Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.3, July 2026, pp. 02603040-01 ~ 02603040-014
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i3.2959

Effect of Salt Bath and Oil Quenching Heat Treatments on SKT4 Forging Dies for Sustainable Undercarriage Link Production

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Abstract. SKT4 steel, classified by the Japan Industrial Standard (JIS) as a hot-forming mold steel, is widely used for forging dies due to its favorable chemical composition and mechanical properties. During forging, dies are subjected to repeated impacts and high temperatures, which gradually reduce their performance and contribute to product defects. However, quantitative comparisons between salt bath and oil quenching treatments for SKT4 dies in high-cycle forging applications remain limited. This study evaluates the effects of salt bath and oil quenching, combined with tempering at 400°C and 450°C, on the microstructure, mechanical properties, and service performance of SKT4 dies used in undercarriage link forging. Forging trials were conducted for 3,000 and 6,000 production cycles. The results demonstrate that salt bath quenching significantly improves die hardness and wear resistance compared with oil quenching. The optimum condition was achieved with salt bath quenching followed by tempering at 400°C, producing the highest hardness of 46.1 HRC and the lowest specific wear rate of 6.98×10^{-5} $mm^3/kg \cdot m$. Dies treated under this condition showed no visible product defects after 6,000 forging cycles. Microstructural analysis revealed finer and more homogeneous tempered martensite laths in salt bath-quenched specimens. Unlike oil quenching, salt bath quenching eliminates vapor blanket formation, enabling direct convective cooling, more uniform temperature reduction, and minimal distortion. These findings indicate that salt bath quenching with 400°C tempering provides the optimal combination of hardness, wear resistance, and durability, supporting longer die life, reduced rework, and more sustainable forging operations.

Keywords: *Dies Forging,* Heat Treatment, *Salt Bath, SKT4, Oil Quench*

(Received 2025-11-07, Revised 2026-07-14, Accepted 2026-07-24, Available Online by 2026-07-28)

1. Introduction

With the development of technology, heavy equipment plays an important role in every industrial sector: construction, mining, and manufacturing. Its main purpose is to achieve operational effectiveness and efficiency. One of the most critical components of heavy equipment is the undercarriage system; it provides the driving mechanism for machines like excavators and bulldozers [1]. This system consists of several components, one of which is the link. It is used as a connector between tracks to integrate other components into an assembled unit. The undercarriage components go through extreme conditions, including high pressure, continuous friction, and abrasive environments. In order to sustain those conditions, undercarriage links are supposed to have a combination of mechanical properties such as high strength, toughness, and wear resistance [2].

The quality of an undercarriage link greatly depends upon the dies which were used to form the component. Dies act as the first molds that would determine the shape, dimensions, and surface quality of the product. Thus, dies are subject to high hardness, excellent wear resistance, and dimensional stability during repeated production cycles. If the dies do not exhibit optimum mechanical properties, the products could result in quality degradation, which might include deformation, inaccuracy in dimensions, or even functional failure during their operation [3]. One of the most widely used materials in dies is SKT4; this is a high-carbon tool steel which gives great performance in forging applications.

SKT4 is a type of tool steel that belongs to the hot forming mold category and is specified by JIS G4404. It is also widely used as the base material for dies or molds in forging due to its exceptional chemical composition and mechanical properties. Moreover, the material used for making undercarriage links also contributes to product quality significantly. However, the success of the production process is rather dependent on the dies used during forming. Dies without proper heat treatment have a tendency to wear down and eventually lead to dimensional deformation, hence reducing production efficiency [4].

Forging is a type of metal-forming process in which the material is compressed at an elevated temperature into the desired geometry [1]. In the forging process, a class 3T forging machine that has a maximum energy capability of 80 kJ is used. First, the round bar material is heated in a billet heater at a temperature of 1150–1250°C, while the forging dies are preheated to a temperature of 150°C. After preparation is complete, forging is done according to the set standards. During this process, the dies bear continuous impact from the hot material, causing them to change in dimensions. Additionally, as time goes on, the dies experience thermal cycling, which further degrades their performance and leads to an increase in defects across the various stages of product flow.

