A Case Study for a Worn Tool Steel in the Hot Stamping Process

JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY 2023;22:1065–1075

Available online at www.sciencedirect.com

jmr&t
Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Original Article

A case study for a worn tool steel in the hot stamping process

Miwen Yuan [a,b], *Seshendra Karamchedu* [c], *Yicheng Fan* [d], *Libin Liu* [b], *Lars Nyborg* [a], *Yu Cao* [a,*]

[a] *Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg 41296, Sweden*
[b] *School of Materials Science and Engineering, Central South University, Changsha 410083, PR China*
[c] *Uddeholms AB, Hagfors 638 85, Sweden*
[d] *ASSAB Tooling Technology (ShangHai) Co., Ltd, Shanghai 201108, PR China*

ARTICLE INFO

Article history:
Received 30 August 2022
Accepted 1 December 2022
Available online 6 December 2022

Keywords:
Hot stamping die
Failure mechanism
Surface softening
Transfer materials

ABSTRACT

A good understanding of failure mechanisms can help us improve the lifetime of the dies. This paper presents a case study investigating the wear behaviour of a QRO90 die insert utilized for stamping uncoated boron-alloyed high-strength steel sheets. Topography and microstructure were characterized by means of scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), hardness measurement and X-ray photoelectron spectroscopy (XPS). Severe galling due to accumulated layers transferred from the boron-alloyed steel workpieces occurred on the die surface. Material softening was detected in the sublayer of the tool steel (up to ~200 μm). In addition, white layers with a in a thickness of 1–2 μm were frequently observed on the surface of the round corner of the tool. The main wear mechanisms are discussed. Galling caused by surface softening and the spallation of white layers are considered to be the primary wear mechanisms for the tool.

1. Introduction

In recent years, a remarkable development of materials and manufacturing processes has significantly influenced the automotive industry. Components made from high-strength steels can be tailored and shaped by advanced hot stamping technologies. Consequently, the weight reduction of the metallic structure body of automobiles will be realized and the CO_2 emissions can be reduced [1,2], being beneficial to sustainable development. On the other hand, the increased strength of the shaped metallic components puts higher requirements on the stamping dies. A key concern for the industry is therefore to reduce die wear and increase die durability.

In real applications, the dies used in hot stamping processes are under harsh conditions, including intense thermal load, high mechanical stress and sliding between die and components. This can cause severe damage to the die including adhesive wear, galling, ploughing, softening, and

* Corresponding author.
E-mail addresses: yu.cao@chalmers.se, emmy.cao@hotmail.se (Y. Cao).
https://doi.org/10.1016/j.jmrt.2022.12.006

Table 1 – Nominal composition (in wt.%) of the steels in this study.

Steel	C	Si	Mn	Cr	Mo	V	B	Al	Ti	Fe
QRO 90[a]	0.38	0.30	0.75	2.6	2.25	0.9	–	–	–	Bal.
22MnB5[b]	0.225	0.25	1.25	0.155	–	–	0.0035	0.02	0.035	Bal.

[a] Composition of the tool steel for die insert.
[b] Composition of the workpiece manufactured by tool steel die.

thermal fatigue [3,4], the consequence of which is the increased cost of die maintenance and reduced production efficiency. Therefore, high wear resistance is required for dies used in hot stamping. This will ensure homogeneous mechanical properties of the components and to achieve a short cycle time of the hot stamping process. It will also result in a smooth contact between the die and the blank sheet during the hot stamping process, by which efficient heat transfer is ensured. Furthermore, the stamped parts can obtain desirable mechanical properties and geometric shapes [3].

22MnB5 steel, a type of boron steel, is a commonly used high strength steel for B-pillar parts in automobiles [5]. Hot stamping is often applied during the manufacturing processes. The initial state of this steel before hot stamping is usually pearlite and ferrite with a moderate strength [6]. In order to obtain high strength and desired geometry, the blank sheet of this steel is first heated to a high temperature above 900 °C and then transferred to the hot stamping die for rapid hot forming and quenching. After being taken out from the die set, a martensite structure [3,7] is formed and the boron steel sheet can obtain a tensile strength up to 1500 MPa and a yield strength of 1100 MPa. Generally, this boron steel sheet is covered by an aluminium silicon coating, in order to protect the steel sheet during its heat treatment and reduce the friction against the forming die during the hot stamping process [4,8,9]. The coated workpiece has some disadvantages, including welding difficulties for future assembly and increased manufacturing cost. On the other hand, uncoated 22MnB5 steel has equivalent mechanical properties and obvious economic advantage, and hence still holds a large share of the market. To the authors' knowledge, few investigations have been focused on the uncoated boron steel sheet interacting with the die in hot stamping.

In order to extend the lifetime of hot stamping die, many methods utilized on tool steels have been investigated, such as laser surface modification technology [10], PVD [11] and nitriding [12]. Schirdewahn et al. [10] performed a laser implanting locally on the tool surfaces for hot stamping application. With a proper implanted spot parameter, the modified tool showed an increased wear resistance. However, the protrusion of the hard implanted spots led to increased removal of the sheet materials. Vilaseca et al. [11] investigated the wear behaviors of tool steels with PVD coating. It was illustrated that the surface coating with CrN and AlCrN could effectively reduce the adhesion of the transfer material. However, the coated layer had a lower thermal fatigue performance under high-frequency thermal cycling. Boher et al. [3,12] evaluated the failure mechanism between some specific tool steels with and without surface nitriding treatment and the coated boron steel at high temperatures. The results showed that the steel with a hard surface formed by nitriding had the best wear resistance. Still, a dense and smooth transferred layer was formed after 5000 cycles [3].

As described above, most of the tribological investigations of the tool steels were tried to simulate the hot stamping process under experimental conditions. However, industrial hot stamping is a dynamic process in terms of the temperatures and the applied load, which is difficult to mimic in a laboratory environment. The failure mechanisms of hot forming die from real industrial applications have seldom been studied. In addition, there are few works related to the hot stamping of uncoated boron steel sheets. The Al–Si layer on the commonly used steel sheets could be transferred to tool steel and then have a lubricating effect [13]. Hence, the wear mechanism of hot stamping process for uncoated steel sheets could be significant and needed to be further studied.

In this paper, an investigation was performed on a worn die used for the hot forming of uncoated boron steel sheets. The surface and cross-sections have been studied to focus on the origins and the evolution of various wear phenomena during the hot stamping process. An insight into the real wear situation that the dies undergo and a potential solution for the failure of hot stamping dies are expected to be provided.

2. Materials and experiments

In this study, a die insert made by Uddeholm QRO 90 Supreme tool steel was investigated. This was an overworn die insert for hot stamping and had been served after several thousand cycles. The chemical composition is given in Table 1 [14]. A hardness of 51–53 HRC for tool steel was obtained by hardening and tempering when it was delivered to the serving. No surface treatment was conducted. This die insert was used to fabricate the B-pillar component of the automotive body using blank boron alloyed steel sheets (22MnB5, hereafter referred to as "workpiece", the composition is also given in Table 1) without Al–Si coating. The thickness of the workpieces varied between 1.6 and 1.8 mm.

