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Tool Life and Tool Quality in Bulk Metal Forming

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Summary: Due to their intermediate position between machine and workpiece, tools represent the interface of the manufacturing system to the process. Near net shape production, new materials and techniques are the new challenges in metal forming and specially in tooling. A significant economical effect can be achieved through an increase in the service time of tool elements, as well as through proper tool management strategies. The greatest problem connected with the preliminary estimation of tool life is the enormous dispersion of tool lives for the same construction of tool. The uncertainty in estimating the expected service time of tools and thus the tooling cost is caused by an enormous variety and confluence of damaging factors, factory-specific character of tool life, stochastic phenomenon of tool failures. From the confluence of aspects influencing the tool life it is clear, that there is no general recipe for increasing tool life and tool quality. Each of the influencing aspects contains some possibilities for increasing the service-time of tools. Paper shows some examples in tool design and tool manufacturing and points out, that a knowledge based approach can be the bridge between CA-techniques and human experience in prediction of tool life.

KEYWORDS: forming, tool life, wear, fracture, design, materials, coatings, simulation, knowledge based systems, monitoring.

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1. Introduction

Near net shape production, new materials and techniques are the new challenges in metal forming. Efficient models for the simulation of metal flow enable the production of very complex shapes, but the biggest uncertainties in preliminary cost estimation and the production are still connected with the tools. According to Fig.1 the tools represent a decisive part of the process influencing factors. They are the link between the process core, determined by geometry and kinematic, and the material and tribology on one hand and machine tool and automation on the other. Their task is to allow full utilization of the capabilities of the process [1]. If this role applies to all tools, independently of the particular process, in bulk forming metal forming operations and, particularly, in the restricted-flow forming operations, the tooling system "stores" (together with the desired geometry of the forged component) most of the information related to the shape and property transformation resulting from the deformation of the material [2].

The quality of the tools has a direct influence upon the quality of the finished product [3,4]. Fig. 2 gives an example for the dimensional accuracy of the product, which is severely affected by both the tool and the process. Moreover, the tooling costs can consume 5% to 30% of the manufacturing costs [5]. Due to the relatively high initial costs for tooling and setup metal forming technology economically is limited to large scale production. In small scale production the part for machine change over time becomes comparable to the actual run time, thereby raising the production costs per piece considerably. In Fig. 3 the costs for initial tooling, machine setup and maintenance for a typical cold forged stepped shaft are compared for different batch sizes [7]. For large quantity manufacturing, the costs for tool replacement and maintenance become the dominant part. Each time a tooling element has to be replaced, three types of costs have to be considered:

- costs for downtime of the machine,
- costs for fabricating, reworking or refurbishing the replaced tool elements, and
- costs of tool pre- and post-operative handling and assembly.

![Fig. 1: Interaction of metal forming processes with various components (Lange)](image1)

![Fig. 2: Effect of the tool on product accuracy (Lange/Dolmann)](image2)

![Fig. 3: Initial tooling cost, machine set-up cost and maintenance cost for a typical cold forged part (Bariani)](image3)

![Fig. 4: Breakdown of tool maintenance costs for a forged shaft processed on a 5-station transfer machine (Bariani)](image4)
- the service time of tool elements, and
- the concept of tool maintenance.

A significant economical effect can be achieved through an increase in the service time of tool elements, as well as through proper tool management strategies. Fig. 5 illustrates the differences in manufacturing costs, related to 100%, 150% and 50% of the expected tool life of a punch ([9]-[10]). At the same time the diagram points out the greatest problem connected with the preliminary estimation of tool life: the enormous scatter of tool lifes for the same tool design and tool layout.

**2. Main factors limiting tool life**

In bulk metal forming operations the life of tools is mainly constrained by three causes (Fig. 7):

- fracture,
- plastic deformation and
- wear.

Depending on the kind of forming process, the frequencies of tool damages and the resulting costs are different ([6]-[7]). Because of the high loads, fracture is the main reason for tool failure in cold forming. Thermal load and the contact with the hot metal during the deformation process makes wear the most frequent reason for failure in warm and hot forging.

