TOOL FAILURES -CAUSES AND PREVENTION

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Abstract The aim of this project by the VDEh Subcommittee on Tool Steels is to document the various types of tool failure occurring from the design through to the tool application stages. Apart from systematically classifying these failures according to type and occurrence, the project is intended to deliver practical solutions to the problems associated with the respective failure modes.

Manufacturing defects, operating errors and unforeseen events all have an impact on tool service life. Heat treatment naturally plays a major role due to its significant influence on the tool properties, and indeed most defects appear after the heat treatment stage. Especially with some more recent heat treatment methods, remedial action is undoubtedly called for.

To optimize the service life of a given tool, failures must be minimized in all manufacturing steps going into its production and its proper use must be ensured. A register of tool failures covering the full range of failure sources can therefore contribute significantly to a tool service life improvement and hence, to more efficient manufacturing.

INTRODUCTION

The present project was set up to record the numerous problems currently observed in the heat treatment and use of tool steels, and to develop appropriate suggestions and remedial strategies.

Heat treatment problems are mostly attributable to a lack in structural toughness resulting in premature failure in the form of tool breakage/fracturing. This problem has several causes, one of which is the widespread conversion of virtually all heat treatment operations to vacuum-hardening technology. The previously common brine hardening method has become rare as a result of environmental considerations. However, it had the advantage of permitting quenching at variable rates in oil, air, or water. With the vacuum method, the quench rate lies somewhere between air and oil quenching, i.e., it is slower than in the brine hardening process. In addition, quench rates are now influenced significantly by the furnace load and hence, the degree of furnace capacity utilization. This essential parameter, which eludes measurement, defines the quench rate in today's applications.

Several years ago, the exodus of toolmaking operations to low income countries began as part of corporate outsourcing strategies. Today, heat treatment operations in these countries are focused mostly on standard tools while the production of high performance products has mostly reverted to western Europe. But premature tool failures due to defects (including heat treatment failures) are particularly critical in high performance tools pushing the limits of achievable material properties. An optimized heat treatment can help greatly in these cases to make the performance potential of such high performance tools fully accessible.

The working group's original subject was therefore extended to include all tool failures currently observed, whether in toolmaking or downstream operating contexts. The aim was to systematically record and classify all failures according to type and occurrence while offering solutions at the same time. A key factor here is that many failure-causing tool defects will appear conspicuously often and over long periods after the introduction of new manufacturing methods as the latter are becoming increasingly widespread (as was the case with spark-erosion methods a few years ago). Here we have the opportunity to identify such systematic failures and to suggest remedial approaches. A comprehensive description of all tool failures observed is of special importance inasmuch as the performance of a given tool is determined by numerous and diverse factors, from design through to the toolmaking, finishing and heat treatment stages and, ultimately, service conditions. We are looking at a control loop in which all subordinate steps contribute to the tool's behaviour. To maximize service life, it is therefore important that each such subordinate step is performed in a virtually flawless manner. A Tool Failure Register of the type now being compiled should contribute effectively to an improvement in tool service life.

TOOL FAILURES AND THEIR SIGNIFICANCE

Our understanding and prevention of tool failures must be viewed from several perspectives:

- Prevention of economic loss to
- Tool users
- Tool manufacturers
- Steelmakers
- Safety issues, i.e., the need to ensure
- Operating safety
- Labour safety
- Environmental safety
- Compliance with quality assurance requirements, e.g., QS 9000
- Performance and service life improvement
- Increased production reliability, since tool failures usually entail production disruptions up to the point of a production shutdown.

The overall economic loss resulting from tool failures is significant, given any analysis of tool failures from a business management viewpoint must today reflect the resulting processing and consequential costs, which usually amount to many times the costs of material. The service life improvement potential is not yet factored into this equation. As a general estimate, it can be stated that a 20 - 25% performance increase is achievable across all tools. In other words, the economic potential of many tools is far from being adequately utilized. With manufacturing failures now being routinely trackable to the source, the associated costs can be charged on all the way to the liable party. Given the large number of different production steps involved in toolmaking today, all companies contributing to the process are forced to furnish evidence of zero defect manufacturing. Under this aspect too, a detailed understanding of tool failures and their prevention is an economic must.

INFLUENCES ON TOOL SERVICE LIFE

The factors determining the service life of a tool may be viewed as a control loop starting with its design and ending with its use, Fig.1. As early as during the design stage, the tool's essential load bearing capability is determined via shape and load rating calculations. At the materials level, a steel grade is selected and desired finish and working hardness are determined. Incorrect design specifications and an improper choice of materials will usually result in tool breakage or deformation. At the manufacturing stage including machining and heat treatment, the design specifications are then put into practice. Failures in this phase (and specifically heat treatment failures) will usually reduce the toughness of the tool, possibly resulting in tool failures due to breakage. In use, failures may occur as a result of improper handling, maintenance or repair practices, which likewise tend to result in breakage.