According to the company's data, the PC200 SKD NEW undercarriage link product has the highest defect rate of all product types. In this product, the defect takes the form of burrs or untrimmed excess materials that are not detached from the product during the trimming process. The root cause of this defect is the deformation of the die contour during forging, which means that products have oversized diameters compared to the desired level. According to the company's standards, the production process for the PC200 SKD NEW undercarriage link was designed based on 6,000 items per production run for the die lifetime. However, in practice, a die often reaches the end of its functional life at around 3,000 items due to severe degradation, as evidenced by the presence of contour deformation and product defects. To deal with these kinds of defects, additional repair processes are required, adding to the production time and cost per cycle.

Heat treatment is one of the most critical processes for modifying the mechanical properties of materials to meet specific application requirements. This process involves heating the material to a certain temperature followed by controlled cooling in different media such as air, water, oil (oil quenching), or molten salt (salt bath). Oil quenching is the most commonly used method due to its cost-effectiveness and ease of application, although it can cause distortion or cracking if cooling is uneven [5]. In contrast, salt bath heat treatment provides more uniform cooling, reducing the likelihood of distortion or crack formation, and produces a more homogeneous microstructure, especially in materials requiring high hardness and wear resistance [6]. Each cooling method results in distinct material characteristics that directly influence the performance and durability of the final product. Therefore, selecting the appropriate heat treatment method is crucial for enhancing die performance and ensuring high-quality undercarriage link production for heavy-duty applications [3]. Based on this rationale, this study aims to provide a deeper understanding of how different heat treatment methods affect die performance and the resulting product quality.

Although extensive research has examined heat treatment effects on tool steels in general, detailed comparative studies on SKT4 dies specifically under high-cycle forging conditions for undercarriage link production remain scarce. Most prior work addresses hardness and microstructure in isolation, without directly linking these properties to defect rates and die life under industrial-scale operational cycles. This study addresses that gap by posing the following research questions: (1) How do salt bath and oil quenching treatments affect the hardness, wear resistance, and microstructure of SKT4 dies? (2) How do these property changes translate into product defect rates and die life over 3,000 and 6,000 forging cycles? Beyond their technical relevance, these questions also carry sustainability implications: extending die life and reducing defect rates directly lowers material waste, energy consumption in remanufacturing, and rework costs, aligning this study with the broader goal of sustainable manufacturing practices in heavy equipment production.

2. **Methods**

2.1 Dies Material Preparation

The dies material SKT4 was in the form of plain dies blocks devoid of contours. In order to create the contour corresponding to the undercarriage link product on the surface of the dies, machining should be effected using a VMC OKUMA V2 machine. VMC OKUMA V2 is a vertical CNC milling machine that shapes the contour of the dies through vertical cuts on the surface until it meets the required undercarriage link profile.

2.2. Austenitizing Process of Dies

In this stage, the contoured dies were heat-treated with austenitization, quenching, and tempering. Austenitization of SKT4 die specimens was carried out by putting four specimens of identical characteristics into the furnace. A furnace is fitted with a homogeneous atmosphere, which cannot be contaminated with other substances. The preheating process was carried out through two stages: the first at 400°C for 30 minutes and the second at 650°C for 120 minutes. These stages should be performed in order to avoid thermal shock due to severe changes in temperature, homogenous heating along the dies, reduction in internal stresses, and preparation of the microstructure for homogeneous phase transformation during the austenitizing stage. Therefore, the austenitizing temperature for SKT4 material can take place at a temperature ranging from 800°C to 850°C with an increase in temperature of 5–10°C for every minute and 20–40 minutes for every inch in thickness. After preheating, the austenitizing process was done at a temperature of 830°C for 120 minutes. This time duration was chosen in such a way that homogeneous phase transformation will take place within the 10 cm thick die material.

2.3 Quenching Process of Dies

The SKT4 dies were heat-treated by austenitizing and then underwent different quenching cooling media. This study used molten salt (salt bath) and oil (oil quench) as quenching mediums. A mixture of 50% potassium nitrate (KNO_3), 50% sodium nitrite ($NaNO_2$), and a small amount of sodium nitrate ($NaNO_3$) was used in the salt bath quenching. Before quenching, the salt bath was heated to 180°C. Two SKT4 die specimens were quenched at 180°C for a holding time of 20 minutes in a salt bath. The dies were removed from the quenching medium and cooled in ambient air until room temperature (25°C–30°C) was reached. In the oil quenching process, two other SKT4 dies were quenched using a medium of 80%–90% polyalphaolefin (PAO) synthetic ester, 3%–5% viscosity stabilizer (polymethacrylate, PMA), 1%–2% corrosion inhibitor (sulfonate), and 0.1%–0.5% anti-foam additive to prevent foam formation. Before quenching, the oil was preheated to 70°C. The dies were kept in this oil for 30 minutes and were then removed and air-cooled to room temperature (25°C–30°C).