Before hot forming, the workpiece was first heated in a furnace to 930 °C for 8 min to form austenite and then transferred to the die set. At this moment, its temperature dropped to around ~800 °C. The hot workpiece was then formed within 1–2 s. Simultaneously, the fabricated B-pillar component in the closed die set was quenched via the internal cooling channels. The tensile strength of the workpieces increased to around 1500 MPa.

A failed die insert for hot stamping, as shown in Fig. 1, was considered for analysis. The main worn areas on the die insert are displayed in Fig. 1. The area on the round corner is marked

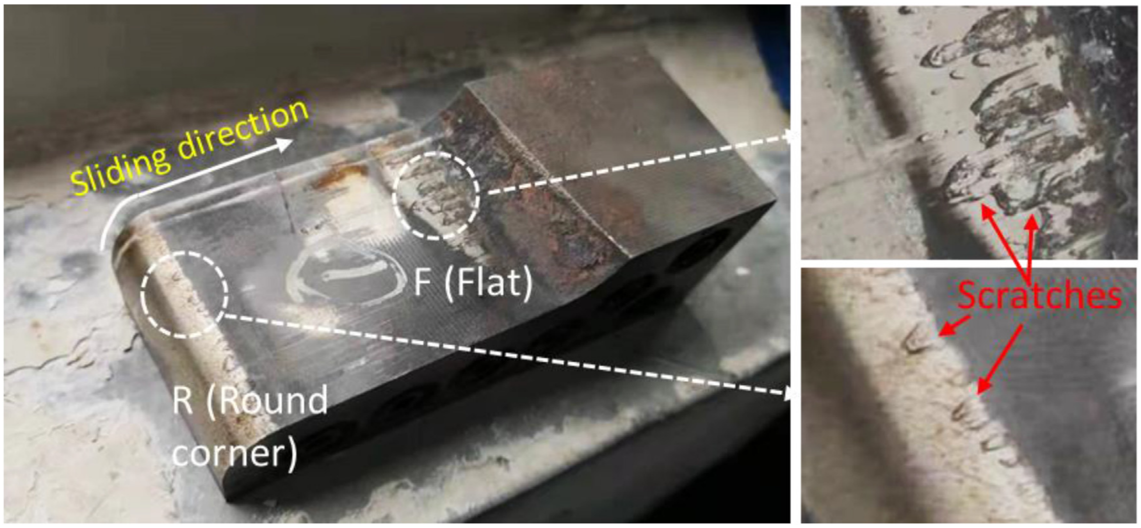


Fig. 1 – The main worn areas on the die insert.

as "R" and the flat part is marked as "F". Specimens were extracted from these two areas for investigation.

The extracted specimens were cleaned ultrasonically using ethanol and isopropanol for 5 min to remove the dirt, oil and rust. The microstructure and the wear surface along the "round corner" and "flat part" were characterized by scanning electron microscopy (SEM, Zeiss LEO Gemini 1550) and energy dispersive spectroscopy (EDS), whose acceleration voltage is set as 15 kV. X-ray photoelectron spectroscopy (XPS) was used to analyze the chemistry of tool surface by means of a PHI 5000 VersaProbe III equipped with a monochromated Al Kα radiation using X-ray beam size of 100 μm and pass energy of 69 eV. In order to protect the worn surface from contamination, XPS examination was performed prior to microstructure inspection and hardness test on the cross-section. Metallographic specimens were mounted, ground and polished until 1 μm suspension fluid. An etchant of 5% picric acid +1% HCl +94% ethanol was used to reveal the microstructure. Optical images from the cross-section were recorded by using a Carl Zeiss Axioscrope 7 instrument. The obtained images were stitched together to show a large field of view. Micro-hardness was measured at the round corner from the surface down to ~0.8 mm using a small load of 0.1 kgf with a dwell time of 15 s considering the shallow depth of the softened layer.

3. Results

3.1. *Adhesive and abrasive wear of the die*

It was noticeable that, during hot stamping, severe adhesive and abrasive wear took place on the die after several thousand cycles. Hence, frequent maintenance was conducted to remove the stuck lump by manual grinding, which significantly reduced the production efficiency and the tool lifetime according to the feedback from the manufacturing company. Also, distinct galling was observed on the die surface after thousands of stamping strikes. However, most of the galling lumps had been removed by maintenance and were not visible by visual inspection. Only some deep scratches were found at both the round corner and flat part of the die, as indicated by the red arrow in Fig. 1. The surface morphology of

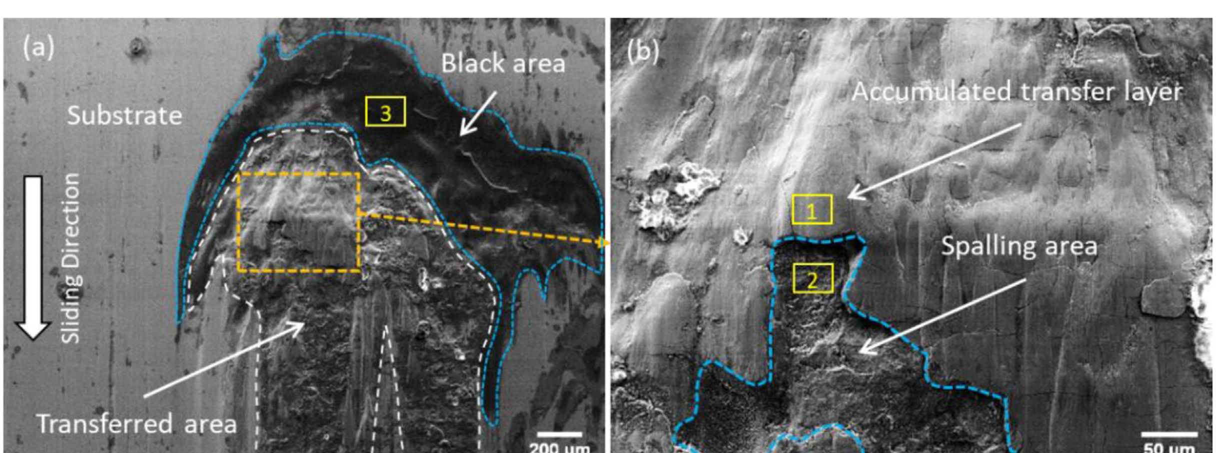


Fig. 2 – SEM images showing the transferred materials on the flat part. The sliding direction (S.D.) is marked in the figure.

a scratches was thoroughly examined by SEM, as shown in Fig. 2. A large area of transferred materials was found on the top of the scratch. The transferred material showed a glazed surface. The extremely low concentration of Cr and Mo and high concentration of O at Site 1 (see Fig. 2b), as revealed by EDS analysis in Table 2 indicated that this transferred material was from the workpiece which was oxidized with a remarkable oxide layer thickness in the micrometer level. The oxide was mainly iron oxide. A spalling area was found on the top of the transferred material, implying that the transferred material was accumulated during the stamping process. EDS analysis conducted on the spalling area (Site 2) showed a relatively lower O concentration compared to the un-spalled zone (Fig. 2b and Table 2), indicating less oxidation of the transferred material in this region. In addition, a black/dark area (upper area indicated in Fig. 2a) was also observed in front of this big scratch. The EDS (Site 3 in Table 2) result shows that this area has an even higher O content than that of Site 1. The material in this area was suspected to be mainly iron oxides with some contamination.

