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Improving the performance of domestic pin punches using failure analysis investigation techniques

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Abstract

The study investigates the failure of locally manufactured pin punches, aiming to identify the factors contributing to these failures and to improve performance and production processes in line with international standards. This study explicitly aligns with Sustainable Development Goal (SDG) 9, which emphasizes the promotion of sustainable manufacturing. The improved pin punches reduce material waste and the time consumed in replacing failed tools, thereby supporting environmentally friendly industrial practices. The target performance benchmarks were 1 million punch cycles for the M50 steel and 250 thousand for the D2 steel, measured after heat treatment and coating with a TiN layer. The key factors examined in the investigation included excessive pressure, design flaws, material selection, heat treatment, and the machining process. Various analytical techniques, such as chemical analysis, mechanical testing, and optical and scanning electron microscopies, were employed to investigate the samples. After examining the primary samples, mechanical fatigue was identified as the primary failure mechanism. The Slippner and D2 steels were investigated as alternatives to the M50 steel. Initially, controlled heat treatment processes for Slippner were conducted in salt furnaces, followed by machining of the pin punches. This process led to a significant increase in production rates, reaching 140 thousand punches compared to the previous 10 thousand. For the D2 steel, majorly modified heat treatments, followed by controlled finishing, led to highly improved performance and obvious changes in microstructure. Remarkable reduction in carbide sizes and their distribution in the matrix were obtained. The performance improved dramatically, surpassing 3 million punch cycles due to the improved heat treatment. This was achieved without TiN coating.

Keywords: Failure analysis, Tool steels, Fatigue, Pin punches, Manufacturing, Heat treatment, Fractography

1. Introduction

Failures of equipment and structures lead to several economic losses of assets and production and might constitute harmful incidents of injuries and life losses. Therefore, failure analysis investigations are carried out to identify the root cause of such failures and propose recommendations to prevent similar failures [1] [2] [3]. These efforts contribute directly to SDG 9, emphasizing the importance of building reliable, sustainable, and resilient infrastructure while promoting industrialization and fostering innovation [4].

The conditions that lead to metallurgical failures include mechanical, chemical, or mechanical-chemical conditions. Fatigue is mechanical damage resulting from repeated or dynamic loads. As a result of increasing industrial technology, more failures of components subjected to repeated loads were recorded. This made it essential to do more research and development in several departments like metallurgy and material science engineering, production and design engineering, structural analysis, liability engineering, testing technology, and maintenance engineering [5], [6].

It is not necessary to have fatigue fracture due to abnormal conditions, excessive overloading, inequivalent material, corrosive environment, or any other known reason. The reason that fatigue fracture is considered to be the most dangerous and serious fracture type is that it can occur in normal conditions without any warning [7]. Addressing such failures aligns with SDG 9's objective to improve industrial processes and ensure the safety and longevity of equipment, thus contributing to sustainable industry.

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Any steel used to make cutting tools, forming tools, or any shaping material into a part is considered tool steel. Simple plain carbon steels were the earliest known tool steels. Still, in the 20th century, many new complex, highly alloyed tool steels were developed. These contain several amounts of elements like molybdenum, manganese, chromium, vanadium, and tungsten, and lead to increased mechanical properties, decrease or eliminate cracks during heat treatment which result in increasing service demands and also, perform better dimensional control [8].

Tools are subjected to rapidly applied loads and must withstand loads even in low or high temperatures for a long time without wear, cracks, buckling, broken parts, dimensional changes, or failure. That is why nowadays there is a wide range of tool steels, each family with distinct chemical and mechanical properties responsible for specific applications [8], [9], [10]. Optimizing these materials aligns with the industrial sustainability issues.

The aim of this paper is to identify firstly the damage mechanism and then the root cause of premature failures in domestic manufacturing of pin punches or tool steels in order to improve the performance and lifetime of local manufacturing pin punches [11]. This research supports the development of sustainable manufacturing practices, reducing material waste and contributing to SDG 9's goals.

2. Background

A pin punch of a punching machine used to fail and collapse after one million punches. The original material of the punch was 80MoCrV42-16, Coated by 0.002 to 0.003 mm titanium nitriding layer "TiN." This material is not available at the local market. Thus, purchasing a pin punch with the same material was impossible. The feasible choices were punches made of equivalent materials such as the X155CrVMo12 steel (commercially known as K110), or D2 tool steel coated with TiN layer. The pin punch was acceptable, but the production rate decreased to two hundred - three thousand cycles before failure [12], [13].

Domestic manufacturing of these pin punches became inevitable. However, the problem was the lack and limitations of raw materials in the local market. Thus, more than one was investigated in this work. A list of these materials is listed in Table 1. The readily available materials were the K110 and the Slippner steels [14] [15] [16]. The production rate of punches made of these materials varied from two thousand to twenty thousand cycles till failure. The low performance of these punches was the motive for carrying out a failure analysis investigation to identify the main causes of early and premature shortcomings [17], [18], [19].

Manufacturing history:

Heat treatment is the main controllable process in determining tool lifetime. It was carried out as shown in Table 2 and Figure 1.

Table 1 Alloys used in manufacturing pin punches.

No.	DIN Designation		Chemical composition									
			C %	Si %	Mn %	P_{MaX} %	S_{MaX} %	Cr %	Mo %	Ni %	V %	W %
1	80MoCrV42-16 M50 1.3551	Min.	0.77		0.15	__	__	3.9	4	__	0.9	__
		Max.	0.85	0.4	0.35	0.025	0.015	4.3	4.5	__	1.1	0.25
2	X155CrVMo12 1.2379 K110	Min.	1.5	0.1	0.15	__	__	11	0.6	__	0.9	__
		Max.	1.6	0.4	0.45	0.03	0.03	12	0.8	__	1.1	__
3	slippner	Min.	0.9	0.9	0.5	__	__	7.8	2.5	__	0.5	__
		Max.	0.43	1.2	0.5	0.03	0.03	5.5	1.5	__	1.1	__
4	M3 CLASS 2 HS6-5-3 1.3344	Min.	1.15	__	__	__	__	3.8	4.7	__	2.7	6
		Max.	1.25	0.45	0.4	0.03	0.03	4.5	5.2	__	3.2	6.7

Table 2 Heat treatment cycle.