2.4 Tempering Process of Dies

Tempering of each dies and its cooling medium was performed at two temperature variations, 400°C and 450°C. The tempering cycle was done twice to ensure a uniform distribution of carbon in the material, thus reducing internal stresses from the previous quenching process. The heating rate was first increased gradually at 5–10°C per minute until it reached the target temperature; then, the dies were held for about two hours (240 minutes) and allowed to cool slowly in air.

2.5 Forging Process

Each SKT4 die that had undergone the respective heat treatment variations was then used in the forging process. These included oil-quenched dies that were tempered at 400°C and 450°C, and similarly salt bath-quenched dies that were tempered at the same temperatures. Each of the dies underwent forging operations for 3,000 and 6,000 production cycles each. Forging was done using an Anyang 3T (80 kJ) hydraulic drop forging machine. This machine is characterized by the impact that occurs repeatedly between the upper and lower dies to produce the desired product, in this case the PC200 SKD NEW undercarriage link component.

2.6 Machining Process

The required machining involved the cutting of portions of each forged variation of the SKT4 die material down into smaller samples. This was done on a Shibaura milling machine operating on a CNC principle. In this operation, the forged die surfaces were machined by a rotating cutting tool moving horizontally. At the end, the SKT4 die specimens were machined to dimensions of approximately 20 mm × 20 mm × 10 mm and prepared for further testing.

2.7 Hardness Testing

Hardness Testing The hardness test was done to check the resistance of the material against plastic deformation or surface penetration. The idea behind this technique is that the material's resistance to indentation, due to a given applied load by an indenter, can be used to define the material's hardness. In the present work, the hardness testing was made to identify the hardness values of SKT4 die material processed under different treatment conditions. The testing was conducted according to the standards of ASTM A956. The measurements were made using a portable hardness tester Mitutoyo Hardmatic HH-411 with compact dimensions.

2.8 Wear Testing

The wear test was conducted to determine the wear rate of the test specimens. The fundamental principle of wear testing is that the material is subjected to a frictional load from a rotating disc. Such contact creates abrasion that progressively removes material from the surface of the specimen. The amount of wear mark formed on the specimen determines the wear rate. For this reason, a larger and deeper wear track corresponds to a higher amount of material loss and hence, higher wear rate. In this investigation, the wear test was conducted with the help of an Ogoshi High Speed Universal Wear Testing Machine-Type OAT-U.

$$W_s = \frac{B\,.\,bo^3}{8\,.\,r\,.\,Po\,.\,lo} \tag{1}$$

Equation (1) was used to calculate the specific wear rate (W_S) of the SKT4 die specimens tested using the Ogoshi High-Speed Universal Wear Testing Machine. The specific wear rate represents the volume of material removed per unit load and sliding distance, providing a quantitative measure of wear resistance. In this equation, B is the width of the rotating wear disc (mm), b_o is the width of the wear track formed on the specimen surface (mm), r is the radius of the wear disc (mm), P_o is the applied normal load (kg), and l_o is the sliding distance (mm). Lower values of W_s indicate better wear resistance because less material is removed during the wear process. Therefore, the specific wear rate was used as a key parameter to compare the wear performance of SKT4 dies subjected to different quenching and tempering treatments.

Where:

W_s = specific wear rate $(mm^3/kg \cdot m)$
B = width of wear disc (mm)
b_o = width of wear track (mm)
r = radius of wear disc (mm)
P_o = applied load (kg)
l_o = sliding distance (mm)

2.9 Metallographic Testing

Metallographic testing is an analytical technique that involves the visual or microscopic observation of the microstructure and macrostructure of materials, generally metals and their alloys. The intention of the test is to establish some relationship between structure and mechanical, physical, and chemical properties of the material. The metallographic process comprises several stages such as preparation of the sample, observation, and analysis thereof. Sample preparation includes cutting, mounting the specimen in resin, grinding, polishing, and etching to show the grain boundaries and the microstructural features of the material. After preparation, the specimen will be examined under an optical or electron microscope to detect the material phases, grain size, inclusion distribution, defects, and other structural characteristics.

