TOOL LIFE AND TOOL QUALITY - A SUMMARY OF THE ACTIVITIES OF THE ICFG SUBGROUP

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Abstract
Tool life and tool quality belong to the most decisive factors of cold forging technology. Therefore, the activities of the International Cold Forging Group (ICFG) were focussed as well on this subject for the last years. The presentation will summarize the main topics of a special ICFG Document, Part I "General Aspects of Tool Life" published recently. Due to its importance for tool life optimisation, in particular chapter 3 and 4 of the document will be considered in this paper, containing practical aspects and methods to approach tool life problems. Prior to the start of any tool life improvement activities it is most important to have a clear view of the actual tool life problem and its root causes. Since tool life reacts rather sensitive to the influence of various process parameters, a comprehensive analysis of the circumstances of tool failure starting from development phase to production phase is highly recommended. The paper presents a practical, process oriented concept of tool life approach, reaching from systematic recording and analysis of tool life data to process data monitoring and FE-simulation of tool failure.

Keywords: International Cold Forging Group ICFG, cold forging tools, tool life, fatigue damage

ICFG DOCUMENT "TOOL LIFE AND TOOL QUALITY, PART 1"

In order to cover the importance of tool life and tool quality for cold forging technology, a special Subgroup Tool Life was founded by the ICFG
about 10 years ago, which is working on the various aspect of tool life and tool quality. The overall goal of the Subgroup Tool Life for the last few years was to publish a special ICFG Document "Tool Life and Tool Quality". After some years of intensive work now, the subgroup published part I of this document: "General Aspects of Tool Life" [1]. In particular the following chapters are included in the document:

1. Economical Motivation

2. of Tool Life

3. Practical Aspects of Tool Life Approach
   3.1 Systematic investigation of tool life problems
   3.2 Analysis of damage, failure and occurrence mode
   3.3 Examples of influential parameters on load and strength

4. Methods of Tool Life Approach
   4.1 Recording and analysis of process data
   4.2 On-line process monitoring and recording
   4.3 Theoretical modelling and process simulation

5. Prediction and Optimisation of Tool Life
   5.1 Prediction of tool life
   5.2 Optimisation of tool life

6. Tool Management Strategies
   6.1 Logistics and procurement of tools
   6.2 Tool inspection and estimation of remaining tool life
   6.3 Tool exchange policy

7. Literature

   Details about economical motivation for tool life activities are given in chapter 1. Based on definitions of tool life in cold forging from different points of view, presented in Chapter 2, the document describes a practical approach to tool life problems in Chapter 3. Furthermore Chapter 4 provides
information about methods to collect and analyse tool life data in practice, as the basis of any careful modelling or simulation of tool life problems. Chapter 5 shows methods for the prediction and optimization of tool life, based on collected data or process models, important for the improvement of average tool life and its scatter, during the phase of process development and production. Chapter 6 deals with the aspect of tool life management, particularly important for cost optimization in production and tool supply. Eventually, Chapter 7 provides a detailed collection of relevant literature.

LIMITED TOOL LIFE - PROBLEM OR CALCULATED RISK?

Tool life and tool quality are decisive criteria for the successful application of bulk metal forming in industrial production. They directly affect production costs and therefore competitiveness of the process and may as well have a considerable impact on tool supply, stability of production and last but not least delivery performance. Since tool failure is unavoidable, tool life must be properly taken into account for the calculation of tooling cost and planning of tool supply for production. For regular production parts direct tooling cost (cost for tool replacement) may range from 5-10% of total manufacturing cost. For complex near net or net shape products they may even reach up to more than 30%, caused by low tool life due to extreme process conditions and/or high tool manufacturing cost due to complicated tool geometries. In addition to that indirect tooling cost for machine down time and tool maintenance of 5-10% should be considered. It is obvious that the average service life of tools for net shape manufacturing with increasing complexity of the process is significantly lower than for the production of workpieces with less accuracy. If under control, tool life becomes a calculated and manageable production factor and tool failure does not necessarily represent a problem. However, tool failure may become a serious problem in real processes as soon as tool cost and tool supply, influencing profit and delivery performance, are affected beyond the calculated limits. In particular for complex parts and inexperienced processes service life of tools may be very poor during production ramp-up at the beginning of the learning curve. Even more, low tool life then may endanger tool supply and therefore production output and tooling cost may even exceed the calculated manufacturing costs of the entire product. In daily practice this or a similar
situation would call for immediate short term actions of tool life improvement in order to stabilize production or for long term activities of tool life optimisation and cost reduction. In both cases the main question arising is:

