

Influence of the fabrication method on the wear resistance of hot forging dies

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Abstract Tools used for hot forging are subject to simultaneously acting process-related high mechanical, tribological, chemical and thermal cyclic loads. In comparison to other manufacturing methods, the resulting load spectrum leads to a failure of the form-giving tool components after a short tool life. Wear is the main reason for die failure in hot forging processes, accounting for 70 % of all causes. Other kinds of failures are thermal and mechanical cracks as well as plastic deformation (a result of the loss of hardness due to the high thermal charge). In order to reduce wear, several kinds of wear reducing methods are subject of industrial applications as well as research works. For example, nitriding and optional thin hard coating or overlay welding are effective methods to increase the wear resistance of hot forging dies. Beside the process related stresses during the service, manufacturing of forging tools itself initializes microstructural changes in their subsurface zones. During fabrication, the general influence of the fabrication method on the tool lifetime has not been considered so far. The implementation of the knowledge of this influence into the fabrication process could lead to an increased productivity of hot forging processes without using expensive and complex wear reducing methods.

Keywords Hot forging · Wear resistance · Cracks · Hot working steel · EDM · HSC · Martensite

1 Introduction

Hot forging processes are characterized by severe loads. These loads act simultaneously, which leads to several kinds of die failures. Particularly, the thermal conditions lead to initial failures in the form-giving tool parts by initiating a material softening in the edge layers. The loss of hardness in the edge zones leads to a reduced resistance against abrasion. In addition to thermal and mechanical surface cracks, a continuously advancing surface abrasion is the consequence. The work environment of hot forging processes is a non-vacuum environment without the use of inert gas. Due to this environment, the oxidation process on the surface of the work-pieces is unavoidable and hard particles (like forging scale) cause extensive abrasive wear. Furthermore, adhesive wear occurs as a result of the temperature-increased reactivity of the tool material and the workpiece.

The applied lubricant and the cooling medium protect against high temperatures but also intensify the cyclic thermal stress. Wear mechanisms occurring at hot forging dies are described in Fig. 1.

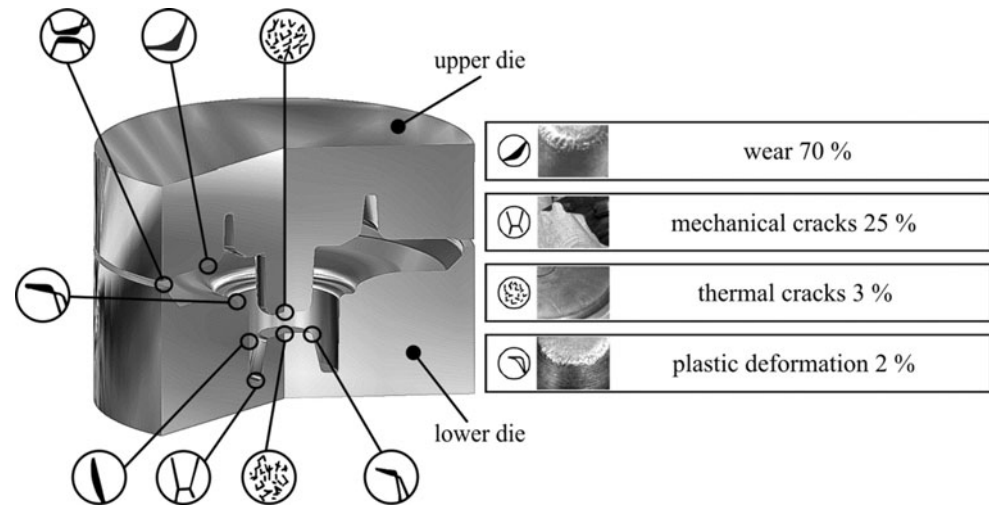
During production these mechanisms lead to the failure of the form-giving die parts causing enormous costs for the forging industry. Previous methods of wear reduction were successfully examined in several research works and implemented in industrial processes.

1.1 Methods of wear reduction for forging tools

As shown in several research works, thin layers with higher hardness than the basic material, supported by nitrided cases, were effectively used to increase the wear resistance of forging dies. The effect of a combined coating of thin boron-containing PACVD layers (about 3 µm) and

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Fig. 1 Failure causes of hot forging tools [17]



nitriding on the tool lifetime quantity is shown in [1, 2]. The additional coating increases the tool lifetime up to 50 % compared to merely nitrided dies. In [3, 4] forging dies for gears were coated with titanium in combination with boron cover layers in a duplex nitriding process. The nitride layer supports the coating and reduces chipping as well as material adhesion [5]. In [6] laser alloyed and nitrided dies were successfully used to increase the tool life time quantity. The effect of only nitrided dies on the tool life time was investigated in [7]. Here, the wear resistance of forging dies could be increased significantly but the variance was high with an average ratio of 50 %.

Positive influences of martensite layers on the surface of forging dies are demonstrated in [8, 9]. The formation of martensite in the edge layers of hot forging dies is forced by lowering the eutectoid-temperature using manganese as additional alloying element. An increased wear resistance of the tools could be directly correlated with the martensite layers in different forging applications. In contrast to this positive effect of martensite layers on the tool life, also negative effects are documented in the literature. In [10] the formation of martensite was held responsible for early die failure on the example of a punching tool for Hatebur forging units.