No.	Type of heating	Furnace	Temperature °C	Time "minute"	Cooling
1	preheating	air furnace "resistance furnace"	500 :550	30	___
2	medium heating	salt bath furnace	800	12	___
3	heating	salt bath furnace	950	12	___
4	final heat	salt bath furnace	1030	12	___
5	quenching	salt path GS 430	500-550	5:10	air

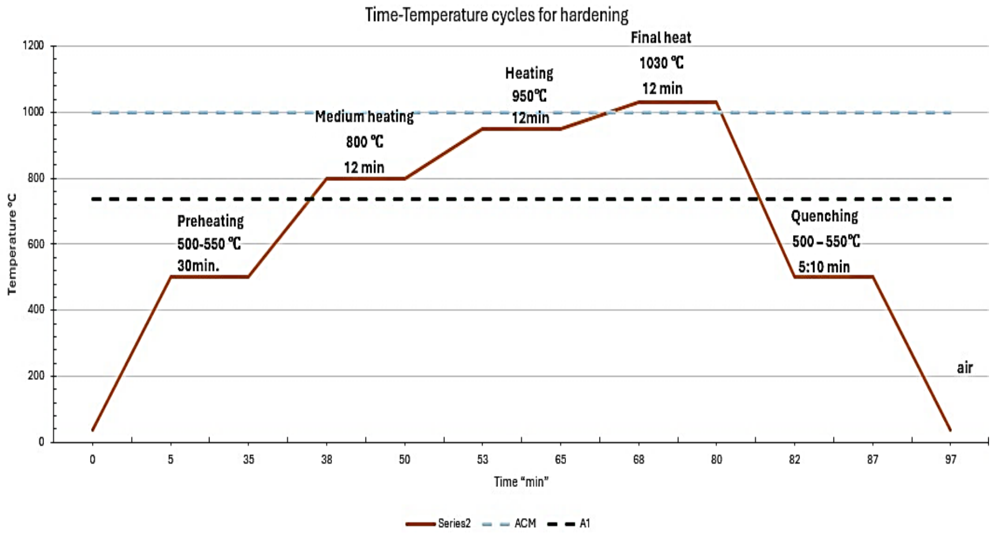

Fig. 1 Heat treatment cycle.

After hardening, the punches become very hard, so tempering treatment controls the required mechanical properties. Single or double tempering, depending on the resulting hardness, might be used. Polishing is done afterward. Two sets of specimens were made to investigate the tempering conditions. The first set was the single-tempering as of sample number 8, while the second set was the double-tempering as of sample number 9. Stress relief is a very important heat treatment process for removing residual stresses of machining. These may cause distortion, loss of tolerance, or cracking. It is done at 675° C for 60 minutes and furnace or air cooling. The furnace was turned off, and the samples were air-cooled, as in samples 10 and 11. Another variation was done by leaving samples to cool slowly in the furnace as of sample number 12.

Hardening

This treatment was tailored especially for this type of steel to control the mechanical properties of the material to meet specific requirements. This procedure will dissolve all carbides during heating process, then produce fine carbides after quenching and reduce the percentage of large primary carbides in the matrix. The tempering process is very important to reduce brittleness of as quenched martensite by reducing the amount of martensite, and stress relief of the internal stresses. This transforms the retained austenite into more stable phases, as well. The tailored heat treatment is shown in Figure 2.

The second tempering is very important to refine and produce small carbides. Good distribution of carbides results in eliminating residual stresses and consequently increases fatigue properties. The treatment was carried out following references [20-22]. Preheat slowly to 650° C, hold for 10 to 15 minutes, heat to 1010°C, and soak for 50 minutes. Salt bath quench at 540° C, then air cool to 65° C. Immediately temper at 515° C and soak for 1 hour. Leave the part cool to room temperature, then temper again at 480° C for 1 hour as recommended in the literature [16] [20] [21].

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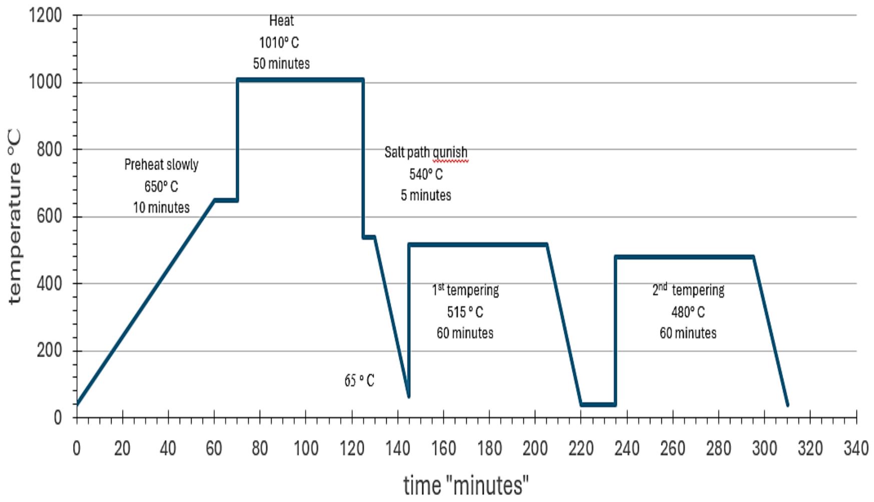

Fig. 2 Tailored heat treatment diagram for D2 steel.

