Tool Optimization by Means of Effective Prestressing System

Dr. Jens Groenbaek, Mr. Erik Lund
STRECON A/S, Ellegaardvej 36, 6400 Sønderborg, Denmark

Summary

Prestressing of forging dies is well-established to improve the service life of forging dies. While the level of prestressing with conventional containers is limited, prestressing by stripwound containers allows to increase the level as well as to improve the stiffness of the tooling system. With regard to low-cycle fatigue, the right choice of the prestressing level and properties of the container allows modification of the macro-mechanical stress-strain response towards reduced maximum stresses and lower cyclic strains, thus leading to a reduced risk of crack initiation. With regard to accuracy, the increased stiffness of stripwound containers with a carbide winding core reduces considerably the deflections of the die. The strip-wound container concept has been developed into a number of pre-stressing concepts intended for optimisation of tooling systems with various reasons for service life problems. The concepts can be dedicated to radial pre-stressing, combined radial and axial pre-stressing, as well as adjustable pre-stressing. The importance of selecting the right pre-stressing concept and prestress level in relation to the specific application case, is described.

1 Introduction

The globalisation of the automotive industry has changed the basic business conditions for all active enterprises within this industry. The manufacturers of cold and warm forging components are no exception, and especially since year 2000 we have seen a considerable move or outsourcing of production to countries in the Eastern Europe, India, China, Taiwan, Brazil, etc. One key reason is the need to follow ones customer to the new and emerging markets for their automotive offerings, but another key factor is simply to exploit cost cutting opportunities. Initially, the move out was of large series production of rather simple components, but these times seems to end. From our own business we experience a growing number of inquiries that contain tooling solutions for complex components, often combined with a need for pursuing modern manufacturing methods.

More specifically, these ongoing tendencies in cold forging, such as net shape forging of more and more complex parts [1,2], ecological manufacturing and 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 tools. Among the various measures to increase tool life [3], the prestressing of the dies is one key parameter. This paper addresses the importance of optimised die support with a view to the value of the strip-wound prestressing system in comparison to the conventional compression rings.

2 Load and loadability of precision forging dies

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 **Fig. 1** and highlights the complex nature of high performing forging tools [4,5]. The load on forging dies is determined by a number of interacting load parameters such as the type of forging process, lubrication, temperature, billet material properties; preform design, part geometry, forging steps. Advanced process design is often required to keep the loads at moderate levels, and can be pursued through means of process simulation and special process designs, e.g. the divided flow method in closed die forging [6]. Despite the value of such analytical tools, they cannot always provide sufficient solutions to high loaded tool designs. In short, - the more complex the part geometry, - the larger the degree of net shape forging, - the fewer the forging operations, - the tougher the billet material, and - the colder the forging operation, the higher will the resulting tool loads be. The higher the tool loads, the higher the need will be for tool systems that can withstand and/or reduce the damaging influence of these load conditions.