All of the described methods lead to additional costs for special treatments or investments in new technologies. The majority of the companies in the forging industry are small and medium sized enterprises (SME). Particularly, SME enterprises are interested in comparably cheap methods of wear reduction.

The general influence of the fabrication method on the tool life in forging dies was examined at the Institute of Metal Forming and Metal-Forming Machines (IFUM). The research project was founded by the German Research Foundation (DFG). It could be demonstrated that microstructural changes in the edge layers influence the tool life.

The choice of the manufacturing method can lead to a higher wear resistance and an enhanced tool life without additional wear reducing treatments.

1.2 Outline of the article

In Sect. 2, the chosen manufacturing methods for forging dies are defined with respect to the resulting microstructural edge layer conditions. This was necessary to manufacture forging dies with defined edge layer conditions. The resulting edge layer changes are typical for the appropriate fabrication method. Therefore, the occurring die wear could be correlated with the different edge layer conditions and with the manufacturing methods.

The manufactured dies were then adopted in serial forging tests to investigate the wear behaviour. To characterize the wear behaviour, tactile contour measurements, photographic and metallographic documentations as well as micro hardness measurements were carried out. The corresponding results are presented in Sect. 3. Finally, in Sect. 4 a conclusion and future outlooks were given.

2 Fabrication routes

All analyses were accomplished based on the example of the hot working steel 1.2367 (X38CrMoV5-3, AISI H10 + Cr). First of all, the influence of turning with subsequent hardening and electro discharge machining (EDM) as well as high speed cutting (HSC) on the edge layer conditions were examined. For this purpose, specimens for beam impact tests were manufactured and the ductility as well as the general influence on the edge-layer texture were investigated in previous works [11, 12].

Turning with subsequent hardening led to the least microstructural changes within the edge layers with respect

to residual stresses, hardening effects or mechanical damages (example: cracks). Regarding EDM and HSC, the manufacturing parameters were diversified and characteristic impacts on the edge layers were examined.

2.1 Electrical discharge machining (EDM)

The EDM process parameters are combined in a set of parameters by the VDI 3400 guide line. The classes are defined by the resulting surface roughness (Table 1).

A solidification process of the melted material on the part's surface is the major impact of the EDM process on the edge layer condition. The size of the affected zone rises with an increasing VDI class number. The electric amperage and pulse time are known as the main parameters affecting the size of the solidification zone [13]. To

examine the influence on the tool life, two different sets of parameters were chosen (K15 and K30). EDX- and XRD-analyses were performed to characterize the composition of the resulting zone within the project. With the help of the EDX-analysis, possible fusing of copper on the tool's surface was investigated. The fusing of copper onto the tool's surface could lead to a reduction of hardness in the surface zones depending on the part or electrode material [14].

Figure 2 depicts, that during the eroding process a local fusing of copper is possible but only occurs at a very small ratio. Micro hardness measurements, down to a minimum load of 10 mN, were examined for a large number of specimens. A loss of hardness could not be detected [12].

To characterize the microstructure of the layers XRD-analyses were examined as shown in Fig. 3.

Table 1 Eroding classes by VDI 3400

VDI class	12	15	18	21	24	27	30	33	36	39	42	45
R _a (µm)	0.4	0.56	0.8	1.12	1.6	2.24	3.15	4.50	6.30	9.0	12.5	18.0

Fig. 2 EDX-analysis of eroded specimen at the white edge layer and the basic material

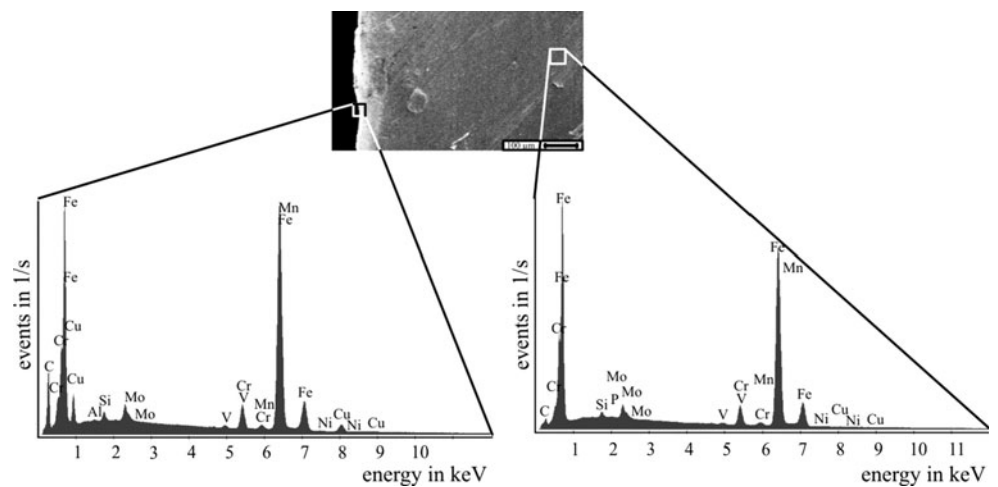
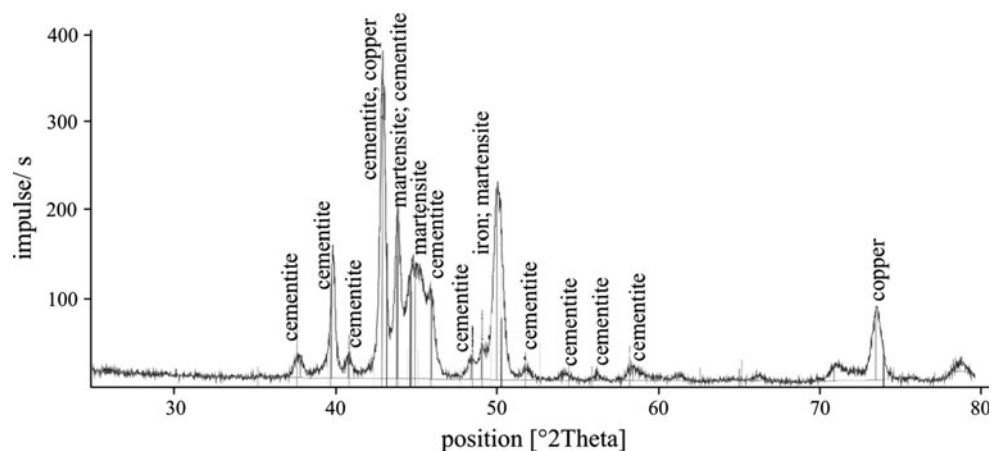