What was the essential reason and root cause for the observed change in tool life?

ASPECTS INFLUENCING TOOL LIFE

The main problem to define the major reason for tool failure is the large number of process parameters and their possible interactions affecting tool life, as well as the lack of any systematic approach to identify the initiating root causes of failure. A classical division of failure reasons and factors influencing tool life distinguishes between (Fig. 1) [2]:

- tool specific and
- application specific.

They cover a very complex network of influencing factors, describing the entire forming system and all requirements for the quality of the product. Starting from this more generalized view reasons for tool failure may be:

- tool design: critical corners or insufficient prestressing causing high internal tool stresses,
- process layout: press force and/or contact pressure exceeding acceptable limits, due to an extreme grade of cavity filling or bad material flow conditions,
- tool material: too low hardness or fracture toughness ensuing cyclic plasticity and low cycle fatigue,
- tool manufacturing: improper surface finish leading to premature failure.

This list could be continued but the main obstacle still remaining for getting a clear answer to tool life problems is the difficulty to separate the influences of various parameters of the forming system due to their complex interactions.

A more systematic approach to describe the influencing factors of tool life and its interactions is based on the concept of load and strength of tools. The basic idea of the concept is to trace back both the load and the strength to
their origins, to the primary parameters of influence, which can be assigned to the areas of billet, tool and interface [3]. Tool life is determined by the strength of the tooling system, mainly based on its material properties, to resist the damaging mechanisms of wear and fatigue, which are controlled by various loads acting on the tool during the forming process. Figure 2 shows the schematic structure of parameters which influence the determination of tool life based on the concept of load and strength.

It is obvious that the large number of process parameters and their possible interactions affecting tool life make it rather difficult to find the main influencing factor for the encountered tool life issue. In addition to that, the greatest problem for an accurate assessment of the influencing factors of tool failure is the reliability of tool life data itself due to the enormous scatter of tool life for the same tool design and tool layout. Figure 3 gives an example for the analysis of tool life data. It shows the service life of all dies for a specific product as well as the floating average value for a production period of one year. It is obvious that scatter of tool life is rather high and several single tools failed very early.
Applying statistical methods the stochastic nature of tool life scatter can be expressed in terms of the reliability of the tooling system or in terms of failure probability [3]. Recent concepts of statistical tool life approach try to combine FE-process simulation with statistical methods to consider load and strength for realistic tool life prediction. However, even if such an approach will be helpful to understand the influence of certain scattering parameters on tool life it will not be in the position so far to give a clear answer to tool life problems observed at shop floor in production. Therefore, in order to support process engineers in daily application of cold forging to solve tool life problems a more practical and straight forward approach, like a systematic procedure or checklist, is still required which helps to quickly identify the responsible process parameters for the observed damage case.
Figure 3. Tool life diagram for 18 month of production and resulting tool failure probability.

SYSTEMATIC APPROACH TOWARDS THE SOLUTION OF TOOL LIFE PROBLEMS

SYSTEMATIC INVESTIGATION OF TOOL LIFE PROBLEMS

Problems with tool life mostly result from two different situations:
a) The unexpected and repeated occurrence of premature tool failure. This situation may lead to critical conditions in production with regard to tool supply and break down of tool cost. It calls for immediate short term actions (trouble shooting) aiming at quick increase of tool life.

b) Permanent low tool life and high tooling cost in combination with increasing price pressure from the market. This situation requires an effective reduction of tool cost and predominantly calls for long term actions of tool life optimisation (see Fig. 6.)