The adjacent protrusion prevented this black area in Fig. 2a from being in contact with the hot workpieces, and thereby its surface was exposed to a high temperature for a relatively long time and was thus heavily oxidized. Notice a significant amount of Si was observed in this region. It could be resulted from the selective oxidation of Si from the steel at high temperatures during processing due to the high affinity of Si with oxygen or the residue from the coolant. The observation of Mo here is a surprise. On the other hand, the protrusion can scrape the hot workpiece, and therefore the transferred layer could be accumulated on the top, as observed in Fig. 2.

In order to further characterize the chemistry of the oxide, XPS was conducted on the black area (BA), transferred area (TA) and substrate (SB), as indicated in Fig. 2a. The surface was slightly etched by argon ions prior to the measurement to remove some contamination and the native oxide. As shown in Fig. 3, the substrate possessed strong peaks of Fe, Cr and Mo in metallic form. However, Fe was identified to be present as Fe_2O_3 in both the black area and transferred material area, indicating significantly thicker oxide compared to the substrate. This was consistent with the EDS results in Table 2. Molybdenum was not observed at the surface of BA and TA regions. High silicon content in BA and TA regions is also agree with the EDS results in Table 2. The area with transferred material had the strongest oxidized Fe peak, indicating that Fe_2O_3 was dominant on the surface of this area.

Fig. 4a shows the morphology of the polished longitudinal cross-section from the flat region (see Fig. 1) with some transferred materials on the top. EDS analysis was carried out on different areas, and the results are presented in Fig. 4c. Here “A” (Site 1 in Fig. 4a) represents the tool steel and shows a typical composition of die material (QRO 90 tool steel). The regions “B” and “C” should be material that differ from the tool steel considering their unique morphology. According to the EDS results shown in Fig. 4c, the “C” layer (Site 3) reveals a much higher O content, and the composition is similar to that of Site 1 in Fig. 2, indicating that the material in this layer is the Fe_2O_3.

The composition of site 2 in the “B” layer was consistent with the nominal composition of the boron steel, indicating it was the transferred material from the boron steel workpiece. The small content of O (2.9 wt%) in the “B” layer suggests that the material was slightly oxidized. In another location of the “B” layer, as shown in Fig. 4b, multi-layers consisting of alternating denser layers (Site 4) and the ones with some black pores (Site 5) were observed. EDS (Fig. 4c) conducted on these different layers shows that the composition of the more porous layers (e.g., Site 5) was consistent with that from site 2 of the “B” layer, while the denser layers (Site 4) had almost the same composition as the “C” layer, suggesting the formation of Fe_2O_3 due to oxidation of the transferred material. However, Mo was detected in both “B” and “C” layers. It was not expected because Mo is not present in the workpieces of the boron steel. One possible reason for this could be that the smearing of the tool steel might occur, which introduces some material from the tool steel into the transferred layer. The mixture of tool steel and transferred materials was also observed in other sliding wear tests [9]. This occurs at the surface of the workpiece, which explains why Mo was only found in the oxide but not the bulk transferred boron steel bulk in the “B” layer.

During the hot stamping process, transferred material with a top oxide layer was stacked on the tool steel layer by layer in an accumulated manner. This type of accumulated and compacted layer has commonly been observed in other high-temperature reciprocating sliding systems [9,15]. An interesting phenomenon observed was the varied bonding strength at different locations. At the head of scratches (Fig. 4a), there was a strong bonding between the transferred materials and the slopy surface of tool steel. It was attributed to the high partial normal load F_1 on the local surface (the slopy region) of the tool steel, as schematically drawn in Fig. 4a. Meanwhile, the transferred material was at high temperatures with high ductility. Consequently, it could form a good bonding with the underlying tool steel. On the other hand, at the tail of scratches (Fig. 4a and b), much lower normal stress led to a weak bonding between the transferred materials and the tool steel. As a result, the spalling of transferred materials could happen in such region, as shown in Fig. 2b.

The surface of the round corner was an ideal place to analyze the wear behaviour because the friction mainly occurred here. Unfortunately, the wear morphology of the round corner was destructed during daily maintenance by grinding using sandpaper. Fig. 5a shows some wear scars left there. Transferred materials were also found on the edge of the groove. EDS analysis (inserted in Fig. 5a) confirmed that the transferred material was an oxide with a high content of O

Table 2 – The EDS analysis results from the surface of the flat part in Fig. 2.

Site		O	Mn	Si	Cr	Mo	V	Fe
1	wt.%	25.5	1.7	0.6	0.2	–	–	72.0
	at. %	54.2	1.1	0.7	0.1	–	–	43.9
2	wt.%	12.8	1.4	0.6	0.2	0.2	–	84.8
	at. %	33.7	1.1	0.9	0.2	0.1	–	64.0
3	wt.%	40.3	1.5	14.4	0.6	5.6	–	37.6
	at. %	66.3	0.7	13.5	0.3	1.5	–	17.7