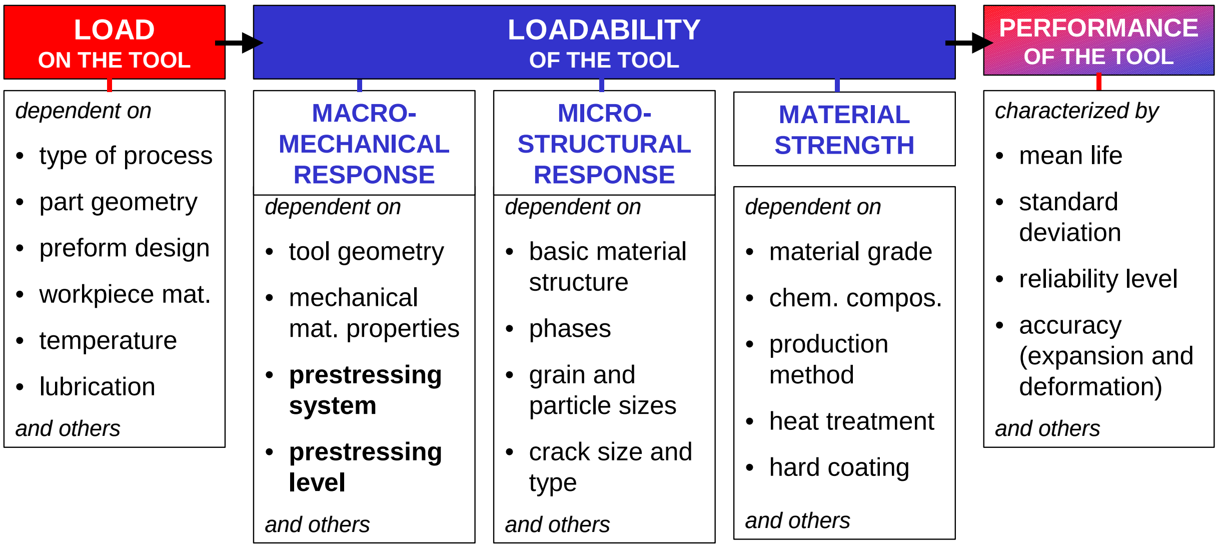

Fig. 1 *The STRECON® load and loadability concept with regard to tool life in forging*

The loadability of the tool, i.e. the ability of the tool to withstand the load given by the forming process, is more specifically defined on three levels:

a) The *macro-mechanical response* is mainly characterized by the geometry of the tool and the mechanical properties of the tool material, i.e. the stresses and strains on a continuum mechanical macro level. The kind of prestressing system and the selection of the prestressing level allow a change of the mechanical response towards less critical stress and strain ranges.

b) The micro-mechanical response of the tool is based on micro-structural properties of the tool material, depending on phases, grain and particle sizes, etc.

c) The strength of the tool material depends on its grade, its chemical composition, the production method and the heat treatment conditions. The application of modern powder-metallurgical steel grades and carbide grades reduces the risk of stress concentrations by inclusions or carbides, and thus diminishes the risk of fatigue cracks.

Wear and fatigue cracks are the main failure mechanisms that limit tool life. In case of complex high-precision dies for net shape parts, low-cycle fatigue is the dominating failure mechanism. Low-cycle fatigue can be divided into four phases, [7] **Fig. 2**:

1. cyclic loading of the undamaged structure,
2. initiation of micro cracks ($a < 0.1$ mm),
3. merging of micro cracks to surface defects and larger cracks ($0.1 < a < 0.5$ mm),
4. stable crack growth phase ($a \geq 0.5$ mm).