MOST FREQUENT TOOL FAILURE CAUSES

If we classify tool failures according to the various failure causes, Fig.2, it emerges that these causes are essentially threefold. The highest frequency can be found among manufacturing failures falling into the tool production cycle (design, material, and execution defects), followed by operating errors at the tool application stage (handling, maintenance and repair defects and consequential effects). Unforeseen events (Force Majeure, exterior factors) are much rarer. Of all failures observed, defective material accounts for no more than 5%. Execution (finishing) and heat treatment emerge as the most common failure sources.

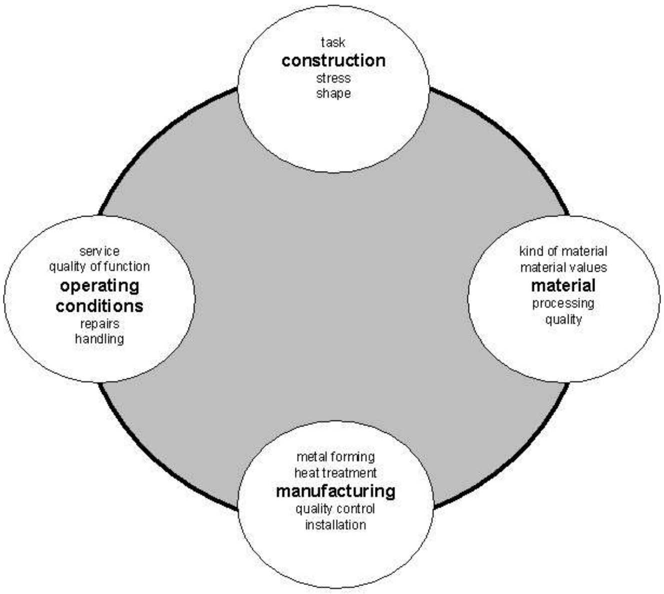


Figure 1. Influence on the life-cycle of a tool.

INVESTIGATION OF TOOL FAILURES

The investigation of tool failures comprises several stages. Starting with the macroscopic analysis, cracks and fracture paths, pores and fracture surface features are evaluated. Chemical tests identify cases of incorrect material identity. Hardness testing is conducted to check for an adequate working hardness or, where appropriate, hardness distribution. The main instrument in tool failure analysis is the metallographic investigation, which determines material properties on the one hand (carbide distribution, cleanliness, grain size) and material defects on the other (porosity, shrinkage holes, excessive segregation, inclusions). Machining defects (grinding or erosion faults) are likewise detected at this stage. The core element of any metallographic investigation is the inspection of the microstructure imparted by heat treatment (tempering condition, retained austenite, banding, coarseness and decarburization).

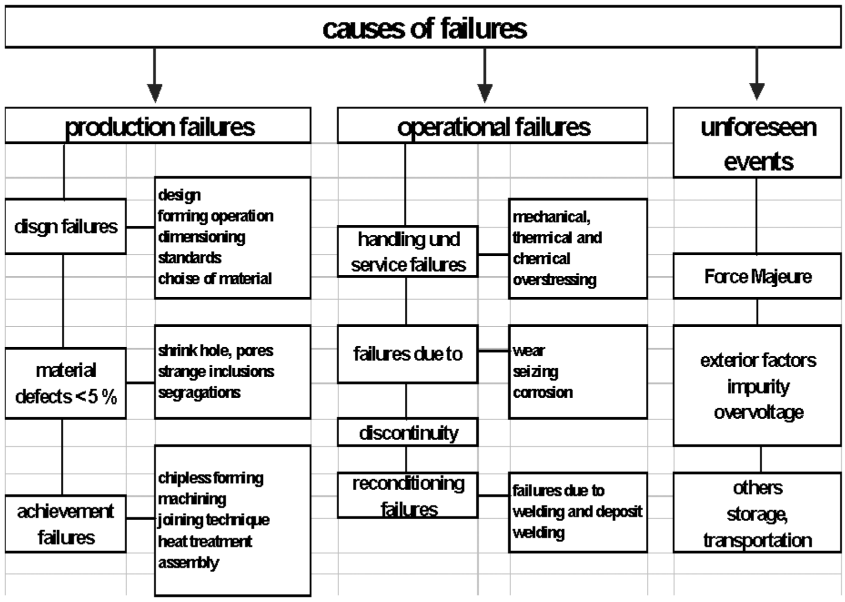


Figure 2. Classification of tool failures.