This view of tool life problems allows to define two different categories, which are ensuing completely different approaches to tool life improvement with specific activities. These are:

- concepts of (long term) tool life optimisation for cost reduction and
- concepts of (short term) trouble shooting for stabilization of production.

Moreover, applying a more process oriented view at the main causes of failure occurrence gives another option for identification of tool life problems (Fig. 4). According to the concept given in the previous chapter (Fig. 2), tool life is determined by load and strength. Tool life problems therefore can be traced back to major causes of unfavourable interactions of various parameters with internal or external load and strength of the tools, showing either systematic or stochastic appearance, caused during development or production process of tool and product.

Problems with internal or external load of tools may originate from

- critical customer requirements regarding part design,
- unsuitable process design regarding unfavourable material flow conditions etc.,
- bad tool design,
- or instable production conditions.

Problems with strength of tools mainly are caused by

- bad choice of tool material and tool manufacturing,
- or critical production conditions.
In addition, customer requirements may affect process design whereas process design may interact with tool design and manufacturing both indirectly influencing load and strength. Tool failure caused by problems with customer requirements, process or tool design created during the development process normally show systematic appearance. Tool failure resulting from problems with tool manufacturing or process parameters under production conditions tend to be of stochastic nature. This simply looking statement is another helpful orientation on the way to evaluate failure occurrence and its root causes.

This distinction of tool life issues to problems with load and strength, originating from the development or production process, represents the basis for a systematic approach to the explanation and solution of tool life problems. Quite simply, it helps to give first indications about the origin of failure causes and helps to quickly focus on the main problems influencing tool life.

In general it is most important for any successful tool life optimisation that all activities, which are required to approach and properly understand the actual tool life issue, must be specified and described by a systematic procedure and must be introduced to the engineers in terms of standardized
working instructions or simple checklists. Since this work has to be done individually for each company, the following activities should be considered as basic guidelines, prior to the implementation of any action plan for tool life optimisation (Fig. 5):

- Immediate report of tool life problems from shop floor to engineering after detection
- Investigation of damage mode, failure mode and occurrence mode of tool life problem
- Detailed description of observed tool life problem including all available information about tool life data, process conditions and damage analysis
- Determination of potential root causes by analysis of influencing parameters and
- Definition of relevant trial outs by Design of Experiment for further clarification
ANALYSIS OF DAMAGE, FAILURE AND OCCURRENCE MODE  
A basic requirement for a successful solution of tool life problems is a detailed understanding and description of the problem itself. At the outset careful damage inspection and analysis of available tool life data is needed, providing information about damage mechanism as well as failure and occurrence mode.

**Damage mode.** In cold forging operations the service life of tooling is mainly constrained by fracture, wear and plastic deformation [2]. Careful analysis of the failed tool section is very important to describe the true reason of tool failure. It may give further clarification about damage evolution and history, since the finally visible damage may have originated from a different kind of predamage, different surface location or neighbouring local defect. The following inspection steps should be considered providing reliable data about the nature and origin of damage:

- visual inspection of tool surface (surface damage by wear or pitting, crack origin)
- 3D-measurement of tool dimensions (plastic deformation, tool manufacturing out of specification, deformation due to stress relief or aging)
- control of tool material specification (wrong material grade, heat treatment specification)
- measurement of tool hardness at surface and cross section (improper heat treatment or burning of tool surface during grinding)
- microscopic analysis of affected tool surface (white EDM layer, surface roughness or microcracks resulting from wear or surface machining, fatigue crack initiation patterns, damage of surface coating)
- electron microscope analysis of crack environment (crack initiation and propagation behaviour, analysis of microstructure of tool material).
Failure mode. For a better understanding of the problem of tool life it is important to know which aspect of tool life is causing problems. The following types of failure (failure modes) are problematical and call for improvement:

- average of tool life too low,
- scatter of tool life too large,
- single tool life repeatedly out of order.