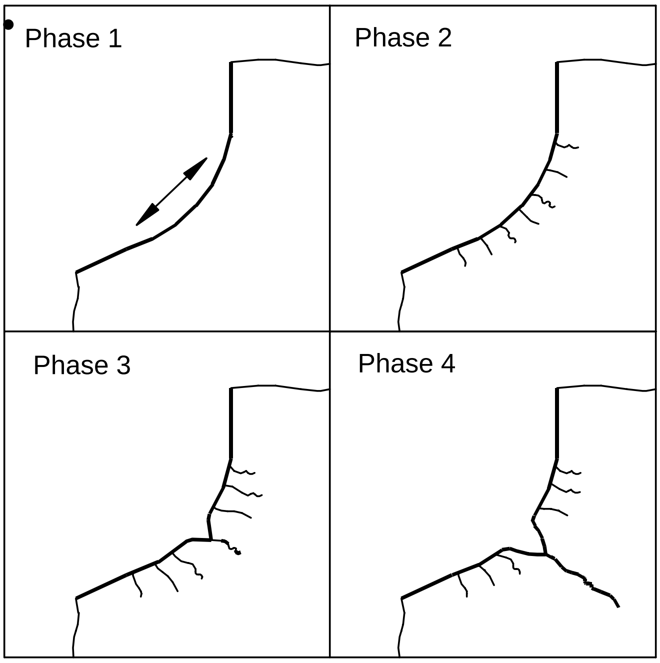

Fig. 2 *Phases of low-cycle fatigue*

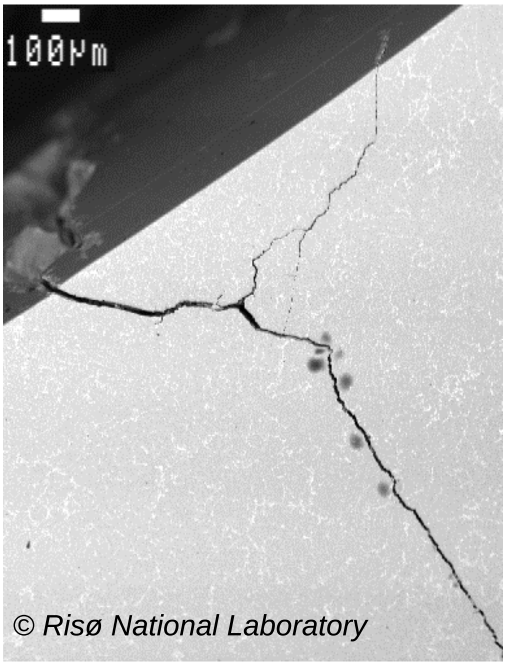

Fig. 3 *Merging of micro cracks*

Most complex cold forging dies will be taken out of service and registered as failed during phase 3 where micro cracks merge to larger surface defects of the die (i.e. seen as chipping), and causing burrs on the forging parts. **Fig. 3** shows an example of the merging of micro cracks in a cold forging die made of high-speed steel.

Less complex forging dies, or dies used for warm and hot forging applications are usually not failing due to low cycle fatigue but to wear. The wear failure can either be explained by a high number of forging cycles that simply wear out the die on critical die dimensions, or wear due to heat cracks of the top surface of the die geometry. In the later case the mean service life of the die insert is often reported rather low (a few thousands parts) and would benefit substantially in case of a more heat resistant tool system.

Consequently, a general strategy for optimizing the performance of the forging dies would be required for effectively addressing the different root causes of the die failure. The solution for complex and highly-loaded forging dies will be different from the ones focusing on the life of the forging dies used for warm and hot forging applications. As can be seen in the next paragraph, understanding the cyclic behaviour of the forging die should in any case be regarded as a key parameter for optimizing the performance and service life of the die insert. The essential contribution of the prestressing system will be elaborated.

3 Principal effects of the prestressing system on the stress-strain response of the die

As shown in the concept model, fig. 1, the stress-strain response of the tool provides the basis to analyse and optimise its loadability on a macro-mechanical scale. **Fig. 4** shows the principal cyclic stress-strain curve of tool material in the loaded area of a forging die. The characteristic parameters of the stress-strain curve, their effects on the fatigue behaviour and ways to influence them by the prestressing system are discussed in the following.