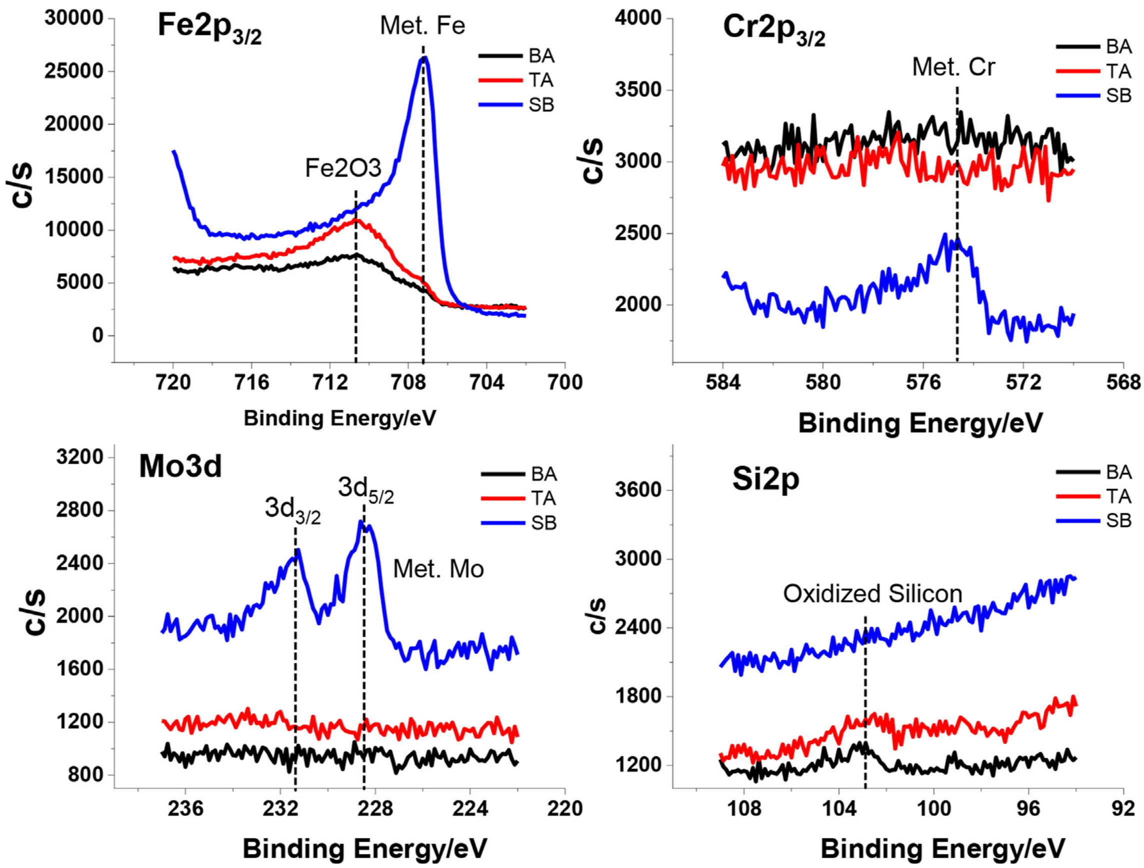
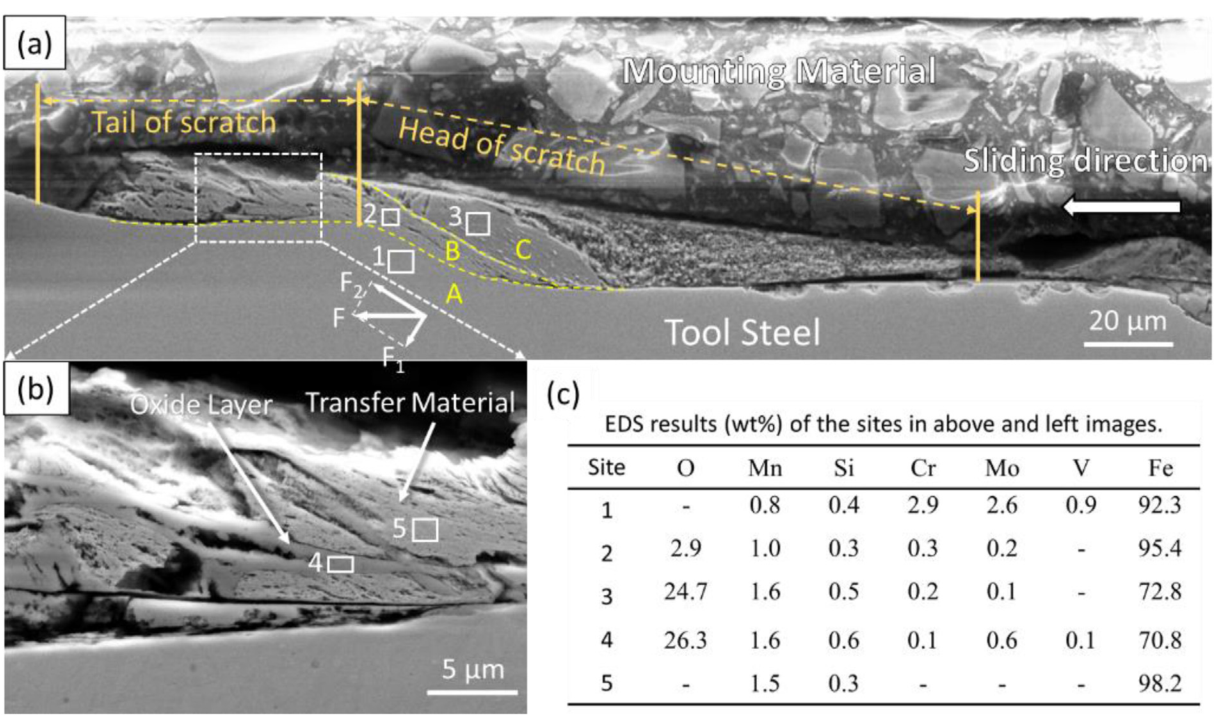
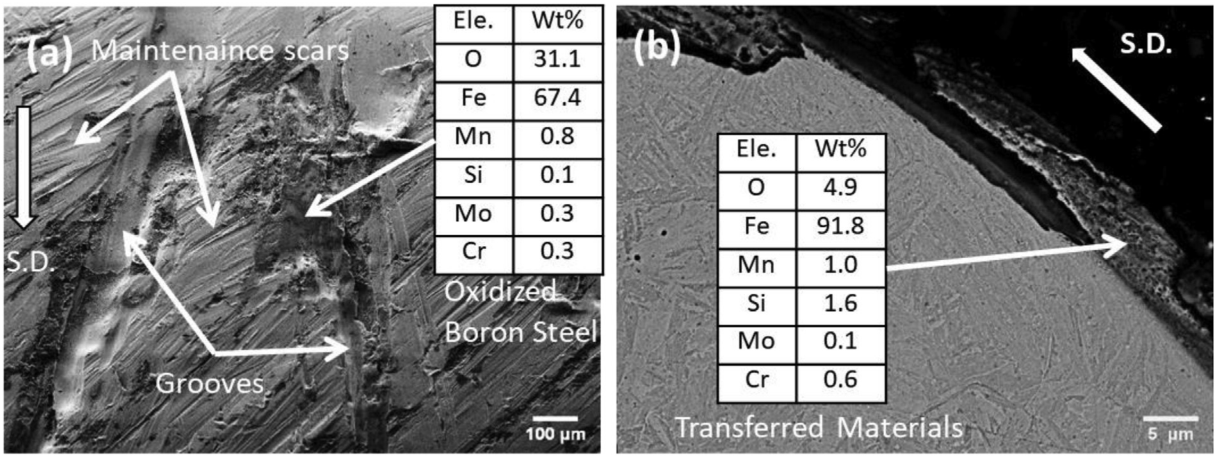


Fig. 3 – The XPS spectra of the concerned elements on the scratch in Fig. 2. BA: black area, TA: transferred area, SB: substrate.



Site	O	Mn	Si	Cr	Mo	V	Fe
1	-	0.8	0.4	2.9	2.6	0.9	92.3
2	2.9	1.0	0.3	0.3	0.2	-	95.4
3	24.7	1.6	0.5	0.2	0.1	-	72.8
4	26.3	1.6	0.6	0.1	0.6	0.1	70.8
5	-	1.5	0.3	-	-	-	98.2

Fig. 4 – (a) SEM image from the longitudinal cross-section (parallel to the sliding direction) of the flat part, (b) Magnified image presenting transferred material in a multilayer form, (c) The corresponding EDS analysis results.



Ele.	Wt%
O	31.1
Fe	67.4
Mn	0.8
Si	0.1
Mo	0.3
Cr	0.3

Ele.	Wt%
O	4.9
Fe	91.8
Mn	1.0
Si	1.6
Mo	0.1
Cr	0.6

Fig. 5 – Material transfer observed at the round corner: (a) the micrograph of worn surface, (b) cross-section illustrating the transferred material.