Fig. 3 XRD-analysis of the white edge layer of an eroded specimen



The microstructure of the white layers is martensite with a high amount of the iron carbide cementite. This result correlates with light microscope microstructure analyses and the micro hardness measurements [12]. The formation mechanism of the white edge layer is therefore a transformation hardening. During the melting process, the ferrite structure changes into austenite. The following charge abrasion together with the dielectric fluid lead to a rapid solidification process and the result is a basic martensite structure.

2.2 High speed cutting (HSC)

The experiments with high speed cutting processes were carried out by varying the parameters v_c (cutting rate), a_p (cutting depth) and f_z (tool feed speed). They were executed by a multifactorial diversification in the process parameters as shown in Table 2.

Depending on the parameters, the plasticity of the machined part rises and the short cyclic mechanical and thermal charges can lead to hardening effects in the edge layers [15]. The major impacted zone is located in a very small edge layer and mostly removed with the milling chips. In any case, a total removal of the impacted zone does not take place and as a consequence, the affected areas remain in the edge layers of milled parts. To examine the influence of these edge layers on the performance of hot working tools, defined parameters were chosen to obtain a maximum impacted zone. A clear correlation between the varied parameters and the size of the affected zone could not be found within the arranged investigations. Additionally, the impacted zones are very thin with an average size of about 2 μm . For the tool life quantity tests the set of parameters from experiment 15 were chosen. This set of parameters led to a white layer up to 2 μm .

2.3 Residual stresses after fabrication

Residual stresses are known as the major influences of the fabrication method on microstructural edge layer conditions. To characterize the remaining residual stresses after

the fabrication, XRD-analyses were carried out. A clear dependence of the fabrication method on the residual stresses was examined as demonstrated in Fig. 4.

The wear level of hard machine tools could significantly influence the residual stresses [16]. For this reason each die used in the forging tests was produced with a completely new tool.

2.4 Manufacturing impacts on edge layer conditions

In addition to the XRD-analyses, surface roughness measurements and beam impact tests were carried out to evaluate the influence of the manufacturing method on the surface roughness and ductility in the case of the chosen parameters.

The major impacts of the considered fabrication methods and parameters are presented in Table 3.

After the general investigation of the major fabrication-induced edge layer impacts, forging tests and wear investigation were carried out to correlate these impacts with the tool lifetime.

3 Forging tests and wear investigations

Raw parts consisting of C45 (1.0503/AISI 1043) with a diameter of 30 mm and a length of 40 mm were used on an

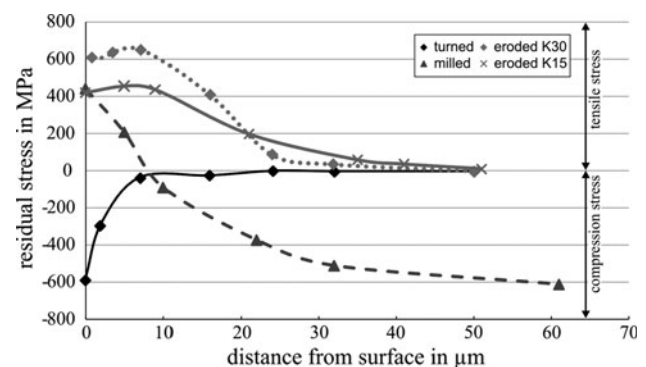


Fig. 4 Residual stresses after fabrication

Table 2 Parameter table for HSC-experiments

Experiment	1	2	3	4	5	6	7	8	9	10
v_c (m/min)	120	120	120	120	120	120	120	120	120	180
f (mm)	0.12	0.12	0.12	0.15	0.15	0.15	1.17	0.17	0.17	0.12
a_p (mm)	0.25	0.5	0.75	0.25	0.5	0.75	0.25	0.5	0.75	0.25
Experiment	11	12	13	14	15	16	17	18	19	20
v_c (m/min)	180	180	180	180	180	180	180	180	250	250
f (mm)	0.12	0.12	0.15	0.15	0.15	0.17	0.17	0.17	0.15	0.17
a_p (mm)	0.5	0.75	0.25	0.5	0.75	0.25	0.5	0.75	0.25	0.25

