear design concept was also applied to the parallel axis drive variant on the front axle. This approach not only reduced the development time and costs, it also optimized the quality of the product.

6 Conclusion / outlook

Optimal prestressing of the forging die is a very important design parameter and deserves equal recognition as other design parameters like the material grade and hardness of the forging die, type of lubrication, coating and lubrication, process simulation of the forging steps, the forming process itself, the press machine system, etc. The task involves not only the proper choice of interference fit but also the balanced layout of the tool system as such. Furthermore, the ambition to obtain optimal prestressing of the forging die does also involve the selection of the right prestressing technology as an integrated element of the overall tooling system.

In our experience, most forging dies are simply prestressed by conventional compression rings, but many tool systems could be improved significantly by adopting a broader and more strategic perspective for optimizing the overall performance and service life. We often see overall cost reductions in the range of 25-40%.

The paper compared the conventional prestressing tools with the stripwound container system, which is a much stronger system than the prestressing tools traditionally used in the forging industry. A special attention was given to the high-stiffness prestressing technology, which effectively addresses both the stress range and the strain range of high-loaded forging dies. Examples of this merit of this tool technology including the STRECON VARI-FIT container system was illustrated at the end of this paper including industrial examples from the German precision forging industry.

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