(31.1 wt%). This meant the oxide layer on the surface was nearly pure Fe_2O_3 with a remarkable thickness (>1 μm). In the central area of the round corner surface, transferred materials were found as well by cross-section observation (Fig. 5b).

In short, material transfer, as one of the main phenomena during the hot stamping process, was confirmed in the above investigation. Accumulated transferred material protrusions could scratch the surface of the workpiece and increase the friction between the workpiece and the tool, leading to the observed galling phenomenon. The occurrence of the galling usually will dramatically increase the friction force and is detrimental to the surface quality of formed components [16].

During the service of hot stamping, abrasive wear was not as serious as the galling phenomenon in the current study. However, ploughing grooves were still found on both round corner and flat part, as shown in Figs. 5a and 2a. The slanted scratch in Fig. 5a was caused by the maintenance. The ploughing grooves on the round corner were relatively deep. It was reasonable because the round corner experienced higher shear stress than that of the flat area. The round corner was the place where abrasive wear most frequently happened. Therefore, some deep grooves were found in the central area of the round corner (one of them was shown in Fig. 6). The groove was parallel to the sliding direction and was filled with debris (Fig. 6b). The high content of O, Cr and Mo revealed by EDS point analysis (Fig. 6c) inferred that it came from the oxidized tool steel. The oxidation and detachment of debris from the tool steel surface took place during the service. Notice these oxidized debris were compacted and trapped in the deep grooves.

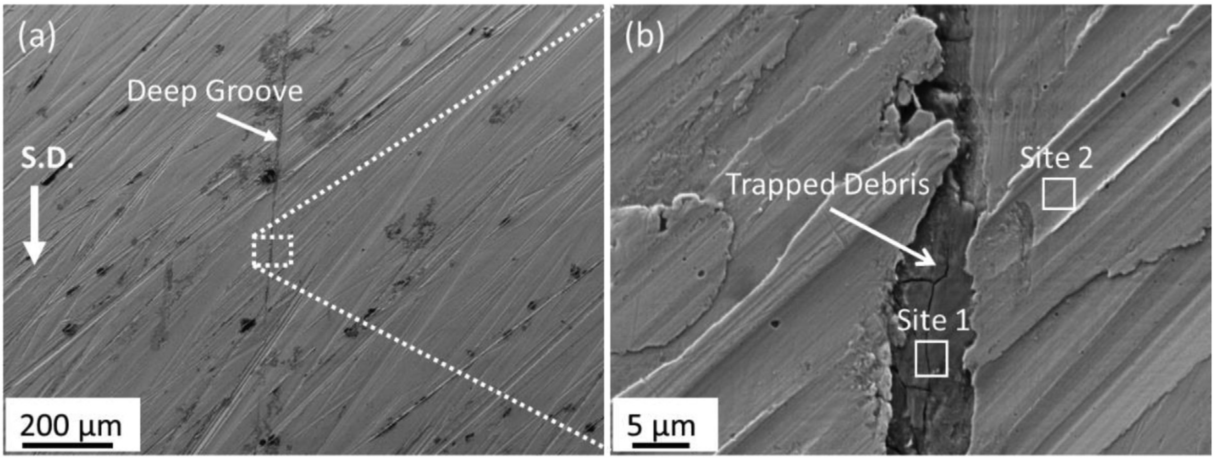
3.2. *Microstructure on the cross-section of the die*

The investigation above mainly focuses on the wear surfaces. The changes of the material beneath the surface (e.g., microstructure, plastic deformation, microcracks initiation, softening etc) are also important, which can provide a better understanding of the failure mechanism of the tool steel and how these changes impact wear behaviour.

Fig. 7 shows SEM images from the cross-section at the center of round corner. Delamination was found in some local areas near the surface of the round corner. The thickness of these layers is about 1–5 μm. A discontinuous line (Fig. 7b) appeared between the surface layer and substrate. Above the line, in the SEM image, the layer was brighter than that of the substrate and it was thus named as “white layer” in this paper. EDS analysis conducted on the white layer showed a similar composition to the substrate. At some places, as revealed in Fig. 7a, fracture found in the white layer suggested that it had experienced remarkable tensile stress during the hot stamping service. In addition, the delamination implied a weak bonding between this white layer and substrate, which could probably lead to spallation under a load of shear stress.

Secondary electron imaging SEM having high-resolution was used to reveal some detailed features. As shown in Fig. 7c and d, the white layer (above the delamination line) had an ultra-fine structure, implying that it probably had higher hardness than the region below the line. As can be seen in these images, the region below the line had severe plastic deformation caused by shear stress while no distinct deformation was found in the white layer, although the regions below and above the line were subjected to similar shear stress. This suggested that the hardness of the white layer may be much higher than that of the substrate. The formation of the white layer will be discussed further in Section 4.2.

At the die exit of the round corner, severe shear deformation was also found in the region close to the surface (Fig. 8). The sites of exit refer to Fig. 9a. In the lower part of Fig. 8a, a typical tempered martensitic structure was observed. In the deformation zone having a depth of 10–20 μm, this structure was stretched along the sliding direction. In Fig. 8b, the grain size reduction was seen in the severe deformed zone. In hot stamping, the die was repeatedly subjected to the shear and normal load at high temperatures. High shear stress can lead to not only the elongation of the grain but also break down the original grains into extremely fine size. As a consequence, the deformed zone showed a different microstructure from the matrix. For other sub-surface regions, the deformation depth



(c)

Element	Fe	O	Cr	Mo	Si	V	Mn
Site 1 (wt.%)	56.5	29.7	5.8	5.0	1.8	0.7	0.6
Site 2 (wt.%)	93.3	0.1	2.4	2.3	0.3	0.8	0.8

Fig. 6 – (a) Deep groove was found on the round corner surface. (b) Trapped debris found in magnified SEM image. (c) EDS analysis shows the trapped material is the oxidized debris from the tool steel.