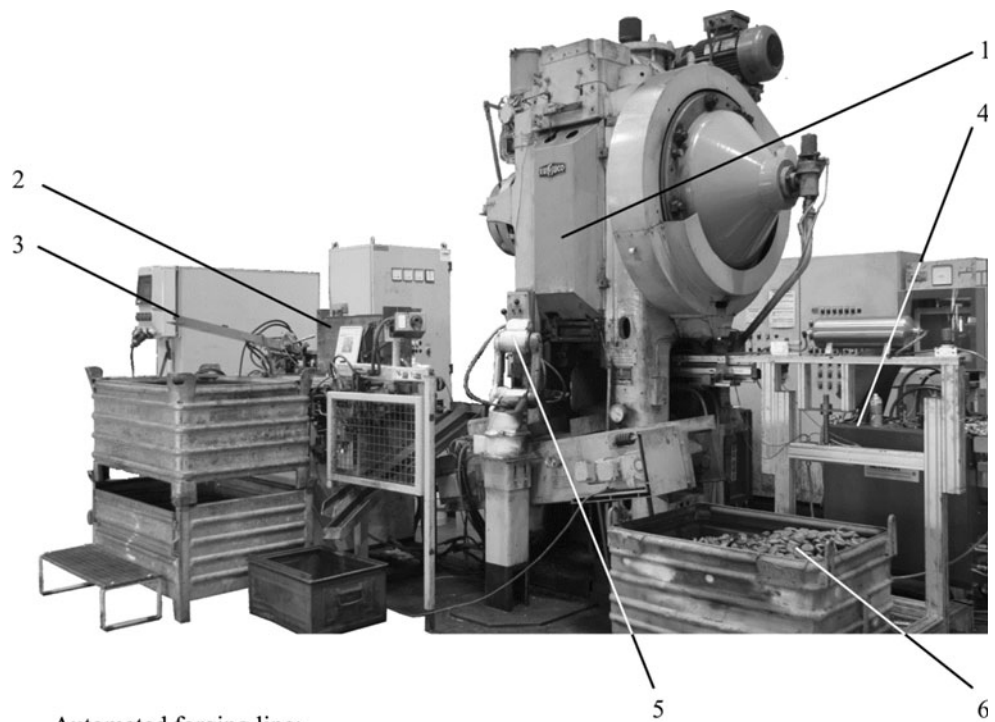
Table 3 Major impacts of the examined fabrication routes

Fabrication	Turning	HSC	EDM (K30)	EDM(K15)
Edge hardening	No	Yes, not penetrable with Vickers test	Approx. +50 % HV0.1	Approx. +50 % HV0.01
Residual stress (surface distance)	Compression stress (0–10 μm)	Tensile stress (0–10 μm) Compression stress (>60 μm)	Tensile stress (0–50 μm)	Tensile stress (0–40 μm)
Texture change (max. surface distance)	No	White layer (0–2 μm)	White layer (0–15 μm)	White layer (0–4 μm)
Surface roughness (R _a) (0 °/90 °)	0.44/0.49	0.35/0.26	3.41/4.03	0.52/0.52
Ductility	22 J	21.5 J	20 J	Unstated
Crack formation	No	No	Yes	Yes

eccentric press with a 315 tons pressing force (Fig. 5). This press is equipped with an automated billet handling, suitable for long term tests. Constant and reproducible process parameters were guaranteed by additional equipment, such as a tool heating device and an automated cooling and lubrication. The heating of the billets up to 1,150 °C is performed in an inductive furnace. The process operates with an average cycle time of about 7 s for each forged part. For all tests, a die temperature of 150 °C was chosen.

To characterize the tool performance and to correlate it with the process-induced edge layer impacts, the following was carried out: tactile contour-, topography-, residual stress- and micro hardness measurements and metallographic analyses.

Fig. 5 Automated forging line for long term tests



Automated forging line:
 1 - forging press
 2 - induction heating device
 3 - raw material feeder

4 - cooling and lubrication device
 5 - handling device
 6 - forgings

3.1 Visual comparison and tactile contour measurement

First, a visual comparison was performed (Fig. 6). The comparison shows a difference in the wear behaviour with regard to the fabrication route. In contrast to the eroded tools, the turned and milled tools show heavier mechanical and thermal cracks on the center radius as well as plastic deformation on the radius and along the flank. In the case of the milled tool, extensive damage is also caused to the center cone.

To quantify the occurring wear, tactile contour measurements were performed. For this purpose, a combined contour and topography analyzer T8000 RC by Co.

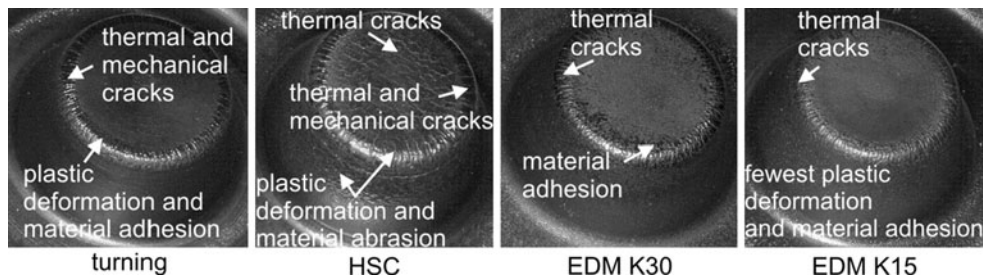


Fig. 6 Visual comparison after 2,000 forgings

Hommel-Etamic was used. An evaluation software based on MATLAB was developed for this purpose. In contrast to the system-immanent software, the newly developed software can compensate effects like warm deformation. Furthermore, different areas of the tools can be compared easier than with the original software. Figure 7 depicts an exemplary profile of a contour measurement with a graphical banking factor of 10.