The grinding process is done so that the whole punch except the indenter using a central polishing machine [23] [24]. Then, the indenter is ground using a turning machine. Pin punches are then coated with TiN using the chemical vapor deposition process.

3. Examination methods

To determine the root causes of failure, it is important to study the fracture surface. The historical data of service and the data obtained from the fracture surface reveal the fracture mechanism [25].

Visual examination was performed using an unaided eye and a digital camera to capture surface details. A stereo microscope was used to gain further insights into macroscopic features, enabling detailed observations of the fracture morphology. For deeper analysis, mounted samples were prepared using conventional metallographic techniques, followed by etching with a 2% Nital solution to reveal the microstructural features [25]. Microscopic examination, performed using an Olympus BX41M-LED light optical microscope, focused on studying the alloy matrix and the distribution of carbide particles across the microstructure [26]. This method is essential for identifying microstructural anomalies that could have contributed to the failure and reveals the morphology and distribution of the strengthening carbides in response to different heat treatments.

A scanning electron microscope (SEM) was employed to investigate the fracture surface and examine microscale features. The SEM (Quanta FEG-250 model) provides high-resolution images at high magnifications with a considerable depth of focus. This enabled us to study fracture morphology, crack initiation, and propagation in exceptional detail [27], [28]. This was invaluable for identifying the various failure modes.

Chemical analysis of the samples was performed using ARL 3460 optical emission spectroscopy, to ensure the material met the required specifications, and to detect any compositional deviations contributing to failure. Microhardness measurements were carried out across the indenter part of the punch to evaluate the mechanical uniformity of the samples. This step helps in assessing the hardness gradients and the homogeneity of the microstructure. After cutting into 10 mm halves using a wire-cutting machine and mounting in cold-curing acrylic mixture, the samples were polished to ensure precision in hardness testing. A Shimadzu microhardness tester (type HMV-G) was employed with a 500-gm load (HV0.5) applied for 10 seconds to determine local hardness values.

Combining these techniques provides a proper methodology for failure analysis, offering comprehensive insights into the material mechanical and microstructural properties. The reason behind each method ensures a good analysis to identify the fracture mechanism, chemical composition, and local variations in material properties. This systematic investigation strengthens the understanding of failure origins and contributes to developing effective mitigation strategies.

4. Results

4.1 Visual examination

The samples were collected as follows.

- Original punch – sample no. 1
- Original failed punch – sample no. 2
- Equivalent K110 punch– sample 4
- Three local failed punches – sample no. 5,6,7
- Controlled manufactured punches 8,9
- Tailored heat treatment samples 10, 11, 12

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Sample number 1: This sample represents pin punch of the original material, which is the M50 tool steel. I was coated with TiN layer as shown in Figure 3. The pin punch was in good condition. The coating layer was partially removed from the tip during service. The performance of the punch was not affected by this.

Fig. 3 (1) original punch, (2) original failed punch, (3) equivalent K110 punch, and (4-6) three local manufactured failed punches.

Sample number 2: This sample represents the original M50 tool steel punch after failure. This punch was coated with TiN layer (Figure 3). The coating was also partially stripped from the surface during service. This partial removal facilitated crack initiation leading to fatigue fracture [29], [30].

Sample number 3: This sample represents failed original M50 tool steel pin punch after failure. This punch was coated with TiN layer. The fracture surface is a fatigue similar to sample number 2, as can be seen in Figure 4.

Sample number 4: This sample represents failed punch with equivalent material D2 tool steel. The sample showed lower performance compared to M5o steel because of its lower fracture toughness compared to M50 steel [15], [31], [32]. This punch was also coated with TiN layer as shown in Figure 3. The coating layer was partially damaged during operation. This might explain the low performance of this punch, which is 50% lower than the original one. The fracture surface is shown in Figure 4. The macrograph shows clear multiple origin fatigue fracture surface. Ratchet marks are seen between the origins as well.

Sample number 5 represents a local punch manufactured from the Slippner tool steel. This punch was not coated with the TiN layer, as shown in Figure 3. The fracture mode was fatigue as can be seen in Figure 4, where multiple origins and ratchet marks can be identified.

Sample number 6: This sample represents failed uncoated local manufactured failed punch of Slippner tool steel (Figure 3). From the fracture surface of Figure 4, it is likely failure due to an accident. It is not similar to the previous surfaces, even though characteristic fatigue features are seen such as multiple origins and other features.

Sample number 7: This sample represents a locally manufactured punch from the M3 class 2 tool steel, which has high strength but moderate toughness [15]. This punch is not coated with a TiN layer, as shown in Figure 3. The fatigue fracture surface is also seen in Figure 4. This pin punch also failed due to fatigue. But this material might have different hardness than the rest of the punches. Origins and ratchet marks can be identified.

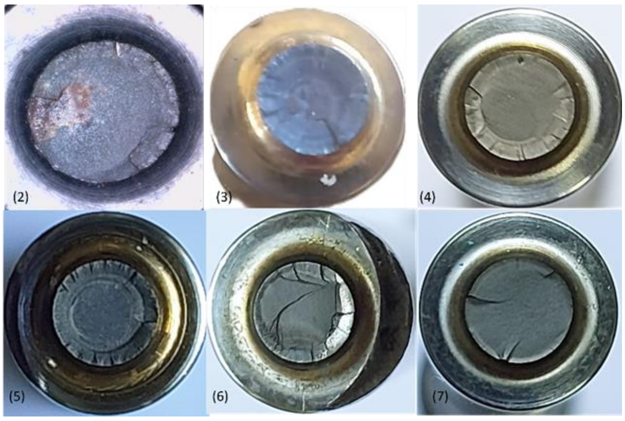

Fig. 4 Photographs of fracture surface: samples no.2,3,4,5,6,7 respectively.