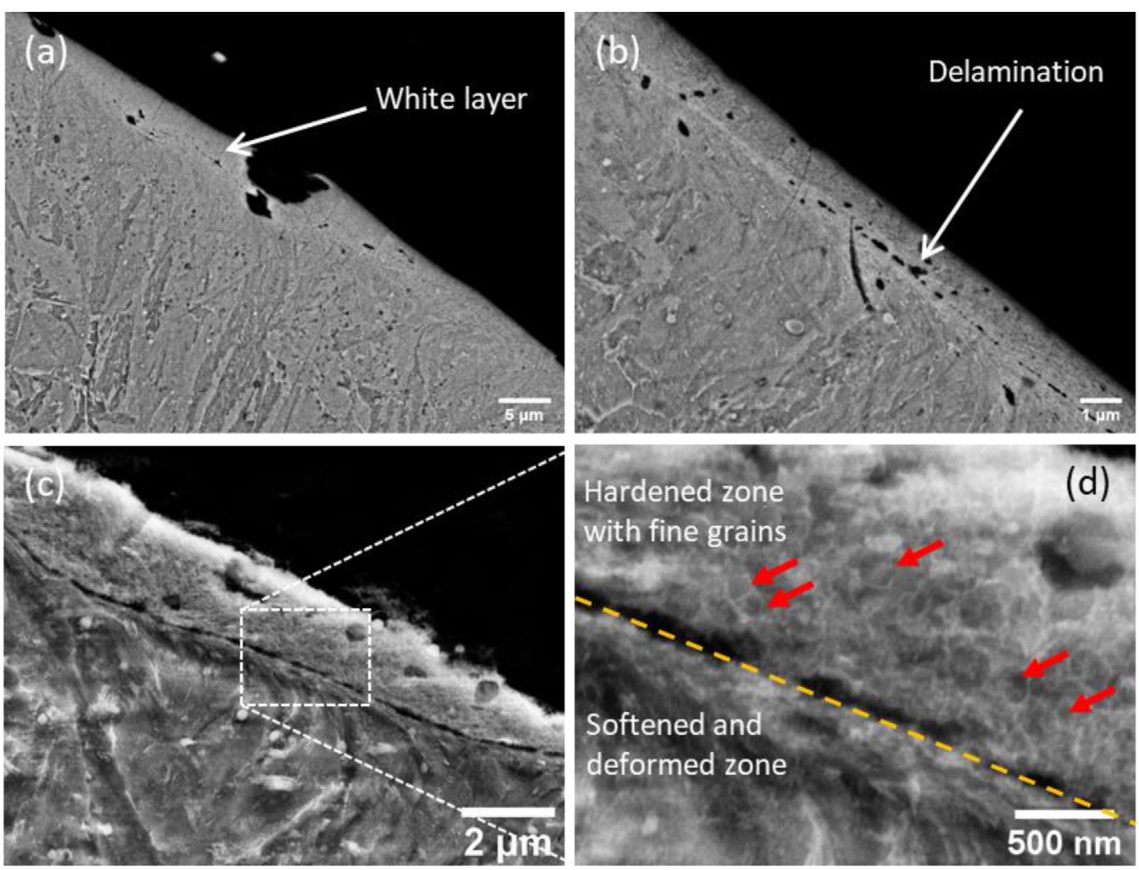


Fig. 7 – Back scattered SEM images from the cross-section reveal the microstructure of the round corner center, (a) fractured "white" layer, and (b) delamination below the white layer. Secondary electron SEM images (c) and (d) detailed features near the surface.

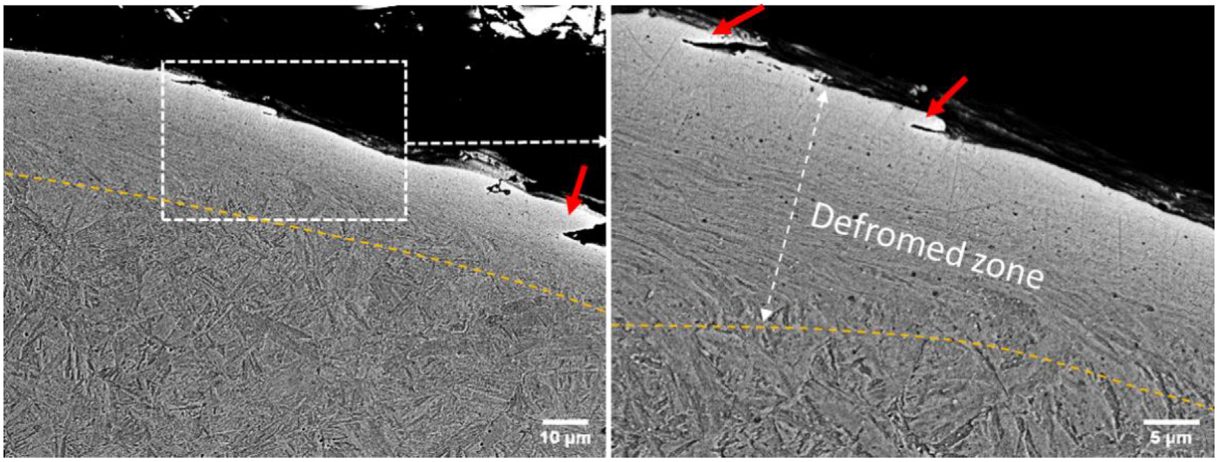


Fig. 8 – Back scattered SEM images from the cross-section of the round corner exit (refer to Fig. 9a), showing severe plastic deformation of the sub-surface of die material. Solid arrows in the images indicate the initiation of wear fragments.

was only about 2–3 μm due to lower shear stress (Fig. 7). Another interesting observation was the initiation of fragments from the uneven surface (marked as red arrows in Fig. 8), which also contributed to the wear in the current study. These fragments could be evolved as well into the third body particles that caused abrasive wear.

3.3. *Softening of the tool*

Hardness measurements of the sub-surface on the cross section of the round corner revealed the softening phenomenon of QRO 90 tool steel during the hot stamping process, as shown in Fig. 9. Microhardness test ($HV_{0.1}$) was chosen in order to reduce the size of indentation and reveal the trend of hardness variation with the distance to the surface. As we can see, the hardness of the sub-surface was significantly lower than that of the bulk (~570 $HV_{0.1}$). The softening of the sub-surface was believed to be related to the heating effect from the hot workpieces. The heat transferred from the workpieces decomposed the martensite into ferrite and carbides. With time, the carbides were coarsened at high temperatures and the dislocation density in the material would be decreased greatly, leading to the softening of tool steel. As shown in Fig. 9b, the softening phenomenon became weaker and weaker from the entrance (Site 1) to exit (Site 6) of the round corner. Moreover, the softening depth of the sub-surface also decreased from ~250 μm to ~150 μm. This could be explained by the decrease in temperature when the boron steel workpieces travelled from the entrance to the exit of the round corner.

4. Discussion

4.1. *Mechanism of galling*

As described above, galling and delamination are considered as the major mechanisms of the die failure. Regarding galling, substrate softening of the die could give a rational interpretation. It should be mentioned that the workpiece is hot and

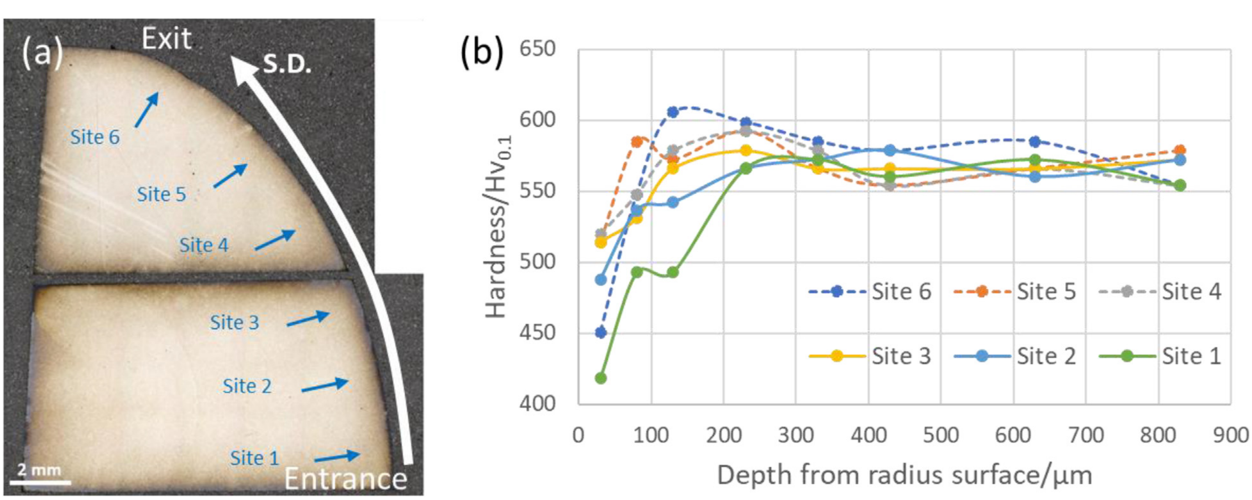


Fig. 9 – The hardness on the cross-section of the round corner shows the softening of the sub-surface, (a) test sites, and (b) hardness profiles of various sites.