THE TOOL FAILURE REGISTER

CLASSIFICATION OF TOOL FAILURES BY DEFECT TYPES

The Tool Failure Register is classified according to the most common defect types and their causes, Table 1. Due to the large number and diversity of failures encountered, we can merely give a selection of the currently most common failure causes here. The results of the data collected to date shows that fractures are by far the most dominant cause, accounting for 70% of all tool failures. Of the remaining failures, about 10% each were due to wear, cold weld/seizing phenomena and other causes.

SELECTED EXAMPLES OF TOOL FAILURES

Design failures. One common design failure are sharp edged radii which cause a pronounced notch effect when the tool is operated under load and may cause it to break if its tensile strength is exceeded. An example of such flawed design is illustrated in Fig.3. The product in question is a die insert made of a hardenable corrosion resistant high wear chromium alloy die steel (BÖHLER M 340). Cracking has occurred due to the high notch stress along the sharp edged radius. This might be remedied by providing a maximum radius in all load bearing areas. Another effective reduction of the radius notch effect can be achieved by polishing the radius surfaces. If these measures should still not give an adequate fracture resistance, a tougher material must be used.

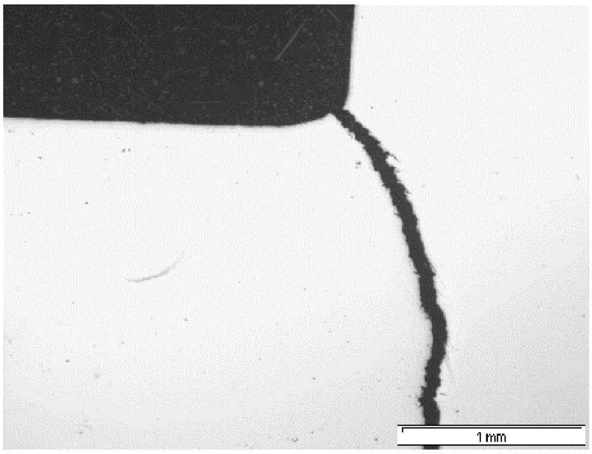


Figure 3. Crack initiation at the sharp radius of a plastic mould die of a hardenable corrosion resistance plastic mould steel.

Material defects. Given today's high levels of process reliability, material defects in steels sourced from technologically advanced countries have become rare. On the other hand, a large number of imported tool steels reaching the Western Europe market does not always meet EN ISO 4957 material quality standards. The number of internal and surface defects observed (e.g., shrinkage holes, porosity, excessively decarburized surfaces, metalworking cracks) has been on the increase again in recent years, as shown here for a HS6-5-2C (material No. 1.3343) steel bar in Fig.4. Material failures of this type are found specifically in steels from CIS countries and emerging Asian markets. The damage caused by such material defects is particularly high since they will usually entail substantial consequential costs, e.g., machining costs, production shutdowns, and the like. The loss to the overall economy is considerable, although the material costs of a contemporary tool will usually account for only 5% of the defect costs described.

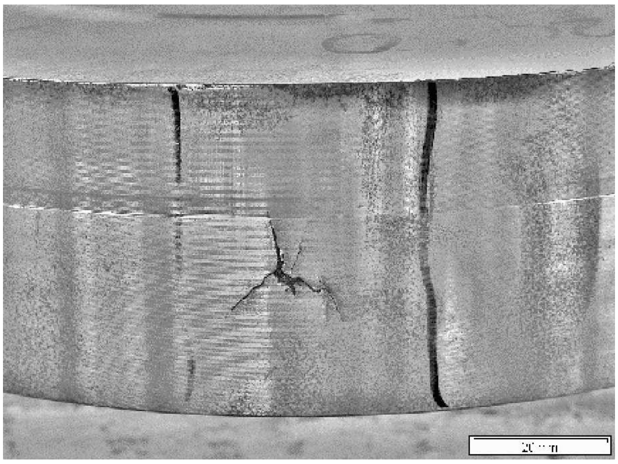
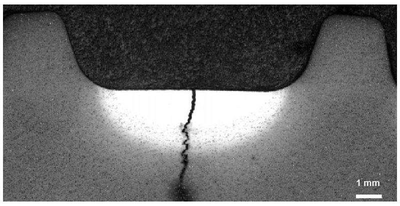


Figure 4. Forging failure at the outer surface of a round bar (253 mm Ø) of steel grade HS6-5-2C (steel number 1.3343).