The tools were removed from the process and measured after 500, 1,250 and 2,000 forging cycles. The defined tool areas 1–9 were compared for each manufacturing method. The results of the contour measurements, in dependence of the fabrication and forging cycles, are illustrated in Fig. 8a–d. To differentiate material adhesion from material abrasion, the measured data were separated into negative and positive deviation from the geometry before forging.

Each of the figures describes the deviation from the original geometry after 500, 1,250 and 2,000 forging cycles. The values are generated by the mathematic average of six profiles allotted over the perimeter. Positive deviations are caused by material adhesion or plastic deformation. Negative aberrations are caused by plastic deformation or material abrasion. To differentiate among plastic deformation and material abrasion as well as adhesion, additional investigations will be displayed.

An initial differentiation by the tactile measurements can be made. In the case of the milled tool, the occurring negative aberrations show the same absolute value as the positive aberrations. Hence, material bulk is a more probable result of plastic deformation than material adhesion. In the case of the eroded tools, basically positive geometry

aberrations occur. Material adhesion is probable. Altogether, an increased geometry change can be detected for all defined tool areas in the case of the turned and milled dies.

In the case of the eroded dies, positive and negative aberrations do not occur simultaneously. Material adhesion without plastic deformation is the main wear mechanism. In case of the turned and milled tools, material abrasion as well as plastic deformation occurs. In the areas 1 and 9 only negative deflections are found. And in areas 4 and 6 negative as well as positive deflections could be determined. Supposedly, the main wear mechanisms are plastic deformation and material abrasion. Thus, the eroded tools show a highly increased resistance against plastic deformation and material abrasion up to 2,000 forging cycles.

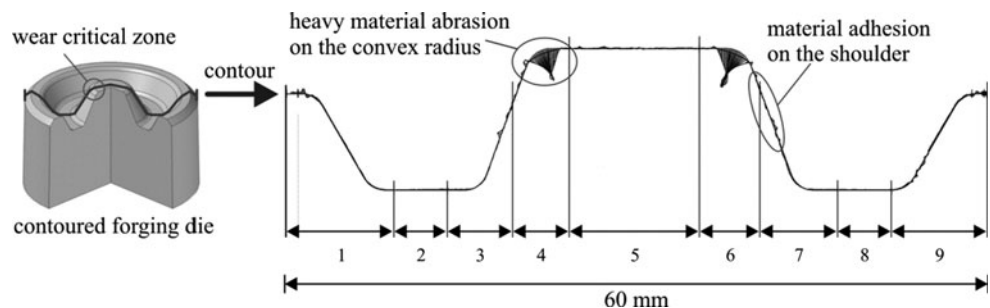
To evaluate the entire wear across the contour, additional investigations were carried out. Six contour profiles, allotted over the diameter, were measured and the entire wear was defined by the following formula with the number of profiles “n” and the tool area “i” according to Fig. 7.

$$\text{Total wear} = \frac{1}{n} \sum_{i=1}^9 (\max . \text{positive aberration}_i + | \max . \text{negative aberration}_i |)$$

The total wear in dependence of the fabrication methods is shown in Fig. 9. Each bar results from the mathematic average of six profiles.

The total wear investigation depicts that in case of the K15 eroded die, the wear was reduced by a factor of 2.2

Fig. 7 Contour profile with defined tool areas



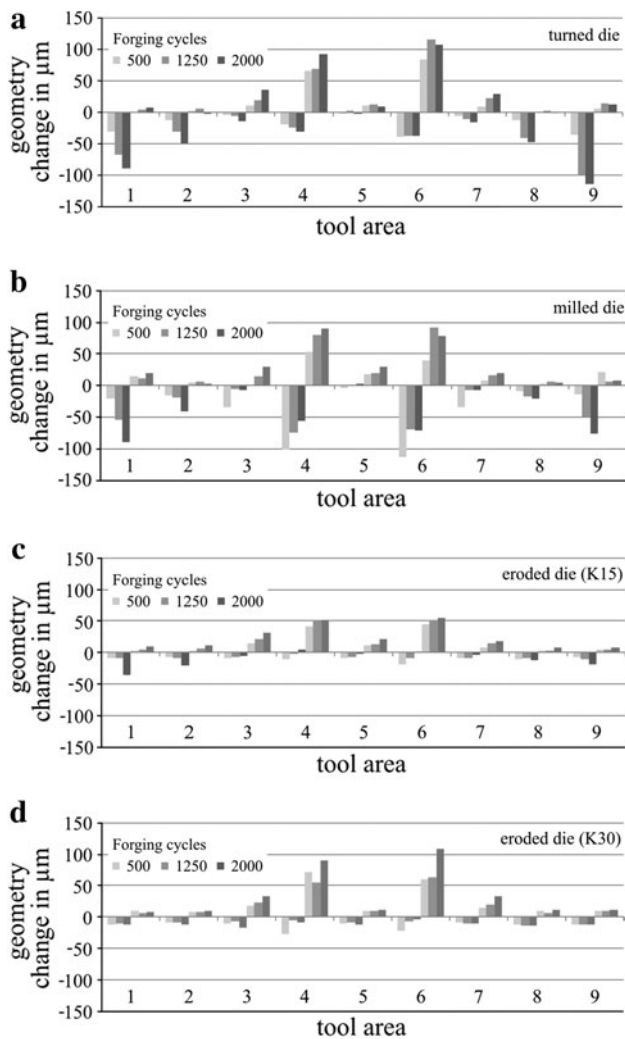


Fig. 8 **a** Average geometry deviations for the turned die. **b** Average geometry deviations for the milled die. **c** Average geometry deviations for the eroded die (K15). **d** Average geometry deviations for the eroded die (K30)

