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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 enormous variety and confluence of damaging factors, factory-specific character of tool life, stochastic phenomena 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 expected 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 immanent 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 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).

Fig. 1: Interaction of metal forming processes with various components (Lange)

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],[6]). Due to the relatively high initial costs for of 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 down-time 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. 3: Initial tooling cost, machine set-up cost and maintenance cost for a typical cold forged part (Bariani)

Fig. 4: Breakdown of tool maintenance costs for a forged shaft processed on a 5-station transfer machine (Bariani)

Fig. 4 shows the breakdown of maintenance costs for the cold forged part (stepped shaft) of Fig. 3 ([8]). The frequency of appearance of these three types of costs is determined by...
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 lives for the same tool design and tool layout.

Fig. 5: Dispersion of tool life (Noack/Thompson).

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 (Fig. 6-7 [11]-[12]). 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.

Fig. 6: Typical tool failures in cold extrusion (Griger/Nieiss).

Fig. 7: Typical tool failures in warm bulk forming (Doege/Kunapun).

2.1 Wear of tool parts

The main kind of surface damage is wear. It is the principal reason for scrapping 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]-[23]) gives an efficient basis for industrial research. This has shown, that:

Despite a high degree of hardness, wear always takes place!

Fig. 8: Preform geometry and the measured wear distribution after 2000, 3800 and 5200 forgings (Boy).

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 ([20]-[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]-[35]).

Fig. 9: Systems, measuring initiation and propagation of cracks in a cold extrusion tool (Reiss).
subsequent crack propagation ([37]). Both methods are of enormous importance for proving theoretical considerations of fracture simulation and for on-line monitoring. Using these measurement techniques the role of heat treatment and surface quality has been shown (Fig. 10) e.g., for a rod extrusion die. The combination of fracture mechanics with FE analysis in the following enabled the computer simulation of crack propagation to produce results that agree well with the results of practical measurements ([38]-[44]).

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]).

Another dimension in tool life is connected with the traditions and culture of production - with human factors. Consequently factory-independent tool life estimation is always very uncertain ([12]). The schematic structure of consequences (Fig. 12, [48]) shows some possible reasons of this claim. Two examples shall be given in the following: 1) careless lubrication, preheating or cooling can cause an elevated temperature of the forging die may lead to quick permanent deformation or thermal fatigue or 2) the deviation of workpiece temperature results in either oxidation with elevated friction and wear or in increased contact pressure, higher stresses in tool elements and thus wear or fracture.

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.

The generalized failure model explains the reasons for this phenomenon (Fig. 13, [49]). In accordance with this model all types of damage are active at the same time during the exploitation of the tool. Wear, roughening, plastic deformation and crack propagation are of deterministic, but initiation of microcracks is of probabilistic character. Thus the path leading from the initial state of the tool to the dominating failure not only depends on the design- and exploitation-specific factors but on the entire "pre-history" of the tool. The overlapping of these deterministic and stochastic processes result in a dispersion of failure types, which may be very large as already mentioned.
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 15C). 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]).

Compared with conventional stress rings, the STRECON® stripwound prestressed containers (Fig. 15D) 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 HR, was originally used as die-insert material. The negative effect of this is a relatively low elastic limit: \( \sigma_y = 1300 \text{ N/mm}^2 \).

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.

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670
The higher pretress of a STRÉCON® 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 pretressing with a powder-metallurgical high-speed steel die insert (σ_{UTS} = 2400 N/mm², HRC ≥ 60) fitted with high interference (≥ 1.0%) reduces the cyclic plasticity which mainly determines low-cycle fatigue fracture and results in a remarkable die-life improvement of app. 2400 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 (Fig. 27/[53]). Fig. 16 in this connection displays:
- the hardness distribution of the refrozen layer carbide-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/mm² 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. 17: Fracture toughness and hardness of tool materials (Arttinger).

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

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Fig. 18: Subdivision of wear protective coatings (ICFG).
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 environmentally-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
- 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 (58¹). 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 (eg. [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 resistance-heated 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). Scarcely 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. Industrial practice shows an average increase of tool life after laser alloying of 100%, in some cases up to 500%, compared with the traditionally treated tools (65), as is shown in Fig. 22 for a hot forging die.
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) deterministic 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 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-Project, 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 paralled damage processes is carried out on the level of form elements of active tool parts in order to increase the transfeability 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 is 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 modul 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 confident factory information. However collecting and compiling international tool failure cases could be useful for all tool designets, 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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