4.2 Macroscopic examination

Sample no. 1: The macrographs of specimen no 1 is not shown.

Sample no. 2: At higher magnification as shown in Figure 5-2, multiple origins and ratchet marks are observed. The area was cleaned by washing in alcohol ultrasonic path, then polished slightly with alumina and then dried with dryer. The fracture surface of this sample is not of good quality as shown in Figure 5-2-a.

Sample no. 3: The SEM macrograph is shown in Figure 5-3. Typical ratchet marks, multiple origins and beach marks are seen. These confirm the fatigue fracture. The final fracture zone is very small, *i.e.,* 2.54 mm^2compared to total fracture area, *i.e.*, 15.4 mm^2, constituting only 11.6% of the surface. This indicates the proper design and/or the suitable material properties. This punch showed the best performance.

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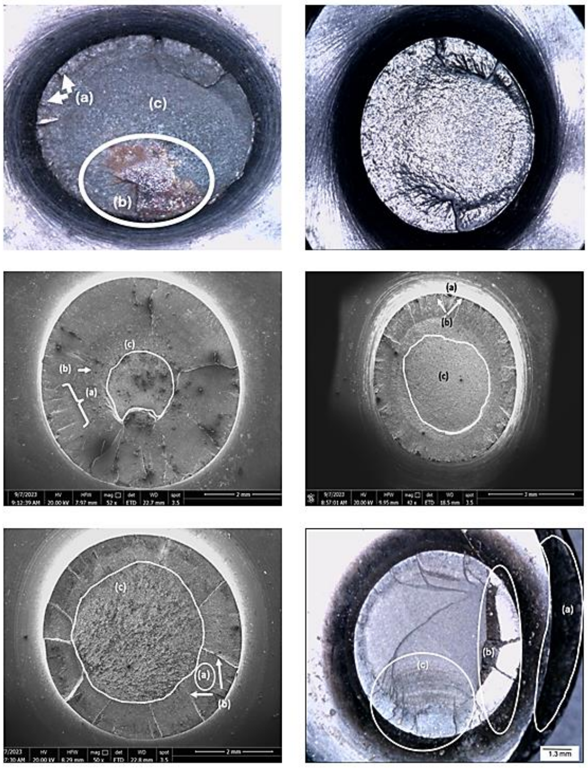

Fig. 5 Stereoscopic examination for samples no. 2 before cleaning, sample no. 2 after cleaning, SEM examination at 50X for samples no. 3,4, 5 and 6.

Sample no. 4: The SEM macrograph is shown in Figure 5-4. Typical ratchet marks, multiple origins, and beach marks are seen. These confirm the fatigue fracture. The final fracture zone is large, *i.e.*, 7 mm^2 compared to the total fracture area, *i.e.*, 15.4 mm^2, constituting only 45% of the surface. This indicates the proper design and/or the suitable material properties. This punch showed accepted performance as an equivalent material.

Sample no. 5: The SEM macrograph is shown in Figure 5-5. Typical ratchet marks, multiple origins, and beach marks are seen. These confirm the fatigue fracture. The final fracture zone is very large, *i.e.*, 11.03mm^2compared to the total fracture area, *i.e.*, 15.4 mm^2, constituting only 71.6% of the surface. This indicates the proper design and/or the suitable material properties. This punch showed accepted performance as an equivalent material. The fracture segments of the first stage of fatigue clearly appear. The sample contains 18 crack origins and 19 ratchet marks. The primary macroscopic examination shows that the final fracture zone of sample no.5 is very large compared to the total fracture area and seems to be a ductile fracture. This means that slippner tool steel either was not treated well or was not the suitable material for this pin punch as the punch could not withstand the applied force even over a large area.

Sample no. 6: The macroscopic examination clarified the accident effects, especially in zone (a), as shown in Figure 5-6. It appears that a malfunction in the punching process led to a fracture. The fracture surface shows ratchet marks, multiple origins, and beach marks, which appear in zone (c).

4.3. Microscopic examination

Microscopic examination is important in failure analysis as it clarifies the microstructure characterization, showing phases, grains, carbides, and precipitates. Through the observed microstructure, more information could be gained about the history of the material and more information about the failure's root causes. In addition to that, studying the microstructure of tool steels like M50, D2, and Slippner tool steels emphasizes the role of carbides influencing fatigue life [3], [15] [20], [33].

Sample no. 3: The microstructure of M50 steel at 50X as shown in Figure 6. Shows the presence of carbides distributed inside the tempered martensitic matrix in the form of secondary carbides, either large secondary carbides or small secondary carbides [34].

Sample no. 4: The microstructure of D2 in Figure 6 shows the presence of undissolved chromium carbides distributed inside the matrix. These carbides are divided into a small number of elongated dendritic primary carbides (PCS) and a large number of secondary carbides, either in large secondary carbides or small secondary carbides in a tempered martensitic matrix.

Sample no. 5: The microstructure of Slippner shows the presence of undissolved chromium carbides distributed inside the matrix. But with a small number of primary carbides, a medium number of secondary carbides, and very high amounts of small secondary carbides, as shown in Figure 6. After microstructure examination, it was found that there were differences between the samples that appeared in the form of carbide sizes and distributions.