The analysis of failure mode gives the first indication about the origin of influencing parameters for later optimisation concepts. In the case of average tool life being too low, it is probable that either the tool or process design has some systematic weaknesses (Fig. 6). Large scatter of tool life in most cases results from uncontrolled stochastic fluctuations of process parameters or the influence of tool material. Problems arising from extreme low tool life of single tools, in many cases results from problems with setup or handling on the press or wrong heat treatment of tool material.

Figure 6 shows the evolution of tool life for more than 24 months of production for a die of a near net shape forming process. It is obvious that the average of tool life could be improved at a first optimisation step after some modifications to the tool design (enlargement of a critical radius area). But it is obvious as well that the scatter of tool life did drastically increase at the same time and that the average of tool life could not stabilize on a much higher level. It may be concluded that after the load was reduced to a lower level, low cycle fatigue due to cyclic plasticity became less dominant for crack initiation, giving room for the growing influence of other parameters with individual process scatter. It is interesting to note that a new PM material grade with higher fracture toughness at higher hardness, used for a second optimisation step, delivered considerably better fatigue life due to further reduction of cyclic plasticity. After 10 more months of production now, not shown in the diagram, this positive trend could definitely be confirmed, rising average die life from approx. 60000 for the conventional PM material to 130000 with the new PM material grade.

Occurrence mode. In addition to the analysis of failure mode a closer look at the occurrence of tool failure over a longer period of production (e.g. the time dependent development of tool life or the occurrence mode) might
Figure 6. Evolution of tool life for a near net shape forming die over production time of 2 years.

be very helpful for discovering the source of problems. The occurrence of tool failure may be of the following type:
stochastic,
- systematic,
- cluster,
- trend.

The display of tool life data as shown in Fig. 3 and 6 is a very good and simple way to visualize the occurrence mode. The calculated floating average value clearly indicates trends of deterioration or improvements of tool life as a function of time. Concentration of bad tool life cases (clusters) can be simply identified as well as systematic repetition of tool failure (patterns). For the tool life case shown in Fig. 3, the periodical decrease of average tool life was caused by repeated problems with the surface treatment equipment. The problem remained undiscovered until the final occurrence, but could have been avoided earlier by continuous observation of the average tool life function and early trend analysis.

METHODS OF TOOL LIFE APPROACH

RECORDING AND DOCUMENTATION OF TOOL LIFE DATA

For the purpose of collection and documentation of all necessary tool life data, the application of tool life cards in production is highly recommended [1]. Together with additional information about the applied tools or other related production data, it may be possible to find correlations between low tool service life and certain process parameters rather easily. Therefore, apart from basic information about tool failure, like number of parts produced, type of damage, obvious cause of failure etc., the applied tool life card should show the serial number of the tool (an individual identification code connected to the batch number of tool manufacturing which is printed on every tool) as well as the order number of the part production batch. Using all these references, modern production planning systems like SAP easily allow to retrieve the relevant data from their database about the applied tools (e.g. supplier, manufacturing operations, inspection report, material, hardness, date of use etc.), the related production data (e.g. forging press, date of surface treatment, slug annealing and forging, specification of workpiece material etc.) or even additional information about production
problems. Referring to Fig. 4, all this information mainly helps to reveal problems with tool manufacturing or production process. Computer aided data mining, which is automatically checking all these information for possible correlations, certainly will help to support the search for failure relevant process parameters most efficiently in the near future [4].