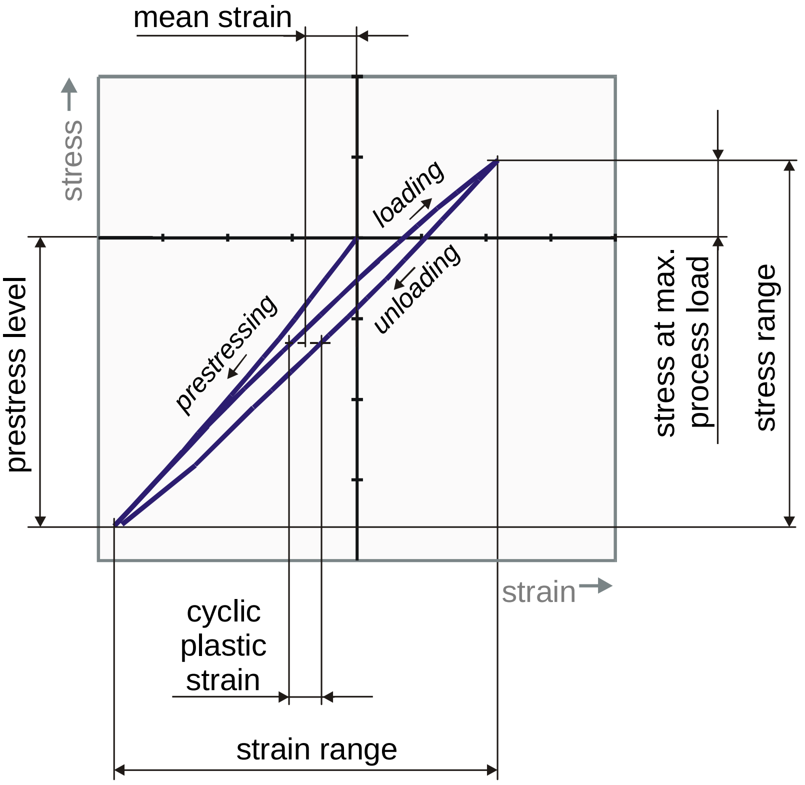

Fig. 4 *Principal stress-strain response in the critical point of a prestressed forging tool*

The design of prestressing systems according to existing guidelines [8,9] mainly aims at obtaining a high compressive prestress in the critical area of the die insert, leading to reduced critical stresses under full process pressure. The level of interference fit between the die and the (inner) stress ring determines the compressive prestress and the stress of the die under maximum load, while the corresponding stress range keeps the same value. Considering the strain response, experimental results of low-cycle fatigue tests [10] show a significant dependency of the level of *mean strain* on the number of cycles to failure. For most of the tool materials tested, a 0.2-0.3% shift in mean strain results in a change of the number of cycles to failure by an order of magnitude. Therefore, moving the mean strain towards the compressive range by applying a higher interference will significantly reduce the risk of crack initiation as well.

The level of prestressing is limited by the strength limit of the material properties used for normal stress rings. The yielding point is approx 1000 MPa depending on the material grade, the level of hardness, and type of prestressing system. A double ring system offers about 15-25% in increased tool loadability compared with the single ring system. In practice, the expected level of interference fit with a single ring will be 0,4 – 0,5%, and 0,6 – 0,7% with a double ring solution. In many cases this level of interference will not be optimal for the life and performance of the die insert. This means that the conventional stress ring systems cannot fully address the critical and damaging tensile stresses in dies with complex geometry or exposed to high forging loads.

A considerably higher interference can be obtained when fitting the die insert into a STRECON$^{®}$ strip-wound container (hereafter referred to as STRECON container) [11]. This tool system is manufactured by means of a special 0,1 mm thick steel strip material that is wound around a material core (i.e. sleeve) of a high-allowed steel grade (e.g. HSS) or of tungsten carbide. **Fig. 5.** shows the principle layout of the STRECON container. The winding process is fully controlled by special machinery that ensures the winding tension of each single layer of the steel strip material.

Fig. 5 *Prestress factors and other tool design factors influencing the tool performance; illustrated with a die mounted into a STRECON® E+ container.*

The yield strength of the strip material used for the STRECON itself is approx. 2100 MPa; and this unique material attribute combined with a constant stress distribution of the entire strip section is the true explanatory feature of the strength of the STRECON container. During the winding process, the inner sleeve, also called the winding core, is prestressed to such a high level that the inner diameter of the same core is reduced by 1%. This resulting compressive stress of the container is about -2000 MPa, basically allowing the tool designer to assign any level of interference fit that would be required for an optimal die support. The exact of interference is highly dependent on the die geometry and process load but would in most cases vary between 0,6–0,8% for carbide dies, and 0,8–1,0% for steel dies. Because of the strength of the STRECON container (i.e. tool loadability plus (+) 50-100% compared to normal stress rings), the prestressing system will remain fully elastic throughout its service life. No other tool system can offer these design parameters and should be seen as highly effective means in repositioning the die, and the tool system as such, toward the compressive stress state in the stress-strain regime as shown in fig. 4.