3. Results and Discussion

3.1 Forging Product Results

Based on the different variations tested, a number of the test specimens were found to have defects in either the bush or pin regions. This was due to some deformation/wear that took place on the die faces representing the pin and bush areas, which resulted in inaccuracy in the dimensions of the forged products. Such defective products were forwarded for further machining and assembly processes without delay. The following sections highlight the details in the observations for each variation.

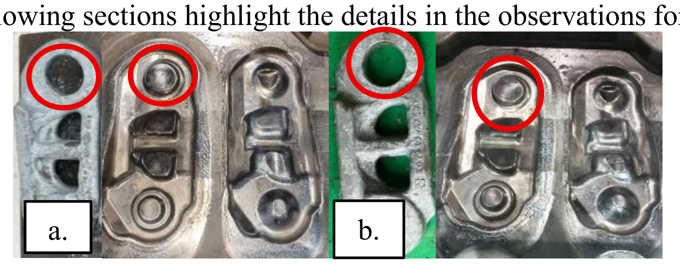

Figure 1. Product and Die Results of Salt Bath Quench Variation at 400°C
(a) Production of 3000 pieces (b) Production of 6000 pieces

As can be seen from Figure 1, the products and dies from the salt bath quenching variation that had been tempered at 400°C at operational cycles of both 3,000 pcs and 6,000 pcs presented very excellent results in terms of appearance. The forged products did not exhibit visible defects in either the pin or bush area, while the dies did not reveal any form of deformation or wear in those regions. This attests to the fact that the salt bath quenching-treated dies that were tempered at 400°C were tougher and lasted longer after evaluation from both the product and die standpoints. Thus, the result was that undercarriage link products and dies remained in normal conditions and possessed excellent quality.

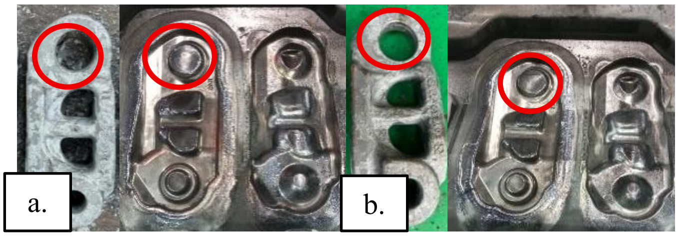

Figure 2. Product and Die Results of Salt Bath Quench Variation at 450°C
(a) Production of 3000 pieces (b) Production of 6000 pieces

As can be seen from Figure 2, the products and dies of the salt bath quenching variation with a tempering temperature of 450°C at operational cycles of 3,000 pcs and 6,000 pcs also had very good visual results. These results were similar to those of the former variation, wherein no defects appeared on the product in the pin and bush areas (red circles), but slight deformation could be seen on the bush section of the die. This deformation probably came from the toughness and hardness reduction of the material. Therefore, it is concluded that dies treated by salt bath quenching and tempered at 450°C had lower wear resistance and toughness compared to the former variation.

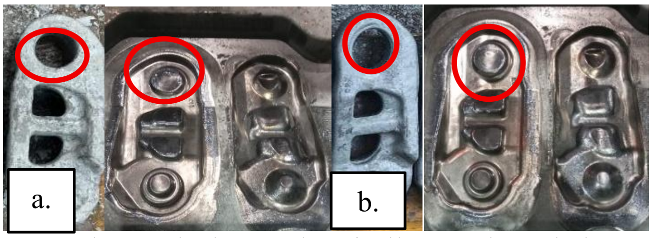

Figure 3. Product and Die Results of Oil Quench Variation at 400°C
(a) Production of 3000 pieces (b) Production of 6000 pieces
(b)

Figure 3 presents the various products and dies that result from an oil quenching variation at a tempering temperature of 400°C in operational cycles of 3,000 pcs and 6,000 pcs. At 6,000 pcs, some defects appeared on the product surface, especially in the bush area (red circles). The corresponding die section exhibited minor deformation. The deformation of the die resulted in the emergence of product defects in the bush area. This result suggests that dies tempered at 400°C after oil quenching showed similarly poor wear resistance and toughness compared to the previous variation.