ON-LINE PROCESS MONITORING AND RECORDING

Tool life cards mainly support post-failure retrieval of failure relevant data about certain process conditions. However, the stochastic behaviour of important, time dependant process data, which are directly influencing tool load, are not covered by this post-failure data recording system. For this purpose on-line process monitoring and recording of all essential process parameters is recommended, which provides additional information about the individual history of each tool and which reveals unacceptable scatter of certain process conditions, for example fluctuation of press force resulting from oversized billets, due to problems with shear quality. Fig. 7a, 7b a shows an example of multi-parameter process monitoring during regular production, used for the on-line quality control of the process, displaying the time-dependant behaviour of press force, elastic die deflection and different tool movements for one individual press stroke (Fig. 7a) and for a sequence of several hundred strokes including die temperature in correlation with part accuracy (Fig. 7b). By applying strain gages to the stress ring system, the influence of press force on tool dimensions and part quality can be directly monitored. It is obvious from the example that the critical part diameter shows a significant correlation with die temperature and elastic die opening. However, no critical loading conditions affecting part quality and certainly tool life, resulting from unacceptable peaks of press force as a consequence of oversized billets, could be observed from the stress ring response.

THEORETICAL MODELLING AND PROCESS SIMULATION

On-line process monitoring and tool life card system are mainly useful to analyse the influence of observed process conditions on tool life, with either stochastic or systematic appearance. It should be kept in mind, however, that all these parameters are only of secondary order for the mechanism and rate of tool failure, which primarily is determined by the level of local cyclic
Figure 7a. Complex interaction of tool movement and load for an individual press stroke.

Figure 7b. Behaviour of parameters affecting part quality for a production period of 2500 parts.
loading (stresses and strains) and local strength of the applied tool material. Referring to Fig. 4, systematic problems with tool loading, reaching extreme levels due to inadequate process layout or tool design, or unsuitable choice of tool material, can only be revealed by FE-process simulation and subsequent simulation of ensuing fatigue behaviour. Therefore, it is strongly recommended to conduct careful FE-simulation of tool failure, applying modern concepts of cyclic fatigue and damage simulation, in addition to the above mentioned activities of tool life approach [5]. More details about this concept of fatigue simulation are presented in [6] at this conference. Fig. 8 gives an example of cyclic FE-load analysis for the critical area of the die insert, shown in Fig. 6, [7]. Fig. 8a shows the damage distribution at the die surface after 4000 forming cycles, as the material response to the calculated stress-strain path for the cyclic stress/strain components in this critical area, Fig. 8b.

**SUMMARY - A PRACTICAL APPROACH TO TOOL LIFE PROBLEMS**

The purpose of this contribution was to present a practical approach to tool life problems, which is supposed to consider the reason of tool failure from a more process oriented point of view. It suggests some criteria which enable the engineers to identify the root causes of the considered tool failure faster and more systematically. At first, all available tool life data should be analysed in order to find possible time dependent information or correlations with main production factors, recorded by tool life cards in production. Subsequently the tool system should be checked for the influence of process parameters on load and strength traced back to customer requirements, process layout, tool design and tool manufacturing or production process. Only based on this carefully collected information about potential root causes of tool failure, supported by FE-simulation, further measures for effective tool life improvement can be started [1].

**OUTLOOK ON FURTHER SUBGROUP ACTIVITIES**

It is recognized that of the document "Tool Life & Tool Quality in Cold Forging" is not complete and therefore will be open for additional parts covering special aspects of tool life improvement. The subgroup is now working on part II of the tool life document, which will concentrate on the practical
aspect of tool life improvement, mainly by giving guidelines for engineers about how to detect, analyse and describe tool life problems and how to choose first improvement actions. Since it is very difficult to define general guidelines for the understanding and improvement of tool life problems in practice, major milestones on the way to tool life diagnosis and problem solving will be explained and illustrated by selected practical case studies. An important aspect is which parameters in tool manufacturing (e.g. material quality, machining, heat treatment) influence tool life and tool quality to what extent. Nowadays, many details of tool manufacturing are not covered by the data given on technical drawings, but are mainly based on the know-how and experience of the toolmaker. In this context, the subgroup is working on guidelines that contribute to more defined manufacturing conditions in tool making.

REFERENCES


Figure 8. FE-simulation of fatigue damage at cold forging tools [7] a) Damage distribution in the die insert after 4000 forming cycles b) Evolution of stress-strain path at the critical location for the first thousand forming cycles.