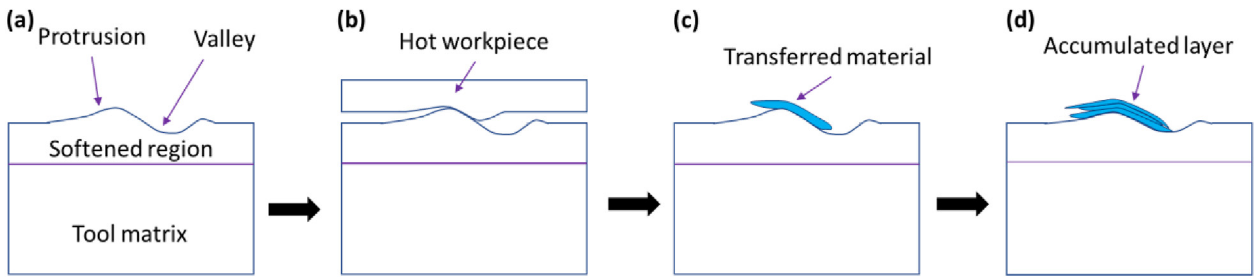


Fig. 10 – The schematic diagram of the galling phenomenon. (a) Formation of protrusion, (b) Scratching the hot workpiece, (c) Transferred material sticked on the tool surface, (d) Accumulated layer (galling) on the tool surface.

soft when it is transferred to the die. After forming, it becomes very hard due to quenching via the internal cooling channels in the hot stamping die. This means the tool material experiences alternation soft and hard workpieces during the services.

The galling process is schematically shown in Fig. 10. During the initial period, the working condition of the tool is good due to the unsoftened substrate and smooth surface. With the ongoing service (few thousands of cycles), the subsurface of the tool is softened, as shown in Fig. 9. On the other hand, the already formed workpieces generally have a high hardness (around 500 HV) due to quenching in hot stamping. During the process of unloading, the hardened workpiece could generate some scratches (the valley in Fig. 10a) on the softened tool surface, leaving some protrusions at the edge of the scratches. In the next cycle of forming, these protrusions could scratch the hot and soft workpiece surface of boron steel (Fig. 10b). Consequently, some material could be transferred from the boron steel workpieces to the tool surface (Fig. 10c). Under the forming force and high temperature from the hot workpiece, the adhesive force between the transfer material and tool steel would be high. According to Ref. [17], the adhesive force is largely dependent on the real contact area (atomic level) of two solid materials. The adhesive force between ductile materials will be enhanced with the increased contact area by plastic deformation. In addition, a large adhesive force is often the case when combining similar materials. In the present study, the workpiece and tool are both made of steels. Considering the possible austenitizing at the surface of tool due to heating from the hot workpieces, both types of steel would have an fcc structure in the surface region when forming. This would further enhance the adhesive force. Hence, the transferred material can easily stick to the tool. Notably, this process can be repeated in the stamping processes, which results in the formation of accumulated layers (galling, Fig. 10d) until they are removed as part of daily maintenance. However, the root cause for galling is the softening of the sub-surface, which could lead to the easy formation of scratches and consequently the initiation of material transfer. This is consistent with Heinrichs' work [18]. From the perspective of this investigation, increasing the softening resistance of tool steel or performing hard facing on the tool could be potential ways to mitigate the galling that happens in the hot stamping process.

4.2. *Formation of white layer and wear due to its delamination*

The formation of the white layer shown in Fig. 7 is the consequence of thermal cycles experienced by the tool steel. During hot stamping, the top surface of the die will be heated up to a peak temperature above 800 °C by the hot workpiece. According to Ref. [14], the austenitizing start temperature of the die material, i.e., QRO 90 tool steel, is about 800 °C. Therefore, partial austenitizing of tool steel occurs within a shallow depth (1–3 μm). The subsequent rapid cooling caused by the water-cooling channels in the die results in the hardening of this surface region owing to martensite formation. During the service, it is expected that the top surface layer of the tool steel is subjected to a repeated austenitizing and quenching, leading to the formation of a layer with ultra-fine grains on the top surface. Hosseini [20] reported a similar white layer on high carbon 100Cr6 steel after fast turning. This layer would have a relatively high hardness due to the quenching process and will not be easily deformed. However, the substrate material, whose peak temperature was below the austenitizing temperature, will not experience austenitizing and just be softened. Hence, plastic deformation could take place easily in these regions, as can be seen in Fig. 7. Different deformation capability makes the white layer and substrate incompatible. This could be one of the reasons for delamination.

Another observation in Fig. 7b is that the black voids near the delamination line have been elongated. The assumption proposed by Suh [19] can interpret it properly. During the deformation, massive dislocations could be accumulated around the hard particles and voids develop. With the growth of the voids, they could be elongated and linked together to form a discontinuous line, as shown in Fig. 7. Further growth of the voids leads to the delamination.

Tensile stress which causes the fracture of the white layer can be interpreted by the cyclic heating and cooling of the martensite. Once martensite is transformed from austenite at the surface, volume expansion could cause a compressive stress in this layer because the substrate below opposes the expansion. However, as the temperature of the die decreases by the cooling channels, the surface layer tends to contract, and the substrate opposes it. The internal stresses change direction and turn to tensile stress. Beside this, austenitizing process in the white layer could also be one of the reasons causing tensile stresses. When the temperature in the white layer exceeds the austenitizing temperature, there is a volume contraction, because austenite (γ-Fe) with fcc structure has a higher atomic packing density than that of the martensite/ferrite phase. Hence, austenitizing will cause a sudden increase in density. The resultant volume contraction will also produce tensile stress in the white layer. As mentioned previously, the white layer with a high hardness has limited ductility. Therefore, fracture could happen in the white layer, as shown in Fig. 7a.

However, delamination is presumably an accumulative event and cannot be accomplished by only one cycle. Therefore, it does not always occur between the white layer and the matrix, as shown in Fig. 7a. After the local delamination, the bonding force between the white layer and substrate is supposed to be weak. Considering the substantial shear stress applied on the tool surface, the white layer should have a high susceptibility to detaching from the substrate, forming fragments. Furthermore, once the detachment of the white layer occurs, the soft and severely deformed substrate will be exposed to the hot workpiece in the subsequent cycles and will possibly form a new white layer. Notice that the delamination is supposed to only occur on the surfaces without transferring material and are close to or in touch with the hot workpiece. The substrate covered by the transfer materials is less likely to be austenitized and develop into the white layer.