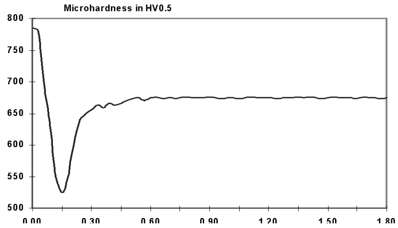
Machining failures.

Grinding failures. The following is an example of a grinding failure. The tool in question is a forming roll made of BÖHLER K 340 (∼X110CrMoV8-2) hardened to 60 HRC, which failed shortly after commissioning. A metallographic section through this roll shows a conspicuously bright area of increased hardness exhibiting a penetration depth of approx. 3 mm at the bottom of the profile in which a further secondary crack can be identified Fig.5a. Such rehardened zones consist of untempered brittle tetragonal martensite which is naturally susceptible to cracking. When the tool operates under load, incipient cracking may easily occur in this increased hardness area and may propagate into the basic microstructure. The hardness distribution in a surface damaged by grinding is shown in Fig.5b; the excessive hardness in the rehardened zone, the hardness drop in the underlying tempered zone and the subsequent hardness increase in the core structure are easily identifiable. These variations in structural conditions and hardness produce an unfavourable internal stress distribution, mostly accompanied by tensile stress, which renders the surface sensitive to cracking. The intensity of such stresses can be seen in Fig.5c: on this plate made of 90MnCrV8 steel (material No. 1.2842), high tensile stresses in the surface have caused a large area to chip off and rise up several millimetres. The only way to prevent microstructural damage during grinding is to provide adequate cooling. It should be noted here that in terms of cooling performance, today's grinding emulsions with their increasingly high water content, a concession, inter alia, to environmental concerns appear to be more inferior to emulsions with higher oil content than has so far been assumed. The minimal lubrication principle widely adopted today additionally imposes higher heat loads on the ground surface, thus increasing the risk of rehardening.

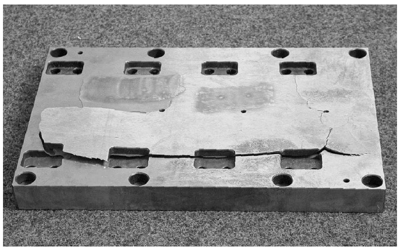
Erosion failures. Erosion machining with excessive power inputs is another widespread cause of failure. Especially with highly alloyed tool steels, excessive power levels may give rise to significant surface damage. Fig.6 shows a metallographic specimen of the coarsely spark-eroded surface of a high alloyed cold work steel grade. The extensive melted zone, with incipient cracks due to thermal overloading, is clearly identifiable. Underneath it we can see a rehardened zone consisting of brittle tetragonal martensite, as in the case of the grinding defect outlined above. The incipient cracks in the melted zone subject to tensile stress may easily propagate under load into the brittle rehardened zone; they frequently extend along the carbide bands, as will be easily appreciated from Fig.6, and will ultimately cause the tool to fail. As with grinding failures, we can observe an uneven hardness distribution along the eroded surface. Fig.6 illustrates the high hardness of the melted zone, the even greater hardness of the underlying rehardened area, the hardness drop in the underlying highly tempered area, and the following gain in hardness toward the core microstructure. Here too these inhomogeneous structures and hardness levels create an unfavourable internal stress situation.



(a) Grinding crack with hardening zone in a grooved roll of high alloyed cold work tool steel (Etchant: 3 % HNO_3).



(b) Variation in hardness within the hardening zone of the grooved roll in Fig.5a.



(c) Crack initiation during spark erosion due to high internal stresses, caused by grinding without sufficient cooling (hardened and tempered plate of steel grade 90MnCrV8 (steel number 1.2842).

Figure 5.

This situation can be remedied by minimizing the power input into the tool during spark erosion. Continuous erosion under fine machining conditions, at low current and high frequency, is preferable. Following the erosion process, the product should be tempered again at about 30 – 50 K below the last tempering temperature to transform the rehardened zone into a tempered, tougher martensite. The melted zone should be mechanically abraded by grinding, polishing or micro peening.

The cracking phenomena frequently observed in erosion-machining of hardened tool steels a few years ago due to internal stresses associated with low tempering temperatures have become quite rare these days since most tools are now subjected to secondary hardening prior to erosion and are largely free from internal stresses due to their highly tempered state.