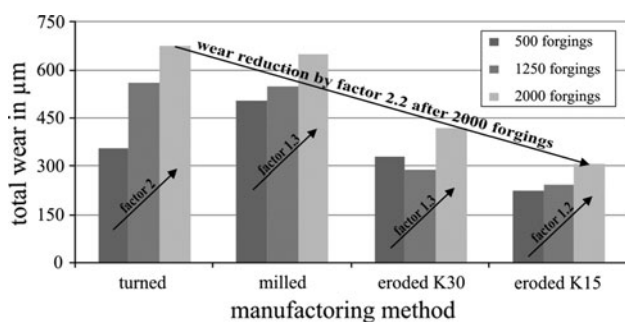


Fig. 9 Total wear and factor of wear increase

compared to the turned die. The increase of wear between 500 and 2,000 forgings is also small compared to the turned die. In the case of the milled die, a comparatively low wear increase was found as compared with the turned die. But in

relation to the eroded dies, the wear was significantly higher after 500 forgings.

In comparison of the eroded dies, a reduced wear was measured at the variant K15. The white layer of this variant was at its maximum 4 μm deep, compared to 15 μm at the variant K30. Therefore, eroding with higher amperage and deep white layers is not the best option for receiving a high wear resistance. It could be demonstrated that deep layers (K30) are suitable for reducing crack depth but show also a higher vulnerability to material adhesion.

3.2 Metallographic analyses and micro hardness measurements

In Fig. 10 metallographic analyses of the wear-critical zones are shown to evaluate crack formations, remaining martensite areas and heat affected zones.

On the basis of the metallographic analyses, a heat-affected zone was detected on the convex radius. The highest values of material abrasion occur in this area. This can be explained with the loss of hardness. The measurement of micro hardness showed a loss of about 200 HV0.1 for all variants. An effect of the fabrication-induced microstructural edge layer changes on the soft annealing process could not be detected (see Fig. 12).

As estimated before in the tactile contour measurements, the eroded tools show material adhesion but less material abrasion than the milled and turned dies. In the case of the K30 eroded die, remaining martensite could be identified. This proves that martensitic layers can resist up to 2,000 forging cycles. Beneath the martensite layer, almost no surface damage could be detected. In comparison to the K15 eroded die, more material adhesion occurs. The milled and turned tools show less material adhesion and larger cracks, as well as plastic deformation. Material adhesion can be found in particular areas but less than at the eroded tools. To estimate the crack depth the cracks were measured with a light optical microscope. The results are compared in Fig. 11. The tool areas 1–5 are analogous to Fig. 7.

Figure 11 does not evaluate the number of cracks appearing in each zone and the crack width. Within a qualitative evaluation on basis of the metallographical analysis, a higher vulnerability of the forging dies to more and wider cracks can be found for the milled and turned dies.

A correlation between the crack depth and the manufacturing method is found in this investigation. In nearly all die zones a comparatively reduced crack depth could be determined for the eroded tools. In case of the K30 eroded die, the cracks are comparatively less deep. The reduced crack depth could be directly correlated with the martensite layers which were most distinct in this tool. In all tool areas the deepest cracks occur at the milled dies.