Microscopic examination of the new sets of pin punches. After using the punches, the results were recorded. It was found that the average production rate of the first set was 22,000 punches, represented by sample number 8, while the second set was 140,000 punches, represented by sample number 9. From this wide range of fatigue life, it is expected that microscopic examination of the two sets of

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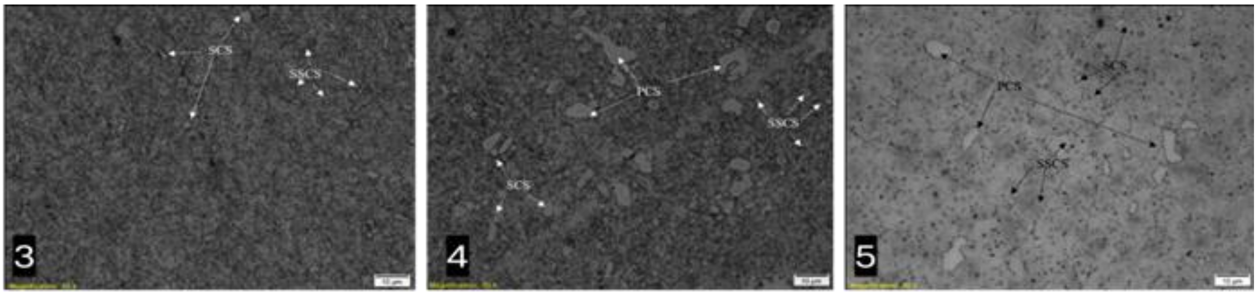

Fig. 6. Microscopic examination for samples no. 3,4 and 5, respectively, at 50X.

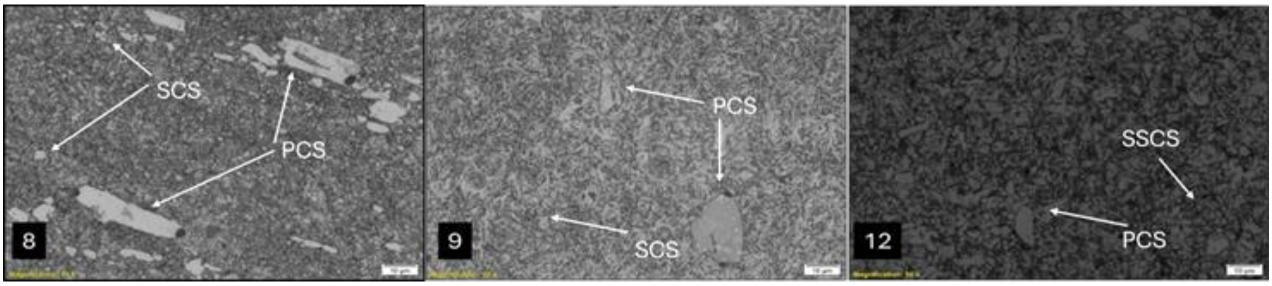

Fig. 7. Microscopic examination for samples no. 8,9 and 12, respectively, at 50X.

pin punches would have clear differences in microstructure, especially in the size and distribution of primary and secondary carbides. The samples were prepared for microscopic examination. As expected, the two patches were unequal as the microstructure showed differences in carbide size and carbide dispersion.

Sample 8 (22,000 Punches): shows large amounts of primary carbides (PCS) which make stress concentration inside the matrix and accelerate crack initiation reducing tool life and leading to fatigue fracture. These carbides are sufficient for decreasing the production rate as shown in Figure 7-8.

Sample 9 (140,000 Punches): microstructure in Figure 7-9 which shows small amounts of primary carbides (PCS) and large amounts of secondary carbides (SCS) especially small secondary carbides (SSCS). This number of secondary carbides (SCS) enhances both toughness and fatigue resistance, which is likely contributing to the improved production rate in this set.

This difference in production rate is probably because of human factors, especially in heat treatment. So, this factor should be eliminated by repeating heat treatment later without human intervention and improving manufacturing processes

Microscopic examination pin punch with tailored heat treatment. As shown in Figure 7, sample number 12 exhibits a very uniform structure, small primary carbides (PCS) distributed along the martensitic matrix, and a large amount of small secondary carbides (SSCS). This microstructure indicates an optimized carbide structure enhances toughness and fatigue resistance, increasing the tool lifetime.

4.4 Scanning Electron Microscopic Examination

Samples number 3,4 and 5 were prepared to be ready for SEM. The maximum accepted length of samples is 10 mm.

Sample no. 3: There are five locations that were studied using SEM. An overview image was taken at 52X magnification, as shown in Figure 8-3. This figure contains labels for the subsequent close-up views.

Figure 8-3-1 shows fatigue striations and intermetallic phases.

Figure 8-3-2 shows ill-developed fatigue striations and ratchet marks.

Figure 8-3-3 shows crack layer on the surface of fracture surface.

Figure 8-3-4 represents part of the final fracture zone at a magnification of 2000X, showing quasi-cleavage fracture and internal crack.

Sample no. 4: There are five locations that were studied using SEM. An overview image at low magnification is shown in Figure 9-4. This figure shows the subsequent close-up views.

Figure 9-4-1 shows the crack origin and ratchet marks.

Figure 9-4-2, Figure 9-4-3, and Figure 9-4-4 are close-up views. Quasi-cleavage morphology of fatigue fracture.

Figure 9-4-4 shows the final fracture zone at 2000X magnification, showing a large number of intergranular fractures with deep secondary cracks between the grains.

Sample no. 5: There are five locations that were studied using SEM. An overview image at 50X magnification is

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shown in Figure 10. It contains labels that shows the next studied and magnified locations.

Figure 10-5-1 shows ratchet marks, and no striations appears.

Figure 10-5-2 shows quasi-cleavage fracture containing voids AT 2000X magnification.

Figure 10-5-3 this location represents transition zone from progressive failure to overload failure with separation surface. Progressive failure is marked by crack propagation under cyclic loading, followed by overload exceeding the material's capacity. Figure 10-5-4 shows final fracture zone at 1200X magnification depicting mostly ductile feature.