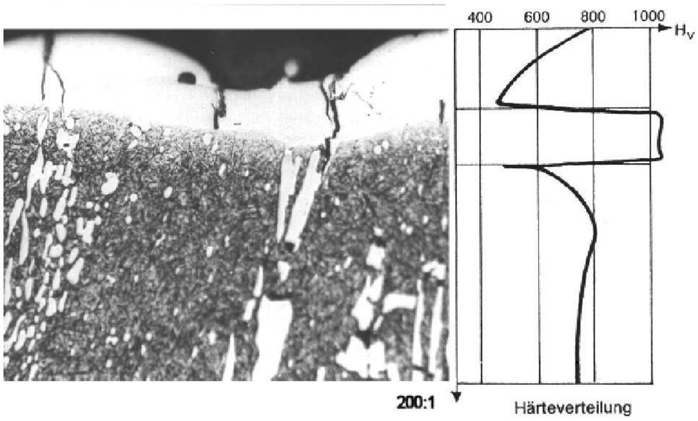


Figure 6. Spark eroded surface mit significant melting zone, new hardened zone and high tempered area of a high alloyed cold work tool steel. Microstructure and variation in hardness.

Nitriding failures. Tool steels are nitrided to increase the wear resistance of their surface. Another benefit of nitriding lies in the creation of subsurface compression stresses which protect against cracking. The increase in wear resistance is due to the penetration of nitrogen into the tool surface, although it must be said that with high alloyed tool steels, a "pile-up" of incoming nitrogen and the resulting formation of nitrides are a common risk. Such nitrides will form mainly at the grain boundaries, where the nucleation energy is minimal and more space is available due to lattice deformation. These grain boundary nitrides actually weaken the grain boundary, often to the point where entire grains become dislocated from the lattice, Fig.7. With higher alloyed tool steels, care must therefore be taken to prevent excessive nitrogen concentrations during nitriding. Optimum levels are easiest to achieve with plasma nitriding or fast acting nitriding solutions. Thus, nitriding is a process which yields high performance improvements when properly carried out, but may just as easily shorten the tool life when improperly applied.

Heat treatment failures.

Quench stress cracking. Quench stress cracking is a stress relieving phenomenon produced by high thermal and transformation stresses, usually

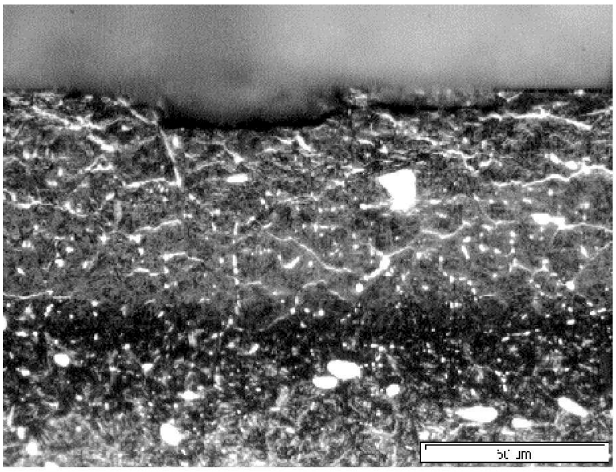


Figure 7. Metallographical section through a overnitrided surface of a drawing die of steel grade X153CrMoV12 (steel number 1.2379) with significant nitride layers on the grain boundaries (Etchant: 3% HNO_3).

during quenching from the hardening temperature. It is facilitated by an unfavourable tool geometry, such as uneven mass distributions with pronounced differences in cross section, the notch effect of sharp edged radii, etc. Fig.8 shows a die made of X38CrMoV5-1 (material No. 1.2343) which is fairly large at $450 \times 195 \times 800$ mm; it was quenched and tempered to a working hardness of 46 HRc, corresponding to 1500 MPa. The heat treatment was conducted in a shielding gas atmosphere, with subsequent quenching in oil to room temperature. The quench stress crack shown here extends along a critical die contour with a sharp edged groove. Remedial measures in this case would have to include an optimized design of the die contour for the heat treatment, and a modification of the sharp edged groove. To reduce thermal stresses between the edge and the core, a soak cycle during the cooling phase or an "interception" at 150°C for subsequent tempering would be recommended.

Another quench crack is illustrated in Fig.9. The tool in this case is a forging die made of grade X38CrMoV5-1 steel (material number 1.2343) which exhibits an unfavourable mass distribution as well as some extremely thin walls in its contoured area. The quench crack originates in the thin wall

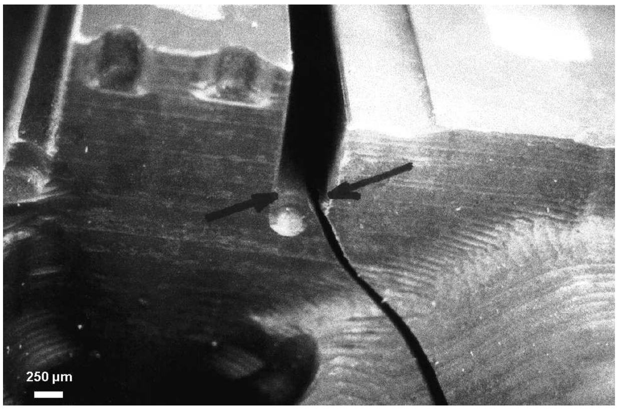


Figure 8. Stress relieved crack of a die casting die of steel grade X38CrMoV5-1 (steel number 1.2343) following a sharp edged groove.