**2.1 Wear of tool parts**

The main kind of surface damage is wear. It is the principal reason for scraping tools used in warm and hot bulk forming processes because it has a large influence on the tolerances and surface quality of the formed part and thereby on tool life. It is generally accepted that this phenomenon is very complicated and that a number of mechanisms and factors are involved ([13],[14]). The actual mechanism causing friction in the contact interface between tool and workpiece is understandable only on the basis of the classical physics. The physical approach ([15],[25]) gives an efficient basis for industrial research. This has shown, that:

![Fig. 8: Preform geometry and the measured wear distribution after 2000, 3800 and 5200 forgings (Boey).](image)

Although the nature of wear still hides a lot of unclear aspects, industrial research has established how the dimensions and surface quality are changing during the forming operation due to wear ([26]-[33]). In hot forging the mechanism of adhesive wear can dominate because of the local bonding between the die and the workpiece on the carrying asperities ([30]). In other cases surface fatigue and tribooxidation can be of importance. Fig. 8 illustrates the development of wear at the surface of a hot forging die, showing the preform geometry and the measured wear distribution after 2000, 3800 and 5200 forgings.

**2.2 Fracture**

Tool fracture is the main danger in cold forming production, because of the high costs arising not only from tool replacement but also from the damage which may be caused by the broken tool in an automatic press environment. Overload fracture can be avoided using modern techniques of stress and strain estimation, like FEM, but fatigue fracture always occurs in highly loaded tools.

Fracture takes place when the sum of mechanical and thermal load exceeds a critical value. This value is not a purely material property: it depends on the state of multiaxial stress ([34],[15]).

![Fig. 9: Systems, measuring initiation and propagation of cracks in a cold extrusion tool (Reiss).](image)

Much effort has been made to measure the crack propagation inside a cold extrusion tool (Fig. 9 [36]). Applying the eddy current testing method crack initiation can be indicated whereas the ultrasonic testing method monitors.
3. Various aspects influencing tool life

The uncertainty in estimating the expected service time of tools and thus the tooling costs per piece is caused by:

- the enormous variety and interaction of damaging factors,
- the factory-specific character of tool life and,
- the stochastic phenomenon of tool failures.

The classical division of factors influencing tool life distinguishes between tool-specific and application-specific failure reasons. They cover a much more complicated network of factors however, practically describing the entire forming system and all the requirements for the quality of the product, putting the tool now in the centre of consideration (Fig. 11).

Thus the question arises:

**What was the essential reason for the change in tool-life?**

An increase in forming energy e.g. results in a higher tool temperature. The additional elevation of temperature due to friction between workpiece and tool may raise the local surface temperature critically above the tempering temperature of some cold working steels (45-47). In hot forging all these phenomena are combined with the predominating adhesion in wear (30) and with thermal cracks (47).

The types of failure for identically designed tools in identical exploitation environments also vary. Highly loaded cold extrusion tools always break while the main failure reason in mass production of simpler workpieces is wear. Typical failure rates for tools in cold extrusion are e.g. 80% failure by fracture but only 20% replacement due to wear.
4. Increasing the efficiency of tooling

As there normally is the goal of increasing the efficiency of tooling, at the time being this problem is often reduced to coating or tool material problems only. From the aspects shown in the former chapter it is clear that there is no general recipe for increasing tool life and tool quality. Each of the influencing aspects contains some possibilities for increasing the service-time of tools. Because of the factory-specific character of tool life, different solutions can result in similar effects in different factories, so that we can formulate the statement:

There is no general way to increase tool life, there are only some steps towards this goal.

This chapter shows some examples of modern solutions based on the analysis of different aspects influencing tool life.

4.1. Tool design

Numerical solutions e.g. by FEM, on the one hand providing the loads in forming operations and thus the stresses in tool elements on the other hand, enable the design of optimized tool geometry with more homogenous stress distribution avoiding stress concentrations. The optimization of die design can be carried out

- for active tool elements, such as punch, die or ejector, as well as
- for the stress rings or die plates.

4.1.1 Design of active elements

Fig. 14 shows as a result of FEM simulation the profile of strain energy density along the surface of the transition radius of an extrusion die for different contour shapes. The fatigue life profile moreover directly yields the associated fatigue life for this area, which indicates the expected number of cycles. It is evident that already an enlargement of the transition radius reduces the surface loads, but it can be seen from the diagram as well, that the applied computer aided die shape optimization ([50]) has significantly more success in delaying crack initiation from only ~20 to over 600 loading cycles.

Fig. 14: Profile of fatigue crack initiation life - influence of the die shape (Hansel).

4.1.2 Combining prestress and high-hardness die insert

A tooling technology which over the last few years had its industrial breakthrough is the STRECON® stripwinding technology for prestressing highly loaded dies. By using stripwound prestressed containers the design and layout of cold forging tools can be improved, resulting in remarkable increases in die-life ([51]).