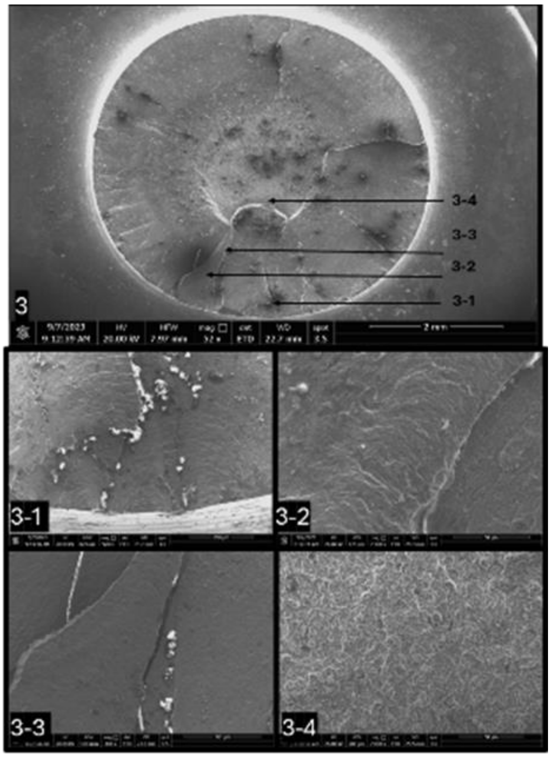

Fig. 8. SEM examination of sample no.3 different zones with different magnifications 3) at 60 x magnification showing the zones that magnified, 3-1) at magnification 500X showing fatigue striations, 3-2) at magnification 2400X showing fatigue striations, 3-3.

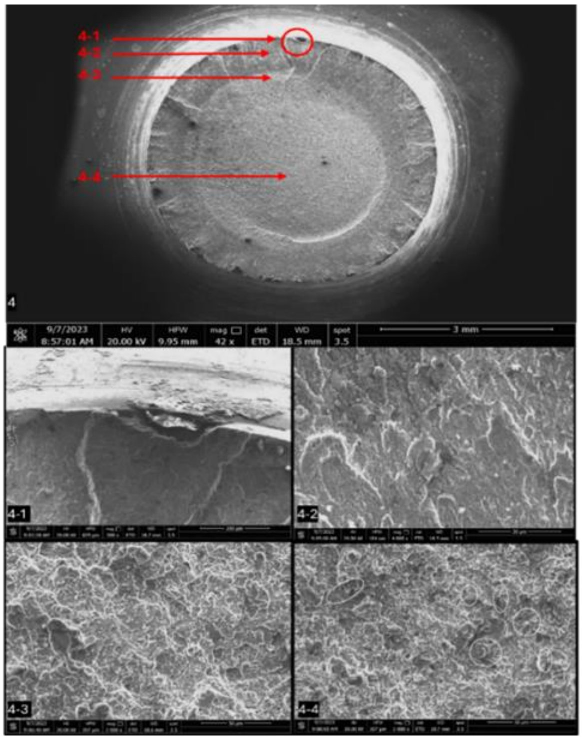

Fig. 9. SEM examination of sample no.4 different zones with different magnifications 4) illustrating the location of different fracture mechanisms is clearly demonstrated, 4-1), 4-2), 4-3), and 4-4).

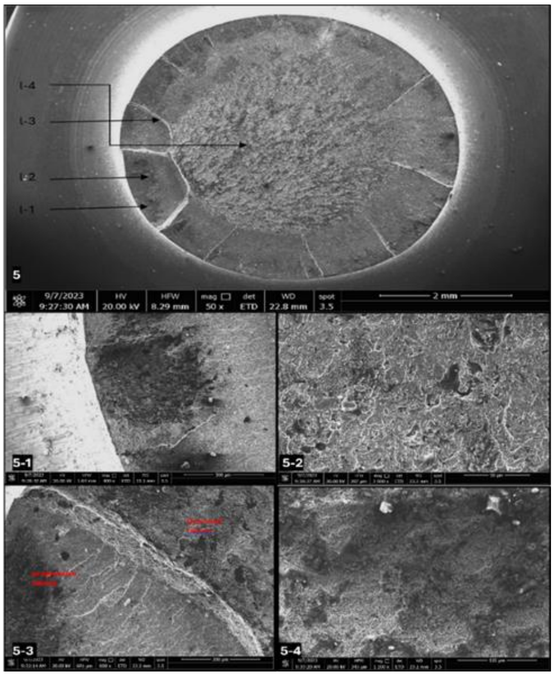

Fig. 10. SEM examination of sample no.5 different zones with different magnifications 5) illustrating the location of different fracture mechanisms is clearly demonstrated, 5-1), 5-2), 5-3), and 5-4.

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4.5. Chemical analysis

The samples were examined using optical emission which is important for samples analysis, depending on the principle of optical emission spectroscopy to identify the chemical composition of the material. Chemical compositions are shown in Table 3.

4.6. Microhardness results

Comparing the hardness measurements data shown in Table 4, it was found that the samples number 3 and 4 which characterized with highest production rate and long lifetime have nearly the same hardness gradient and ranges. Unlike sample number 5 which has the highest hardness and sample no. 7. Which have the lowest hardness and more ductile, this appears in hardness chart in Figure 11.

This test confirmed that the observations taken in the initial tests regarding the hardness of the pin punches were correct, as by comparing the hardness together, it is found that the samples number 3 and 4 which characterized with highest production rate and long lifetime have nearly the same Hardness gradient and ranges. Unlike sample number 7 which has lower Hardness and more ductile. And sample number 5 which has the highest hardness. Also, samples 3 and 4 nearly have no variation between surface and centre, unlike sample number 5 which has great variation between the centre and the surface as hardness decreases from the centre to the surface. Also 7, 8, and 9 have lower hardness compared to previous samples. But here is an important note. Although samples 8 and 9 have the same hardness. But sample no. 9 has very high production rate. Which means that hardness is not the only reference for predicting the performance.