Fig. 10 Metallographic analysis at wear critical zone after 2,000 forgings

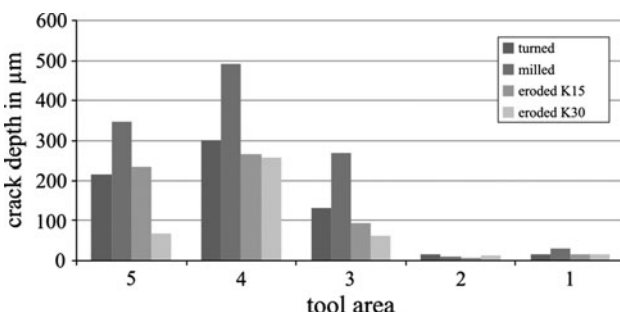
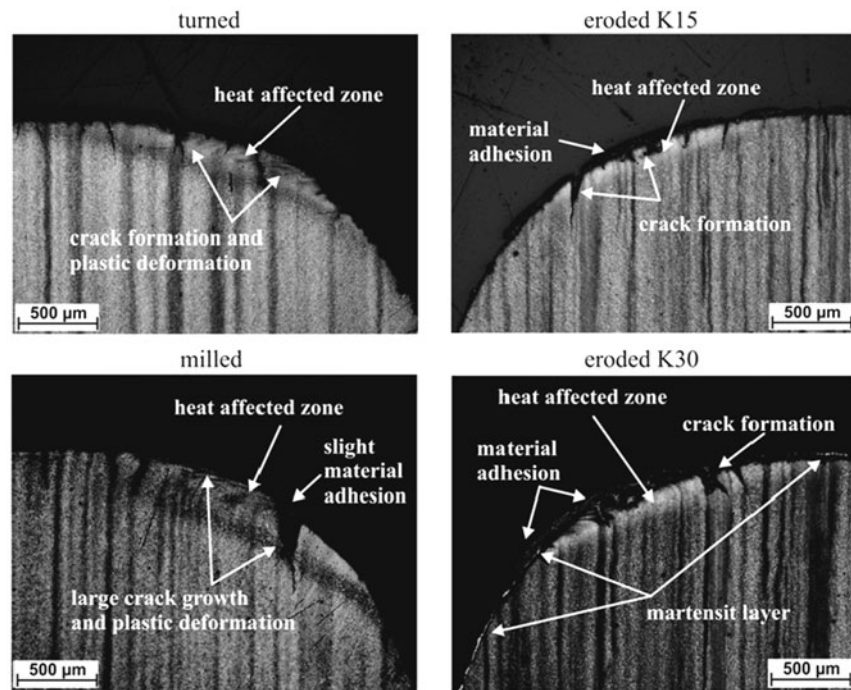
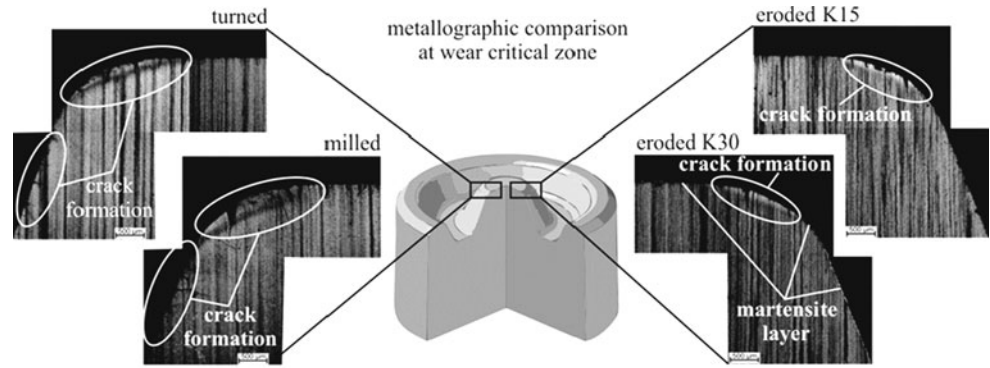


Fig. 11 Comparison of crack depth after 2,000 forgings

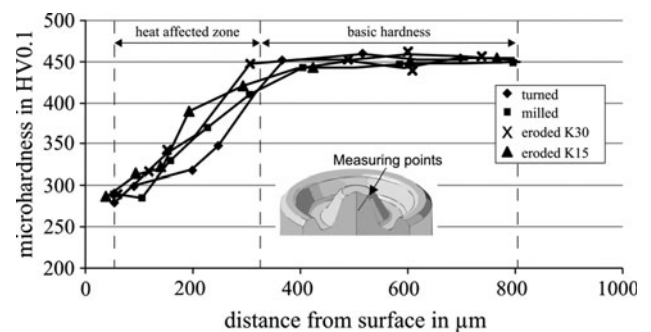


Fig. 12 Micro hardness measurements at convex center radius

To analyze the heat-affected zone in the convex die radius, micro hardness measurements were arranged. The results are shown in Fig. 12.

Figure 12 illustrates that the thermal impact led to a heat annealing process for all variants in the same intensity. A loss of hardness of about 150 HV0.1 could be figured out.

The loss of hardness in this zone could be the main reason for the failure of the martensite layers. As shown in Fig. 10 the martensitic layer of the eroded die (K30) remains on the surface of all tool areas even after 2,000 forgings except for the area of maximum thermal impact. By measuring the micro hardness inside the white layer, it is found that the

hardness of the layers is not influenced by the thermal impact. The result is that the hard martensite layer remains on a comparatively soft basic material and material chipping is unavoidable.

3.3 Residual stresses after forging

The measurements of residual stresses, carried out after 2,000 forging cycles, show about the same values for all variants in the edge layers. The surface tensile and compression stresses at the eroded and milled dies disappear up to 2,000 forgings. Therefore, a correlation between the fabrication-induced residual stresses and the tool performance could not be established within this research work. Nevertheless, a fast elimination of the tensile stresses due to process-related high temperatures could be responsible for the positive performance of eroded tools in contrast to other applications. Further investigations with tensile stress measurements after lower forging cycles are necessary. An effect on the die wear might exist up to a certain number of forging cycles.

4 Conclusions

The manufacturing method causes initial damages and microstructural changes to the subsurface areas of hot forging dies. This research work demonstrates the influence of these factors on the tool lifetime of hot forging dies. In the frame of this work, turned, high-speed-milled and eroded tools were manufactured and adopted in an automated serial forging process.

A significantly higher influence on the wear resistance could be found regarding the eroded dies. The EDM process leads to a melting and solidification process in the edge layers. The resulting microstructure was characterized as a martensite structure with a large amount of ironcarbide and a highly increased hardness. Furthermore, initial crack-formation occurs in this layer. In contrast to the other manufacturing processes, the eroding layers in combination with the resulting topography could be directly correlated with an increased wear resistance. It could be demonstrated that the martensite layer partly remains up to 2,000 forging cycles. The main reason for the failure of the layers is a soft annealing process in the basic material under the layers. By the reduced hardness of the microstructure, the comparatively hard martensite layer could not be supported. Mechanical spalling is probable.