of the contour which, to make matters worse, is quite sharp edged. The resulting notch effect, in conjunction with the high thermal stress encountered in the quench, is responsible for the formation of this defect. Here, too, a remedial strategy would have to focus on an improvement of the tool contour that eliminates sharp edged radii and major thickness differences. Soaking to relieve thermal stresses would be recommended.

An unfavourable tempered microstructure may likewise give rise to quench stress cracking. Fig.10 presents the coarse-grained tempered structure of an aluminium die casting die made of 38NiCrMoV5-1 grade steel (material No. 1.2343) with a working hardness of 45 HRc. This tool exhibited a quench crack after heat treating, indicating a low toughness of the coarse-grained superheated structure. The die was heat treated at 1020℃ with subsequent hot quenching at 180℃. It should be noted that in this case, no stress relieving was performed after the coarse machining step. The internal stresses introduced by the machining cycle thus further facilitated the formation of cracks. Remedial measures would have to include stress relieving at about 650℃ after the machining step, a reduction of the heat treatment temperature to 1000℃, and the adoption of hot quenching at 550℃ to reduce the risk of quench stress cracking.

Below we shall be looking at a number of typical heat treatment failures which are associated with unfavourable microstructures and reduced

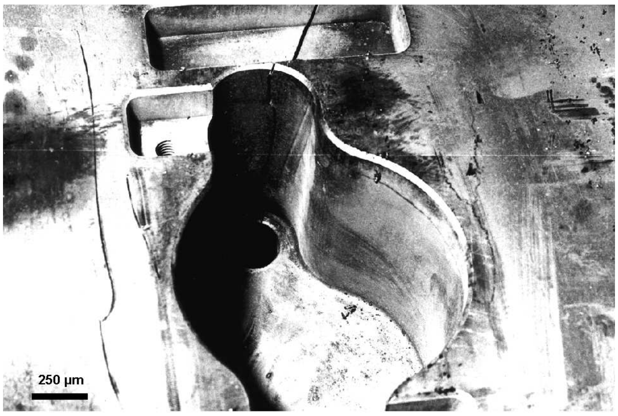


Figure 9. Stress relieving crack of a forging die with extreme varying cross sections.

toughness levels and may therefore result in cracking, spalling and fracture failures.

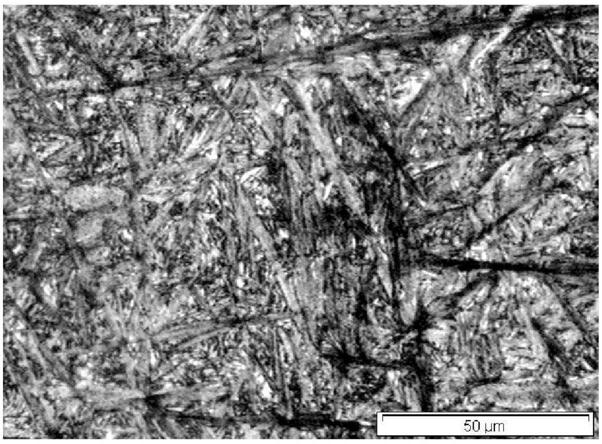


Figure 10. Coarse martensitic quenched and tempered structure of a die casting die of steel grade X38CrMoV5-1 (steel number 1.2343) (Etchant: 3% HNO_3).

Retained austenite. Elevated levels of retained austenite will usually result in tool breakage after very short service periods and is currently one of the main failure causes in tools made of cold work and high speed steels with carbon concentrations exceeding 0.8% by weight. Retained austenite problems have become particularly common with the widespread changeover from brine hardening processes with subsequent oil quenching to the more recent vacuum hardening technology with its lower quench rates. Depending on the furnace load situation, the quench rates in vacuum hardening vary between those typical of oil and air quenching and those achieved with slow cooling under ambient air conditions. Classic oil hardening steels such as hot work tool steels or high speed steels will often fail to reach the necessary through hardening quench rate, especially if the product is fairly large sized.