To clearly compare the effect of materials, heat treatments, and manufacturing conditions on pin punches performance, Table 5 summarizes the performance characteristics, including key indicators like production cycles, hardness consistency, and microstructural uniformity. In addition, the effect of heat treatment parameters and manufacturing conditions on the production rates of punches were also shown in Table 56.

The results emphasize that tailored double-tempering and optimized heat treatment processes are critical for enhancing punch performance. While surface coatings such as TiN provide additional benefits, the material's microstructure and hardness consistency remain the primary factors influencing longevity and production rates. For future applications, K110 with tailored furnace double tempering is recommended for achieving maximum performance. This highlights the role of heat treatment and surface treatments in increasing tool life and reducing material waste, thereby promoting sustainability in manufacturing. By improving the life time of punches, fewer replacements are required, leading to reduced resource consumption, energy use, and environmental impact.

Table 3 Chemical compositions of samples

Sample no.	Chemical composition											
	C %	**Si %**	**Mn %**	**P_{Max} %**	**S_{Max} %**	**Cu %**	**Cr %**	**Mo %**	**Ni %**	**V %**	**W %**	**N %**
1	0.86	0.25	0.25	<.005	<.005	0.04	4.13	4.14	0.055	0.821	< 0.01	___
2	0.87	0.19	0.18	<.005	<.005	___	4.16	4.07	0.048	0.8	< 0.01	___
3	0.88	0.25	0.18	<.005	<.005	0.03	4.16	4.13	0.048	0.823	< 0.01	___
4	1.54	0.033	0.31	0.023	0.006	0.1	11.3	0.77	0.188	0.81	0.005	0.1
5	0.83	0.83	0.47	0.019	0.008	0.038	7.69	2.56	0.106	0.508	0.0238	0.266
6	0.85	0.81	0.47	0.019	0.006	0.035	7.62	2.47	0.099	0.475		0.16
7	1.31	0.20	0.37	0.038	0.012	0.09	4.16	5.07	0.192	2.44	5.72	___

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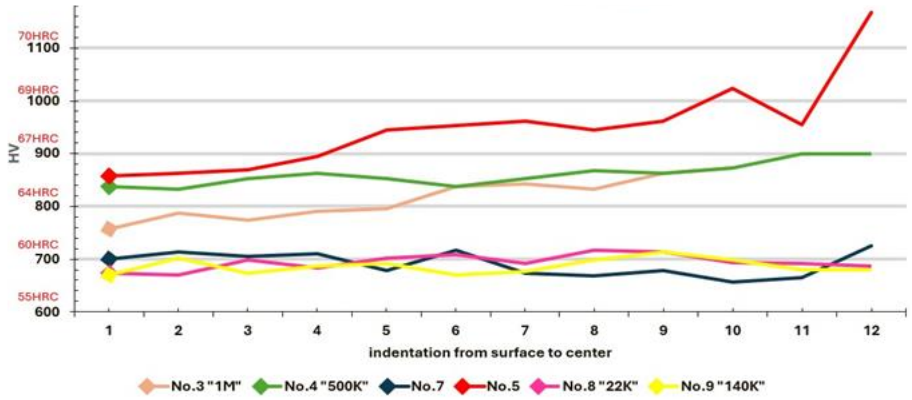

Fig. 11 Microhardness chart of sample no. 3,4,5, 7, 8 and 9.

Table 4. Micro-hardness map of samples no. 3, 4, 5, 7,8 and 9

Sample No.	Distance from surface "mm"												Max.	Min.	Mean	S.t.d.
	1.7	**2.1**	**2.5**	**2.9**	**3.3**	**4.1**	**4.3**	**4.5**	**4.7**	**4.9**	**1.7**	**2.1**				
3	757	787	774	791	796	838	843	833	862	873	___	___	873	757	815	39.3
4	838	833	852	862	852	838	852	867	862	873	899	899	899	833	860.7	21.7
5	857	862	870	894	944	953	961	944	961	1024	955	1168	1168	857	949	84.9
7	701	714	706	711	678	717	673	668	678	656	665	725	725	656	691	23.7
8	673	670	698	684	702	709	691	717	713	694	691	687	717	670	694	14.07
9	670	702	673	687	691	670	677	698	713	698	680	680	713	670	687	13.3

Table 5 Effect of heat treatment on punches performance.

No	material	Local process variables										Performance "cycle"
		Machining		Heat treatment					Coating			
		turning	grinding	Conventional		Tailored treatment			Hard Cr	TiN coating		
				Single	Double	Double	Air	Furnace		PVD	Plasma	
7	Slippner	*										15,000 to 20,000
8	Slippner	*		*								22,000
9	Slippner	*			*					*		140,000
10	K110	*				*	*					Failed in accident
11	K110	*				*	*					+ 3,000,000
12	K110		*			*		*				61,750

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Discussion

In this paper studied how to improve pin punches performance by using failure analysis investigation techniques as started first by collecting samples then making visual examination of the whole collected samples. Which informed that the failure of punches was due to fatigue failure. As it was clear from the appearance of striations and fracture morphology. There were undesired samples like sample number ”2” that contained some discoloration, which is supposed to be rust, and sample number “6” had abnormal fracture compared to others. This facture must be due to an accident on the production line. But overall, the visual examination gave a brief estimation of types of materials in samples number “2” and “3” there was a small fracture area that primarily indicates that this material is the optimum material and has the optimum treatment. Unlike the final fracture that appeared in the rest of the samples, which was large compared to samples number “2” and “3”.