As shown in the first chapter Sect. 1, thin hard layers or martensite layers could lead to a significantly higher wear-resistance of hot forging dies. In principle, the martensite layers (as remaining microstructure from the eroding process) are comparable to the demonstrated methods in the first

chapter. Even if the structure is not homogeneous and initial crack formation occurs in dependence of the eroding parameters, a significantly higher wear-resistance could be directly correlated with these layers within the demonstrated investigations. The requirements for the adherence to the basic materials are identical to the mentioned wear reducing methods. The main reason for the failure of thin hard layers on a comparatively soft substrate is an abrupt change of hardness. Therefore, an additional nitriding of eroded dies probably leads to an additional enhancement in tool life.

Further investigations on this topic have to be performed to investigate the influences of martensite layers (as result of the eroding process) and additionally nitrided dies on the lifetime of forging dies.

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References

- Bistron M, Behrens B-A, Paschke H (2010) Reduction of wear by boron based multilayer coatings on forging dies. In: Proceedings metal forming 2010, 13th International Conference, Steel Research International 81/9, pp 290–293. ISBN 978-3-514-00754-3
- Behrens B-A, Bräuer G, Paschke H, Bistron M (2011) Reduction of wear at hot forging dies by using coating systems containing boron. *Prod Eng Res Dev*. doi:10.1007/s11740-011-0308-z
- Behrens B-A, Bach Fr-W, Denkena B, Möhwald K, Deißer T, Kramer N, Bistron M (2009) Manufacturing of reinforced high precision forging dies. *Steel Res Int* 80:878–886
- Bistron M, Behrens B-A, Bach Fr-W, Möhwald K, Deißer T (2010) Reduction of wear by using boron containing thin coatings at forging of helical gears. In: Proceedings of the 16th International Symposium on Plasticity: “Finite Plasticity and Viscoplasticity of conventional and Emerging Materials”, pp 187–189. ISBN:0-9659463-2-0
- Weber M (2005) „Neue Schichtsysteme für die Umformtechnik - Werkzeugbeschichtungen für die temperierte Umformung. Beschichtete Werkzeuge – höhere Wirtschaftlichkeit in der Ur- und Umformtechnik“, Workshop EFDS, Dresden 2005
- Industrielle Gemeinschaftsforschung 16587 N (2010) „Nitrierte Werkzeugrandzustände für Schmiedegesenke - Anpassung an das Beanspruchungsprofil des Schmiedeprozesses“, Stiftung IWT Bremen
- Klümper-Westkamp H (2009) „Optimierung der Randschichtzusammensetzung durch Nitrieren von Werkzeugen der Warmmassivumformung zur Steigerung der Lebensdauer“, Studie, Industrieverband Massivumformung
- Pfahl A, Puchert A, Behrens B-A, Bach F-W (2009) Wear reduction of forging dies by new alloy development—the influence of manganese on the reduction of the A_{c1b} -temperature. *HTM* 64-5, pp 291–296
- Puchert A, Pfahl A, Behrens B-A, Bach Fr-W (2009) Increasing the wear resistance of hot working steel by lowering the eutectoid temperature. *Advanced Metal Materials and Technologies*, St. Petersburg, pp 46–56

10. Buchmayr B (2011) Reparaturtechnologien – Übersicht der Möglichkeiten. Workshop Schmiedewerkzeuge Technologien – Entwicklungen – Analysen. ISBN 978-3-902078-16-2
11. Behrens B-A, Yilkiran T (2011) „Präzise Herstellung sichert fehlerfreien Umformprozess“, MM Maschinenmarkt, Ausgabe 6, Vogel Business Media, pp 26–29
12. Yilkiran T (2010) „Untersuchungen zu den Randzonenbeeinflussungen von Werkzeugen für die Warmmassivumformung infolge verschiedener Fertigungsverfahren“, UTF Science, Meisenbach Verlag, pp 1–12
13. Grosch J (1989) „Einfluß der funkenerosiven Bearbeitung auf Gefüge und Eigenschaften verschiedener Stähle“, Dr.-Ing. Dissertation, TU Berlin
14. Habedank G (2004) „Neuartige Bearbeitungsverfahren zur Modifizierung senkerodierter Randschichten“, Dr.-Ing. Dissertation, Shaker Verlag Aachen. ISBN: 978-3832236267
15. Pouteau P (2009) „Einfluss charakteristischer Werkstoffeigenschaften auf die Werkstückrandschicht und Spanbildung beim Hochgeschwindigkeitsdrehen“, Dr.-Ing. Dissertation, TU Bremen. ISBN: 978-3-8322-9015-3
16. Denkena B, Boehnke D, Meyer R (2008) Reduction of wear induced surface zone effects during hard turning by means of new tool geometries. *Prod Eng Res Dev* 2:123–132. doi:[10.1007/s11740-008-0089-1](https://doi.org/10.1007/s11740-008-0089-1)
17. Doege E, Behrens B-A (2010) „Handbuch Umformtechnik: Grundlagen, Technologien, Maschinen“, Springer, Berlin. ISBN: 3540234411