Fig.11 shows the coarse grained martensitic tempered structure of a cold forming die (140 mm diameter) made of X155CrVMo12-1 steel (material No. 1.2379). At 30%, the retained austenite level in this tool is quite significant. The failure of this die occurred soon after it was commissioned; it fractured along its interior radius. The hardness of this structure is 61 HRC, it was heat treated under vacuum (5 bar) at 1040℃ with two tempering cycles at 540℃. The hardening and tempering steps were performed as part of a single cycle under vacuum. The root cause of the failure in this case was the high portion of retained austenite which was apparently able to stabilize due to a too slow passage through the martensite stage; moreover, the tool was not allowed to cool down to a sufficiently low temperature after the hardening process and between tempering cycles. To achieve a full martensitic transformation, the quench rate would have to be increased by raising the gas pressure and adopting a more loosely spaced furnace load envelope. After the hardening process and between tempering steps, the product should be allowed to cool down to room temperature to enforce the fullest possible martensitic transformation, particularly after the hardening step. Experience has shown that a common hardening and tempering cycle under vacuum does not favour the achievement of a full martensitic transformation. For economic reasons, the cooling phase after the hardening step and between tempering steps is often set too short; the furnace is frequently fired up for tempering again as soon as the product has cooled to 50 - 70℃. However, in vacuum hardening the product should ideally be quenched to room temperature as quickly as possible. Unlike the oil quenching process following brine hardening, in which the tools are transferred to a tempering furnace to prevent cracking by reheating to about 70°C, vacuum hardening itself entails no cracking risk since the process passes through the martensite stage much more slowly. As a result, the tool should be quenched to room temperature to achieve the fullest possible degree of martensitic transformation. If the martensite stage is passed too slowly and the tool cannot cool down far enough, stabilized retained austenite will remain present. It transforms but sluggishly and incompletely during the subsequent tempering stage, particularly if the tool is not allowed to cool to room temperature after the tempering cycles. The tendency for retained austenite to stabilize will become more acute with large tool dimensions and/or full furnace loads. With all tools made of cold work or high speed steels, which are expected to exhibit maximum toughness and high hardness at the same time, care should therefore be taken to provide maximum quench rates and a generous furnace load spacing. In the case of large hot work tools such as casting dies, an increased cracking risk lies in the high thermal stresses between the edge and the core, so that a hot bath soak cycle at about 500°C is recommended.

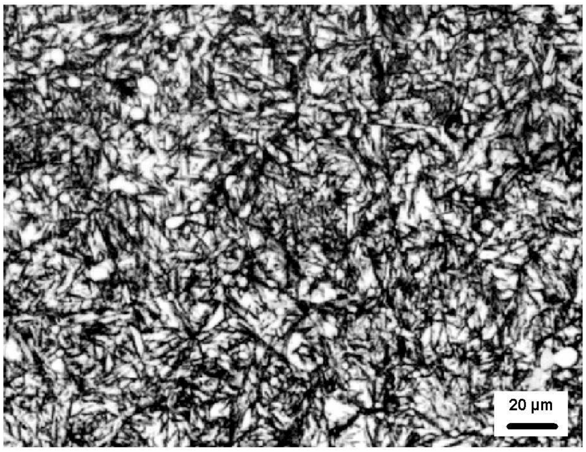


Figure 11. Martensitic hardening structure of a cold work die with large amounts of retained austenite (Etchant: 3% HNO_3).

Another structural state often associated with an elevated cracking risk is inadequately tempered martensite. Its presence may be attributable to an insufficiently high tempering temperature, or to incomplete tempering at higher temperatures. Fig.12 shows such a microstructure in a hob cutter made of HS6-5-2-5 steel (material No. 1.3243) and hardened to 66 HRC. This tool failed through premature tooth breakout. A large portion of inadequately tempered, only marginally stress relieved martensite is evident as a brighter structural area, particularly in the inner grain regions. On principle this deficient tempering state reflects the same mechanisms as the high retained austenite levels discussed above. But in this structure the retained austenite has already been transformed to martensite, part of which will be present in a sufficiently tempered state after the last tempering step. Due to the high portion of insufficiently tempered martensite, a microstructure of this type is extremely susceptible to fracturing, particularly at hardnesses exceeding 60 HRC.

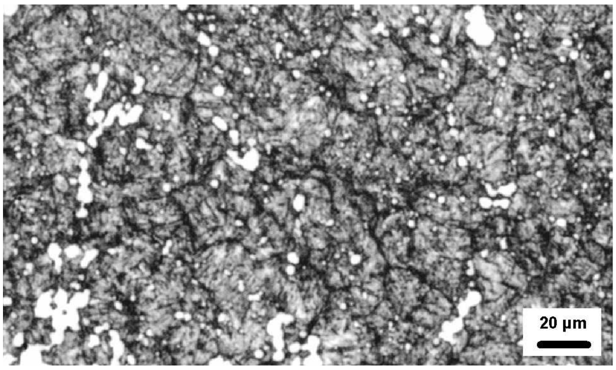


Figure 12. Martensitic hardening structure of a hob of steel grade HS6-5-2-5 (steel number 1.3243) with insufficient tempered martensitic structure (Etchant: 3% HNO_3.)