The cyclic plastic strains as well as the stress and strain range in the die can effectively be addressed by increasing the stiffness of the prestressing system. In the case of the STRECON container technology, this is done by having the winding core made of tungsten carbide. The Young's Modulus of the tungsten carbide is about 500 GPa, and the resulting overall stiffness of the STRECON container will be approx 400 GPa or twice the level of a normal stress ring. The stiffness of the tool system addresses specifically the strain parameter in the stress-strain regime **Fig.6**. Typically, a STRECON container with a winding core of tungsten carbide (also called STRECON E^+ container) would be able to reduce the deflection of a steel die by 25-30%, and with approx 10% in case of carbide die. The stiffness of the carbide die itself explains the reason for the less impact on the strain behaviour.

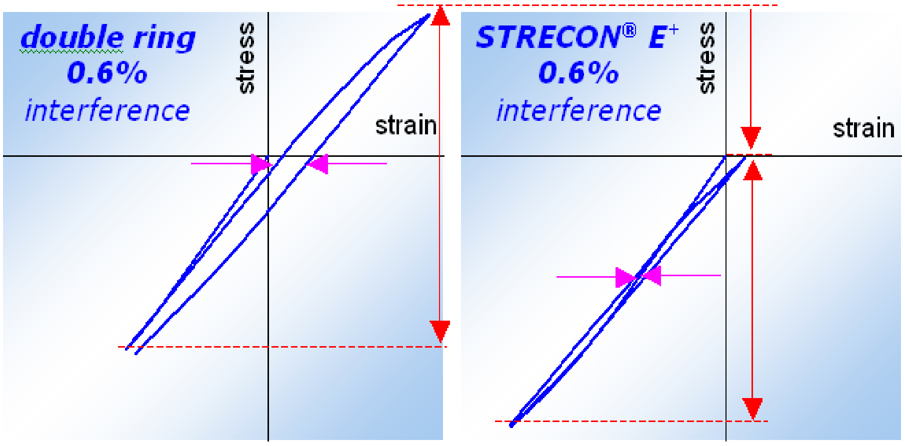

Fig. 6 *Effect of higher stiffness on stress and strain range.*

4 Prestressing concepts

Today the most common prestressing system applied worldwide is the single ring system. In many cases this simple prestressing tool would be sufficient to give the required die support, but in large number of cases it would not. The overall tool performance including the extension of the service life of the exposed tool parts would benefit significantly from an optimized tool design including the selection of prestressing system and the level of interference fit. **Fig. 7** provides an overview table of different prestressing systems based on the STRECON stripwound container technology.

Prestressing of the die insert	Winding core of steel	Winding core of tungsten carbide
Radial prestressing	The die is prestressed in radial direction by means of compressive stress distribution on the outside diameter of the die (i.e. reduced tangential stresses in the die). The system is designed for longitudinal die cracks. Tool systems available: Single ring, double ring, STRECON® Basic container	In addition to radial prestressing, the tool system has a higher stiffness due to the carbide inner ring / winding core. The stiffness reduces the stress-strain behaviour of the die, resulting also in less die deflection during process load. The system is designed for longitudinal die cracks, dies with complex geometry and sharp corners. Tool systems available: STRECON® E$^+$ container
Radial and axial prestressing	In addition to the radial prestressing, the die is prestressed in axial direction. In short, a two-directional die support ensured during tool assembly. The system is designed for transverse and horizontal die cracking. Tool systems available: Single ring and double ring system with axial prestressing feature, STRECON® Axi-fit container	In addition to radial and axial prestressing, the tool system has a higher stiffness that reduces the stress-strain behaviour of the die, resulting also in less die deflection during process load. The system is designed complex die and tool designs suffering from transverse and horizontal die cracking. Tool systems available: STRECON® E$^+$ Axi-fit container

Fig. 7 *Overview table of prestressing concepts.*

Fig. 8 shows the three mostly applied STRECON prestressing systems that can be applied for cold, warm and hot forging applications. The tool design is adjusted to specific requirements, hereunder exploiting any possibility to build company standard containers allow for a fully flexible tool system.