4.3. *Abrasive wear*

Abrasive wear is considered to be a mild wear mechanism in this investigation. The main cause of abrasive wear is the hardened workpieces. As mentioned earlier, the workpiece of the boron steel after being hardened would have a hardness as high as 500 HV while the as-delivered tool made by QRO 90 steel prior to the first stamping cycle has a hardness of about 570 HV. After being softened, the hardness of the tool surface is dropped to ~450 HV (see Fig. 9), which is lower than that of the hardened workpiece. As a result, the tool surface could be scratched by the hardened workpiece during the unloading process, as discussed in 4.1. The deep grooves observed on the die surface in Figs. 1, 2 and 4 are believed to be caused by the ploughing from the hardened workpieces. Another possible reason that may cause abrasive wear on the tool is the debris from the detachment of the white layer due to its potential high hardness. Unfortunately, the evidence of this abrasive wear has not been found yet in this study. One possible reason is that the delamination layer is probably detached as a whole layer. Notice it is the small grit particles which are responsible for abrasive wear. In addition, some wear fragments have been found in Fig. 8 (red arrows). Considering that these fragments are originated from the softened regime, they are less likely to cause abrasive wear to the tool. These fragments could be easily oxidized due to their relatively high specific area and develop into debris consisting of a mixture of metal and oxides. The trapped materials in Fig. 6 are suspected to be this kind of debris.

5. Conclusion

A failure investigation of a hot stamping die (QRO 90 tool steel) insert was performed focusing on its frequently worn locations (the flat site and round corner). During the hot stamping process for uncoated boron steel sheets, severe galling and wear were found on the surface of the die insert. The present investigation aims to improve the understanding of the wear mechanism of the hot stamping tool steel. The main conclusions based on this work are as follows.

(1) Accumulated and compacted transfer layer was found on the die surface, leading to severe galling during the hot stamping process. These accumulated layers are commonly the mixture of transferred material from the workpieces and iron oxides. The strong bonding force between the transfer material and tool steel is attributed to several aspects: similar materials, high temperature and pressure subjected, latter of which is related to the local orientation of the tool steel surface.
(2) White layer in a thickness of 1–2 μm was observed on the surface of the round corner of the die. The delamination was frequently found between the white layer and substrate. The formation of the white layer and delamination is due to the repeated heating and quenching during the hot stamping process. The spallation of the white layer is considered to be one of the major wear mechanisms of the investigated die.
(3) Surface softening of the tool steel was found in a depth of about 200 μm by microhardness profiling. It is considered as the reason not only for galling but also for the formation of the ploughing grooves. Hence, the softening resistance should be considered as an essential criterion in the selection of tool steel for hot stamping dies.

In summary, the findings of this investigation indicate that the galling caused by the surface softening and the spallation of the white layer are the primary wear mechanisms for the tool steel investigated. Abrasive wear is observed but is relatively less significant. Hard-facing the tool with the materials having better softening resistance could be a potential way to improve the performance of the hot stamping tools in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study is supported by Production Area of Advance; Chalmers University of Technology; China Scholarship Council; Uddeholms AB, Sweden and ASSAB Tooling Technology, China.

REFERENCES

[1] Hein P, Wilsius J. Status and innovation trends in hot stamping of Usibor1500P. Steel Res Int 2008;79:85–91.
[2] Streppel AH, Klingenberg W, Singh UP. Advances in sheet metal forming applications. Int J Mach Tool Manufact 2008;48:483–4.
[3] Boher C, Le Roux S, Penazzi L, Dessain C. Experimental investigation of the tribological behavior and wear mechanisms of tool steel grades in hot stamping of a high-strength boron steel. Wear 2012;294:286–95.
[4] Pelcastre L, Kumia E, Hardell J, Decrozant-Triquenaux J, Braham P. High temperature tribological studies on hardfaced tool steels for press hardening of Al-Si coated boron steel. Wear 2021;476:203728.
[5] Min JY, Lin JP, Xin LJ, Li JY. Indirect hot stamping of boron steel 22MnB5 for an upper B-pillar, advanced materials research. Trans Tech Publ Ltd 2011;314:703–8.
[6] Jing Z, Wang BY, Huang MD, Cui D. Effect of hot stamping parameters on the mechanical properties and microstructure of cold-rolled 22MnB5 steel strips. Int J Min Met Mater 2014;21:544–55.
[7] Mori K, Bariani PF, Behrens BA, Brosius A, Bruschi S, Maeno T, et al. Hot stamping of ultra-high strength steel parts. CIRP Ann 2017;66:755–77.
[8] Borsetto F, Ghiotti A, Bruschi S. Investigation of the high strength steel Al–Si coating during hot stamping operations, Key Engineering Materials. Trans Tech Publ Ltd 2009;410:289–96.
[9] Vikhareva A, Macêdo G, Pelcastre L, Hardell J. High temperature tribological behaviour of additively manufactured tool material for applications in press hardening. Wear 2021;477:203859.
[10] Schirdewahn S, Spranger F, Hilgenberg K, Merklein M. Tribological and thermal behavior of laser implanted tool surfaces for hot stamping AlSi coated 22MnB5 sheets. Defect Diffusion Forum 2022;414:69–74.
[11] Vilaseca M, Pujante J, Ramírez G, Casellas D. Investigation into adhesive wear of PVD coated and uncoated hot stamping production tools. Wear 2013;308:148–54.
[12] Staia MH, Pérez-Delgado Y, Sanchez C, et al. Hardness properties and high-temperature wear behavior of nitrided AISI D2 tool steel, prior and after PAPVD coating. Wear 2009;267:1452–61.
[13] Schwingenschlögl P, Niederhofer P, Merklein M. Investigation on basic friction and wear mechanisms within hot stamping considering the influence of tool steel and hardness. Wear 2019;426–427:378–89.
[14] Uddeholm. Uddeholm qro ® 90 Supreme. 2006. 14, http://www.uddeholm.com.ar/files/QRO_90_Supreme_Spa(1).pdf.
[15] Inman IA, Datta PK, Du HL, et al. Studies of high temperature sliding wear of metallic dissimilar interfaces. Tribol Int 2005;38:812–23.
[16] Nosar NS, Olsson M. Influence of tool steel surface topography on adhesion and material transfer in stainless steel/tool steel sliding contact. Wear 2013;303:30–9.
[17] Stachowiak GW, Batchelor AW. Engineering tribology. Butterworth-heinemann; 2013.
[18] Heinrichs J, Olsson M, Jacobson S. New understanding of the initiation of material transfer and transfer layer build-up in metal forming—in situ studies in the SEM. Wear 2012;292:61–73.
[19] Suh NP. The delamination theory of wear. Wear 1973;25:111–24.
[20] Hosseini SB, Klement U, Kaminski J. Microstructure characterization of white layer formed by hard turning and wire electric discharge machining in high carbon steel (AISI 52100), advanced materials research. Trans Tech Publ Ltd 2012;409:684–9.