The sample cutting length was in the range of 8 to 9 mm away from the fracture surface. It was examined using a stereoscope, which confirmed that the failure was due to fatigue failure due to the multiple origins, multiple cracks, and ratchet marks, which were very clear. After that microscopic examination was held to clarify the microstructure characterization, showing phases, grains, and carbides. There was a strong relationship between carbides’ size, dispersion along the matrix, and the performance of pin punches. The higher the percentage of small secondary carbides, the higher the performance of pin punches, as shown in sample “3”. And so, the higher percentage of primary carbides, the lower the performance of pin punches, as shown in samples “4” and “5”.

After that, the "SEM" examination using a powerful microscope was an important step in obtaining high-resolution images at high magnifications, enabling us to investigate finer details [27], such as fatigue striations, ratchet marks, and secondary cracks of the surface. At high magnification, a cleavage fracture of an internal crack inside the material was observed in the part of the final fracture zone. However, in sample number 4, there were large numbers of intergranular fractures with deep secondary cracks between the grains.

Chemical analysis using optical emission spectroscopy samples identified the punch materials of M50 as an original material, K110, Slippner, and M3 class 2 as alternative materials. The chemical composition of each steel was studied very well to realize whether they are suitable to be equivalent or not. This is followed by a micro-hardness line using a microhardness testing machine that provides hardness measurements across the cross-section of the sample. This clarifies the local characteristics of each zone, showing whether there is hardness homogeneity and a reasonable gradient across the sample. By comparing the hardness, it was found that there were samples that were characterized by the highest production rate and long lifetime and had nearly the same hardness gradient and ranges unlike other samples, which have lower Hardness and more ductile or harder hardness. Also, some samples have nearly no variation between the surface and center, unlike others, has a great variation between the center and the surface as hardness increases from the center to the surface. Samples 3 and 4 have nearly no variation between the surface and center, unlike sample number 5, which has a great variation between the center and the surface as hardness decreases from the center to the surface. Also, 7, 8, and 9 have lower hardness compared to previous samples. But here is an important note. Although samples 8 and 9 have the same hardness. But sample no. 9 has a very high production rate. This means that hardness is not the only reference for predicting the performance.

Tailoring the heat treatment and taking care of the critical temperature and the importance of double tempering resulted in significant improvements in the punches' performance. As, it increases the lifetime of the tool to more than 3,000,000 cycle without coating.

To have a clear comparison between different manufacturing techniques, new sets of pin punches were manufactured to assess the manufacturing parameters. Punches were coated with TiN layer using chemical vapor deposition technique. The performance rate varied from 22,000 to 140,000 cycles. The tailored heat treatment produced incredible improvements in punch performance. As the production rate significantly increased to reach over 3,000,000 cycles.

Finally, the fatigue failure was affected primarily by the type of material and heat treatment. Some samples had large final fracture zones, which means that they did not reach the optimum hardness, and the carbides were not in proper size or distribution. Then, the punches must be carefully finished to prevent the temperature from increasing and badly affecting the performance.

Conclusions

The main reason for failure

The pin punches failed as a result of fatigue failure. Which was affected by several factors, like the presence of carbides and the size and distribution of carbides.

Effect of heat treatment

- The presence of carbides, their size, and distribution could be controlled by heat treatment. So, heat treatment should be performed systematically, not by trial and error.

At tailored heat treatment

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- It is important to immediately temper the punches after quenching.
- Double tempering should be taken into consideration to refine the microstructure and ensure uniform distribution of carbides

Material performance

Even though M50 steel has trustable performance but the equivalent materials, K110 and Slippner, which are locally available in the market, could reach very high performance by controlling and modifying the heat treatment procedures. Currently, better performance was reached using Slippner, especially by double tempering. The results were fruitful, as shown in Table 6.

Sustainable and Industrial Relevance

The study highlights the critical role of optimized heat treatments and material selection in extending tool life, which has significant implications for sustainable manufacturing:

- Reduced Material Waste: By increasing tool life (e.g., K110 reaching over 3,000,000 cycles), the frequency of replacements decreases, minimizing material consumption and waste.
- Lower Production Costs: Extended punch performance reduces downtime, energy consumption, and costs.
- Environmental Impact: Improved life time of tools supports sustainable industry practices by conserving resources, reducing energy required for manufacturing replacements, and minimizing industrial waste.
- Industrial Application: The findings are directly applicable to tool manufacturing, offering cost-effective solutions through tailored treatments and coatings to improve tool durability and reliability.

In conclusion, this research demonstrates how systematic heat treatment optimization and double tempering can not only improve tool performance, but also promote sustainable production practices, aligning with industrial goals of efficiency, reduced costs, and environmental conservation.

Recommendations

Manufacturing recommendations

- Use polishing machine for polishing the whole pin punch especially the forming tip. To improve the surface finish quality, reduce any surface defects or pits, reduce surface stresses [35], [36].
- Replace the electric cutting wheel that is used in adjusting the final length of the pin punch tip with CNC Wire machine to reduce the heat effect caused by the rotating desk without cooling.
- Use coolant fluid while removing the final 1mm from the tip to prevent burning the tip of the punch as a result of generated heat. Or polish the final tip gently to prevent heating the tip.

Heat treatment recommendations

- Apply heat treatment in vacuum furnace to eliminate any human error and perform better homogenous structure.
- Try subzero treatment to eliminate all retained austenite, enhance better carbide dispersion, and increase percentage of small secondary carbides [37].

Table 6 Performance of pin punches

No	material	Performance “cycle”
1	Original equivalent K110 material	
	M50	1,000,000
2	Equivalent K110 material	
	K110 “D2”	300,000
3	Locally manufactured	
	Slippner	2000 to 20,000 sometime reaches 100,000
4	Primary controlling in improvement	
	Slippner “single tempering”	22,000
5	Slippner “double tempering” coating	140,000
	Tailored treatment	
6	K110 sample 10	Accident
7	K110 sample 11	+ 3,000,000
8	K110 sample 12	61,750

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