STRECON® Basic Container　*STRECON® E^+ Container*　*STRECON® Axi-fit Container*

Fig. 8 *Visual display of the commonly applied prestressing systems illustrated with STRECON containers.*

Additional STRECON prestressing tool concepts are available for special tool applications. The STRECON® OPTI-FIT concept [12] provides axial prestressing by local modification of the nominal, uniform interference: When varying the radial interference in an appropriate way, it is possible to achieve a concave, longitudinal bending of the internal die surface which results in an axial compressive prestress in the area where the stresses are the highest. Furthermore, STRECON has developed a prestressing system called STRECON® Vari-fit [13] that allows for fine adjustment (i.e. a few microns) of the inner diameter of the die insert. Lately, STRECON has taken a patent to a tool system called STRECON® Dynafit [14], in which the radial interference fit is partly released after the forging process. This advanced tool system is developed for pressing of parts with small undercuts, barrel shape, etc., and for providing a friction free ejection of the part after the forming process. These special processes cannot be pursued with normal tool designs.

5 How to select the optimum prestressing conditions for a precision forging die

Nowadays, the analysis and optimisation of precision forging dies is significantly supported by finite element programs with advanced features. Thus, the influence of the prestressing, the stiffness of the prestressing system and the die geometry on resulting parameters such as stresses, strains, micro plasticity and deformation in critical regions of the die can be analysed.

As described earlier in this paper, the die performance as well as part accuracy can be significantly improved by choosing the right prestressing system and prestress parameters. Concerning the interference, the objective is to find the prestress level that is high enough to minimize the tensile stresses in the die, without overloading the prestressing system and without exceeding the material limits of the die, illustrated in **Fig. 9**.

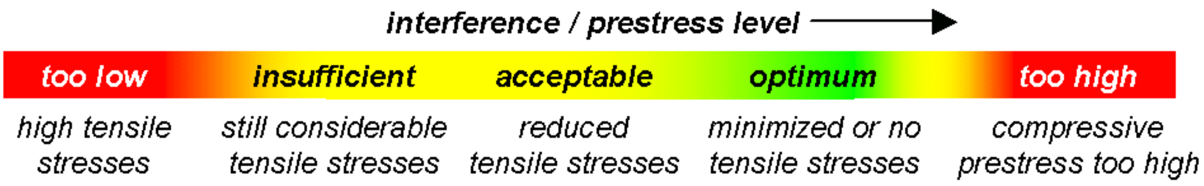

Fig. 9. Schematic illustration of the areas for the choice of the prestressing level

Due to the limited loadability of conventional prestressing systems, many precision forging dies in practice run on an insufficient prestress level. For system with one or more stress rings, the allowable interference is limited to a rather low level because the stress rings plastify and get damaged locally at higher prestress levels. As mentioned earlier, this level is about 0,4% interference for single stress rings, and about 15-25% higher for double stress rings. This limit is not practical limit for the STRECON container because of the strength properties. Actually, a key issue of not to assign too much prestressing to the die as this will equally damaging to the die insert.

In many cases with high die loads and complex die geometries, the stress and strain amplitude is just too large to be within the elastic limit, and a certain amount of yielding cannot be avoided. Since the tool materials are more sensitive to tensile than to compressive yielding, it is usually recommendable to accept a rather high prestress level. However, if the die is manufactured in the prestressed condition and taken out afterwards for surface coating, too excessive prestressing may directly lead to damage and residual tensile stresses in the die after disassembly – in this case, special attention must be paid to the maximum interference.

In practice it shall be recommended to pursue the “perfect” tool design in small and controlled steps. Modern analytical analysis and simulation programs are a great help in designing the tools for precision forging, but production testing would still be required in order to confirm the computer work performed by engineers and tool designers. Furthermore, great attention shall be paid to the actual manufacture of the tools. Quite often we see that non optimal tool manufacture can explain premature failure of the tools designed and used for precision forging applications.