Fig. 15 shows an example of die-life optimization with stripwound prestressed containers. The illustration displays the cross section of the actual die insert for a 350 g cold forged part (Fig. 15A,B). With conventional stress rings these dies gradually failed due to low-cycle fatigue cracks in the corners of the die-inserts. The average die life with conventional stress rings was approx. 5000 pieces.

An FEM analysis of the stress cycle in the critical die-insert corner showed extremely high local stresses (Fig 15/C). The state of stress varied cyclically from compressive plastification, due to prestress, to tensile plastification under internal pressure loading. In the conventional stress-ring system, the amount of local tensile plastification was rather high. This explains the very low die life as crack initiation mainly depends on the amount of tensile plastification ([50]).

A. Corner in die-insert
B. Crack in die-insert corner
D. STRECON® Prestressed Container
C. STRESS 62HRc
E. Plastic load cycles in die-insert corner
F. Die life improvement

Fig. 15: STRECON® prestressed container and the resulting die life improvement (Danfoss/Prestu).

Compared with conventional stress rings, the STRECON® stripwound prestressed containers (Fig. 15/D) allow much higher prestress of the die insert. In actual fact the interference changed from 0.7% to 1.0% and this resulted in a doubling of die life (approx. 10000 pieces per die insert).

Further elastic-plastic FEM analysis showed that the problems with cyclic plastification in tension and compression during each loading cycle were closely connected to the extent of the linear part of the stress-strain curve. To obtain satisfactory toughness, a relatively soft material with hardness of 56 HRc was originally used as die-insert material. The negative effect of this is a relatively low elastic limit: $\sigma_{el} = 1300 \text{ N/mm}^2$.

An extended elastic-strain curve is obtainable through the application of materials with higher hardness, especially HSS types. This means that the plastic strain in every loading cycle is considerably reduced (Fig. 15/E). A negative effect, however, is that the toughness is reduced.
The higher pretress of a STRECON stripwound prestressed container makes it possible to utilize the estimated elastic portion of the stress-strain curve fully and control the reduced toughness. Combining this prestressing with a powder-metallurgical high-speed steel die insert ($\sigma_{UTS} = 2400$ N/mm$^2$, HRC 60) fitted with high interference ($\geq 1.0 \%$) reduces the cyclic plasticity which mainly determines low-cycle fatigue fracture, and results in a remarkable die-life improvement of app. 24000 pieces on average (Fig. 15/F). The reduced toughness becomes a less important problem. One should bear in mind however that this result is part- (and thus size-, geometry- and material-) dependent.

4.2 Tool manufacturing

Taking into account the tool-dependent (internal) factors, the question of tool life becomes more difficult, because the entire history of tool manufacturing and assembly plays a significant role. Aspects concerning the responsibility of manufacturing forming tools in metal cutting are well known, but the role of spark erosion machining on tool life is still a severe problem, to be solved possibly on the level of collaboration of several STCs in CIRP.

At a meeting of the Case Studies Subgroup of the Japanese Forging Research Committee, the majority of tool failure cases in cold forging production was attributed to improper EDM-application, which forms a brittle cracked white layer on the surface ([52],[53]). Fig. 16 in this connection displays:

- the hardness distribution of the refrozen layer carbon-enriched from a graphite electrode,
- the thickness of the refrozen layer and
- the improper microstructure with the microcracks.

Concerning wire cut EDM (WEDM), the remolten-refrozen layer exhibits softening due to copper enrichment from the wire contrary to the case of conventional EDM.

In order to avoid these troubles the following general methods are recommended ([53]):
- decreasing EDM rate by reducing input power,
- softening of the refrozen layer by reducing the carbon content,
- tempering in order to lower the hardness at rather high temperatures,
- selecting tool materials that have a high temperature toughness and a low thermal expansion coefficient.

For subsequent PVD- or CVD-coating, however, the refrozen layer has to be removed completely by mechanical polishing, in order to guarantee a maximum of adhesion between the hard coating and the ground material.

4.3 Tool material

From the analysis of the main damaging processes, it is obvious that the requirements of the tool materials are contradictory. The higher the hardness of the material, the better in most cases is its wear resistance. The schematic illustration of fracture toughness and hardness for different materials (Fig. 17) shows, that the right upper area of the diagram that combines advantages for an ideal tool material is empty. The endeavor of research is to "cover" this area using:

- metallurgical methods, on the level of manufacturing and heat treatment of tool materials,
- special methods of mechanical processing, or
- local change of material properties, like coatings.