Grain boundary carbides. A reduced toughness in high alloyed tool steels will also be observed with microstructures of the type illustrated in Fig.13. The picture shows a $40 \times 40 \times 20$ mm^3 stamping tool made of X153CrMoV12 grade steel (material No. 1.2379), quenched and tempered to 61 HRC, which fractured soon after its first use. The heat treated structure consists of an inadequately tempered martensite which additionally exhibits carbide banding along the grain boundaries. This pattern reflects too slow cooling in the proeutectoid carbide precipitation range between 800 and 600°C. Such carbide precipitation reduces the toughness of the material in the grain boundary areas and will often result in intergranular fracturing under load. No handy remedy exists in this case, since the grain boundary carbides are virtually impossible to remove even by renewed heat treatment.

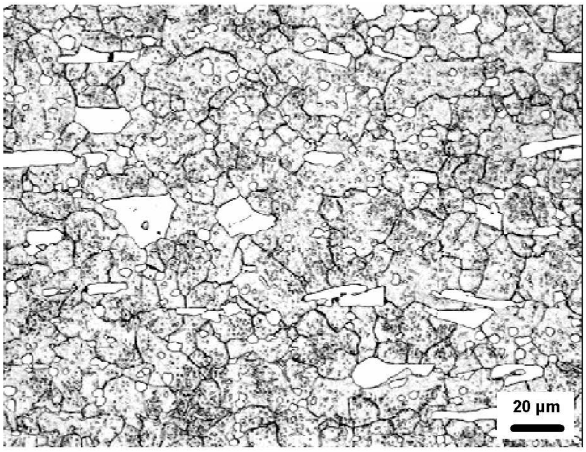


Figure 13. Low tempered hardening structure of a blanking tool of steel grade X153CrMoV12 (steel number 1.2379; D2-type) with carbides, layered on the grain boundaries (Etchant: 3% HNO_3).

SUMMARY

The examples presented can illustrate only a small portion of the cases documented in the failure register. However, they were selected with a view to highlighting currently topical failure modes - specifically heat treatment failures of the type now regularly degrading tool performance.

At the machining level, overheating during grinding operations as a result of reduced cooling (water based grinding emulsions, minimal lubrication) are more frequent today. In erosion machining, fusion zones resulting from coarse erosion finishing are often a source of tool failure. Among heat treatment defects, quench stress cracking deserves to be mentioned although it occurs more frequently in large hot work tools and is largely due to design. In tools made of high alloyed cold work and high speed steels, high retained austenite levels and insufficiently tempered martensitic hardening structures are a cause of concern; these phenomena often occur in conjunction with carbide precipitation along the grain boundaries which usually reflects an insufficient quench rate in vacuum hardening processes and inadequate cooling between tempering phases. Such microstructures will often form during common hardening and tempering cycles in a vacuum hardening furnace when the furnace is charged to full capacity. The economic benefits gained by this process should therefore be carefully weighed against the existing tool failure risks.

As is evident from these examples, newly launched manufacturing methods (such as grinding with minimum lubrication, erosion-machining or vacuum hardening) will usually give rise to new problems which may initially have a detrimental effect on tool performance. An analysis of these cases and the resulting findings are indispensable for making the often significant potential of these new manufacturing methods fully accessible through implementation of appropriate optimizing steps.

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Table 1. Classification of sorts and causes of failures within the Tool Failures Register

1 sorts of failures
   (a) fracture / shelly spots
   (b) wear
   (c) cold weld / seizing
2 failure causes
   (a) design failures
      i forming failures / dimensioning
      ii wrong choice of material
      iii wrong working hardness
   (b) defects in material
      i pores, shrink hole, cracks, strange inclusions
      ii distribution of carbides
      iii undue segregations
   (c) machining failures
      i bad surface quality (notch effect)
      ii damages on surface (grinding failures, erosion failures)
      iii welding defects (joint welding, deposit welding)
      iv nitriding failures
      v missing stress relieving
      vi distortion
   (d) heat treatment failures
      i quench stress crack
      ii decarburization
      iii retained austenite
      iv insufficient tempering stage
      v coarse grain/mixed grain
      vi superheating
      vii precipitations on grain boundary
   (e) handling failures
      i mechanical overstressing
      ii thermal overstressing
      iii corrosive overstressing