6 Conclusion / outlook

The tool performance and tool life plays an important role to ensure that net-shape forging can be realized in a technologically as well as economically successful way. The choice of the proper prestressing system and optimisation of prestress design makes it possible to improve the tool performance with regard to die life and precision, thus ensuring high productivity.

Advanced prestressing systems, e.g. with stripwound containers with a winding core made of high grade tool steels or cemented carbide and containers with adjustable diameter of the die insert, contribute significantly to expand the process limits as well as the tool performance.

On the way towards optimized tool performance, also the other parameters influencing tool life have to be taken into account. Therefore, STRECON® A/S is involved in the research and development activities to optimise the whole tooling system, including the interactions of stripwound containers with advanced die design, high performance tool materials and coatings, advanced modelling of materials, and at latest to optimise the performance of the active functional surfaces on metal forming tools through of nano-scale surface finishing by Robot Assisted Polishing . [12], through the RAP –200 machine developed by STRECON A/S.

References

[1] Osakada, K.: Cold Forging in Japan, Presentation at the 40th International Cold Forging Group, Plenary Meeting, Padova, Italy, September 2007

[2] Tekkaya, E. et. Al. : History and Future of Cold Forging in Europe, Presentation at the 40th International Cold Forging Group, Plenary Meeting, Padova, Italy, September 2007

[3] Lange, K.; Cser, L.; Geiger, M.; Kals, J.A.G.: Tool Life and Tool Quality in Bulk Metal Forming. CIRP Annals 41 (1992) 2, 667-675

[4] Groenbaek, J,; Hinsel, C.: Improved Fatigue Life and Accuracy of Precision Forging Dies by Advanced Stripwound Prestressing System, SME Clinic on Precision Forging Technology, Columbius, Ohio, USA, Nov. 10, 2000

[5] Groenbaek, J,; Hinsel, C.: Optimization of Tool Life & Performance Through Advanced Material and Prestress Design, NACFG Conference, Columbus, Ohio,USA, September, 2003

[6] Kondo, K.: Improvement of Product Accuracy in Cold Die Forging. In.: Geiger, M. (ed.): Advanced Technology of Plasticity 1999, Vol. I. Berlin, Heidelberg: Springer 1999, pp. 41-48

[7] Groenbaek, J,; Hinsel, C.: Advanced Material and Prestress Design of Cold Forging Dies, Prof. Kudo Memorial session at 7th ICTP conference, Yokohama, September 2002

[8] VDI-Richtlinie 3176: Vorgespannte Preßwerkzeuge für das Kaltmassivumformen. Düsseldorf: VDI 1986

[9] ICFG Doc. 5/82: Calculation methods for cold forging tools. In: International Cold Forging Group ICFG 1967-1982 Objectives, History, Published Documents. Bamberg: Meisenbach, 1992

[10] Brøndsted, P.; Skov-Hansen, P.: Fatigue properties of high-strength materials used in cold-forging tools. Int. J. Fatigue 20, 1998

[11] Groenbaek, J,; Hinsel, C.: Optimization of Tool Life & Performance Through Advanced Material and Prestress design. JSTP International Seminar on Precision Forging, Nagoya, Japan, March 2004

[12] Grønbæk, J.; Nielsen, E.B.: Stripwound Containers for Combined Radial and Axial Prestressing. J. Mat. Proc. Techol. 71, 1997.

[13] Groenbaek, J.: Recent Developments in the Area of Adjustable Dies for Bulk Metalforming, 11th International Cold Forging Conference, Chester, UK, September 2005.

[14] Groenbaek, J.: New Developments in the Area of Adjustable Dies for Bulk Metal Forming. Seminar New Developments in Bulk Metal Forming, Stuttgart-Fellbach, Germany, May 2005

[15] Groenbaek, J.: RAP- Robot Assisted Polishing of Metalforming Tools, VDI – Annual Seminar on Cold Forming, Duesseldorf, Germany, January 2008, (in German)