An example of a successful high-speed steel of matrix-type (0.65% C, 4.0% Cr, 3.0% Mo, 2.0% V) was introduced by Hitachi Metals Ltd. in 1976 (branded as YXR3). This steel has high strength against the impingement at the hardness of HRC 60. Its bending fracture strength may reach $5800$ N/mm$^2$ which is about the highest of all existing tool steels. The wear resistance of this steel is somewhat lower, nevertheless the steel offers an extremely high toughness and fatigue strength, and simultaneously a heat resistivity as high as that of other conventional high speed steels. Consequently, it can be applied to warm forging dies as well as to cold forming punches ([54]). A nitrided layer promotes its use in warm forging.

The quality of the tool steels depends on a variety of factors. It is well known for a period that an isotropic microstructure, e.g. for hot forging dies will contribute to increased tool life. This experience was recently confirmed for die steels which were multiaxially forged in Japan to ensure the desired isotropy ([57]).

Fig. 16: Thickness and microstructure of refrozen layer depending on EDM-rate (Kudo).

For subsequent PVD- or CVD-coating, however, the refrozen layer has to be removed completely by mechanical polishing, in order to guarantee a maximum of adhesion between the hard coating and the ground material.

4.4 Surface treatment

Another way of seeking for a compromise is the local change of tool material properties. The wear protective coating can be subdivided into two main groups (Fig. 18):

- reactive coatings, where the alloying element enters into the matrix by diffusion or beam techniques such as ion beam treatment,
- deposited coatings whereby the coating is clearly separated from the material below.

Fig. 17: Fracture toughness and hardness of tool materials (Artlanger).

Fig. 18: Subdivision of wear protective coatings (ICFG).

Fig. 19: Wear and surface roughness of tools with different coatings in backward extrusion (Wasthede).
The methods above as well as their advantages are well known in the practice of metal forming (Fig. 19). The disadvantages of some coating methods are mostly connected with the problem of insufficient adherence of the layer on the substrate e.g. the ground material due to the coating process or with bad mechanical surface treatment.

Furthermore some of the traditional coating methods are not environment-friendly, like e.g. hard chromium-plating.

Two examples, one for cold and one for warm bulk metal forming are described in the following. Both are very efficient in increasing tool life:

- hard coating by plasma assisted PVD technology and
- laser alloying.

4.4.1 Hard coating by plasma-assisted PVD technology

When coating tools using a PVD process the coating material is transformed into the gaseous state either by vaporizing a melt or directly from the solid state via an atomic process ([58]). Though the term ion plating had been introduced in the early 60s ([59]), the application of different PVD coating technologies in tool industry however started as late as the beginning of the 80s. Nowadays approx. 10% of the orders in job coating centers are forming tools ([60]).

The combination of ion plating and activated reactive evaporation includes not only the biased activated reactive evaporation process (e.g. [61],[62]), but primarily those processes utilizing anodic and cathodic arc sources specially developed for high activation of the vapor and high vapor ion bombardment of substrates ([63]). In the termionic arc chamber the evaporation metal is the anode of a non-self-sustaining arc discharge. Its cathode is a resistanceheated filament situated in a separate chamber under relatively high inert gas pressure.

The process invented at Balzers was mainly applied for the production of TiN films, but recently some other coating materials, such as TiCN and CrN were introduced.

Fig. 20 gives a comparison of the performance between uncoated, plasma-nitrided, TiN-coated (BALINIT A) and TiCN-coated (BALINIT B) tools for the forming of collars on suspension arms of passenger cars.

4.4.2 Laser alloying

The laser alloying technology belongs to the group of reactive coating methods. On the critical spots of forging dies the material properties can be locally changed by using this method. Local change in the fracture toughness of the material can help to avoid the crack propagation in heavy loaded tools, or an effective wear protection can be given to the hot forging dies ([64]).

Some additional materials are used for surface alloying which contain WC-Co. For future nitriding some Cr is added. Consequently an alloyed surface layer shows the composition of a high alloyed high speed tool steel. The maximum percentage of alloying elements in the surface layer is as follows: 6-22% of W, 2-4% of Co and 0.8-2.0% of C to a depth of 1.0 mm. Depending on the additional materials, the hardness of the surface is HRC 58-67.

The additional alloying material can be brought onto the surface as a powder in two steps, displayed in Fig. 21, showing as well the influence on tool life.

Fig. 21: Laser alloying of complex rotationally symmetrical tools (Kirner/Rozmoki).

4.5 On-line tool monitoring

The selection of the most favorable tool maintenance strategy also belongs to the steps towards increasing tool life.

In the case of highly loaded cold forming tools the failure-based maintenance strategy and the strategy of regular tool replacement (independent of the state of the tool) are both very uncertain because of the enormous dispersion of tool lifes. An endeavor to completely avoid tool fracture can result in too short tool change-cycles, not utilizing the performance of tools. The analysis of the economical aspects shows (Fig. 23, [65]) that the best solution is to stop the press before the tool breaks. The general question about this basic requirement however is, how the continuous progress of tool failure can be measured during the manufacturing process.

A new solution is presented in Fig. 24 ([66]). The schematically displayed on-line monitoring system is able to follow the crack propagation inside the die and thereby delivering the required information about the state of the tool during production.
5. Systematic approach to the prediction of tool life

5.1 Data based methods of life-time prediction

Prediction of expected tool life at the level of process planning enables the joining of CAPP forming operations with the simultaneous engineering. Information about the expected failure reason gives the necessary basis for the selection of the proper tool management strategy. The methods of life-time prediction can be split into three different approaches:

1. **Deterministical approach**: the expected tool life for the production of new parts is determined by the achieved tool life observed during the production of current parts (empirical approach).

2. **Statistical approach**: the average service life of some tool-sets allows for the prediction of the expected tool life for subsequent production of the same parts. (Statistical methods are providing to the safety and reliability of production.)

3. **Mechanical/numerical approach**: mechanical and numerical modelling enable life time prediction for new parts and new tool designs. (Process simulation mainly by FEM yields the knowledge about tool loading and reasons of failure.)

The first is a purely empirical approach based on the relationship between complexity, weight, deformation and material properties without analysing the failure reasons. The second approach is a pure problem of theory of probability. This category of solutions introduced in [67] is based on the Weibull-distribution of failure cases and delivers the necessary number of tool sets to provide the prescribed safety of production ([68]).

The third approach makes use of the FEM as an excellent modelling tool. However, the lack of necessary data and the difficulties of relating the loads to the damage mechanisms (described in chapter 3), are the main obstacles of transferring results from one tool to the other. The development of a new comprehensive FEM-process design and simulation programme package for metal forming processes (PSU-Projekt, Germany) also includes the mathematical modelling of tool damage ([69]).

5.2 A knowledge based approach

An attempt to integrate the mathematical modelling of all damaging factors has been shown in [49] (Fig. 25). The main ideas of the generalised life-time model for cold extrusion tools are as follows ([70]):

- All damaging factors act at the same time, but only one of them achieves a predominant role in determining tool life.
- The simulation of parallel damage processes is carried out on the level of form elements of active tool parts in order to increase the transferability of material data.
- The necessary constants (material properties) are collected from case studies, and are stored together with the confluences in the form of an object oriented knowledge base. As usual in object oriented knowledge based systems, the generic frame describes the connections between the objects. This generic frame contains all aspects of the forming system, which influence tool life (Fig. 11).
- The acquisition of geometric knowledge is based on automatic processing of the IGES format of tool drawing.

Since a knowledge base is used to store the case studies ("experience"), the knowledge base can be used as a consulting system as well. The simulation module controls the wear and fracture simulation. There is not enough information for a quantitative simulation of the other damaging processes, but the simulation system also enables the inclusion of other models.

6. Conclusions

- Although a large effort has been made to increase the efficiency, tooling has remained the most uncertain factor in metal forming.
- High tooling costs are forcing both industry and research to systematize their know-how, material and technological data, as well as their empirical knowledge, in order to increase the service-time of the tools.
- Because of the confluence of factors influencing tool life, research was limited to a purely empirical sphere up to now. Investigations are very expensive and the results are not transferable, they can only orientate the designer.
- Human experience, collected during the years of industrial activity, combined with finding analogies can be more precise in the prediction of the service time of a new tool design, than "highly scientific" methods.
- A knowledge based approach imitating the activity and knowledge acquisition of human experts can be the bridge between CA-techniques and human experience.
- Data concerning the life-time of tools are mostly treated as confidential factory information. However collecting and compiling international tool failure cases could be useful for all tool designers, tool makers and for the metal forming factories.
- For the simulation of surface welding, crack initiation etc. a bridge between physics and technological practice should be built in order to find the material constants of wear for the different surface combinations.
- Further development of metal forming tools aiming at an improved performance and economy requires the knowledge of experts in forming, materials and machinery, both in research and industry. This should be a challenging task as well for the international co-operation among the STC's of C.I.R.P.

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