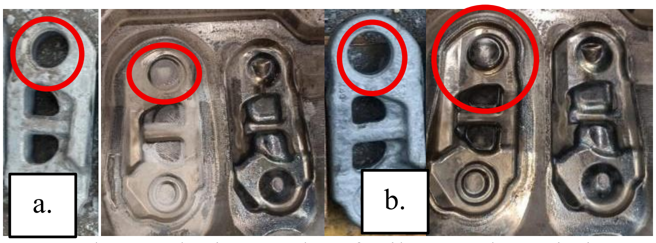

Figure 4. Product and Die Results of Oil Quench Variation at 450°C
(a) Production of 3000 pieces (b) Production of 6000 pieces

It can be seen from Figure 4 that the products and dies from the oil quenching variation with a tempering temperature of 450°C at operational cycles of 3,000 pcs and 6,000 pcs gave relatively poor visual results. This is different from the previous variations, wherein the products showed defects in the bush area-marked by red circles-and the dies presented deformation at exactly the same region. These results demonstrate that dies treated with oil quenching and tempered at 450°C had higher wear resistance and toughness compared to the previous variation. Visual testing must be supported by quantitative testing. The following tests have been conducted to validate these observations and allow supporting data for each die and its corresponding undercarriage link product.

3.2 Hardness Test Results

Table 1 shows the result of the hardness test of each variation.

Table 1. Hardness Values of SKT4 Die Material

Variation			**Hardness Value (HRC)**
Cooling Medium	**Tempering Temperatur e**	**Operational Cycle**	
Salt Bath Quenching	400°C	3000 pcs	46.1
		6000 pcs	42.9
	450°C	3000 pcs	45
		6000 pcs	41.7
Oil Quenching	400°C	3000 pcs	42.8
		6000 pcs	38.5
	450°C	3000 pcs	41.9
		6000 pcs	36.5

From this data, it can be observed that the highest value of hardness is 46.1 HRC from the salt bath quenching variation with a tempering temperature of 450°C at an operational cycle of 3,000 pcs, while the lowest one is the oil quenching variation with a tempering temperature of 450°C at 6,000 pcs. It is also shown that all variations had experienced decreasing hardness. This proves that the longer a die was used in forging production, the more its hardness decreased. According to [7], this decrease in hardness is caused by the failure experienced by dies when performing forging. This is a result or the influence of several factors occurring simultaneously, such as cyclic mechanical loading, intensive thermal stress, and severe friction and erosion.

Cyclic loading arises during forging production, as a workpiece is heated to 1150°C–1250°C and deformed cyclically in continuous thermal cycling. In summary, repetition of mechanical and thermal stresses with a very high surface temperature of the dies eventually leads to material degradation and failure. Figure 5 provides a more detailed description of the hardness characteristics of salt bath quenched dies.

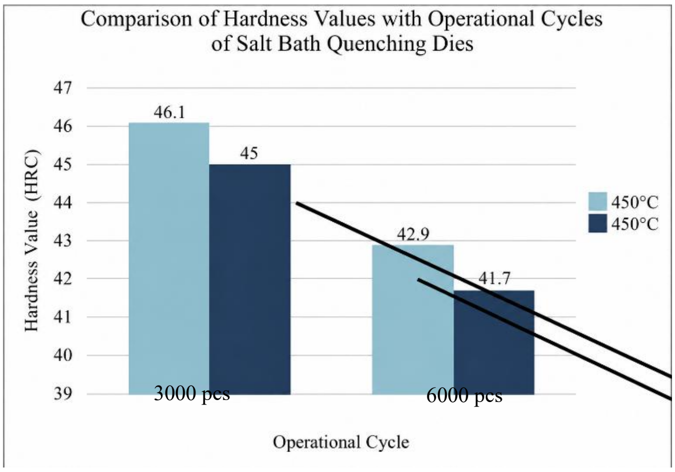

Figure 5. Comparison Graph of Salt Bath Quenched Dies

The comparative graph of the salt bath quenching dies, shown in Figure 5, reflects that each variation of tempering temperature has gone through a decrease in hardness after undergoing the forging process for 6000 pieces. At the tempering temperature of 450°C, the hardness value after forging 3000 pieces was 45 HRC, which decreased to 41.7 HRC after forging 6000 pieces, indicating that during forging, it showed a reduction of 3.3 HRC. In the case of a tempering temperature of 400°C, the hardness value after forging 3000 and 6000 pieces was 46.1 HRC and 42.9 HRC, respectively, with a reduction of 3.2 HRC. Comparing these variations, the reduction of hardness at the tempering temperature of 400°C was smaller compared to that at 450°C. It indicates that at 400°C, there is higher hardness and better ductility. The explanation of hardness values of the oil-quenching dies is given in Figure 6.

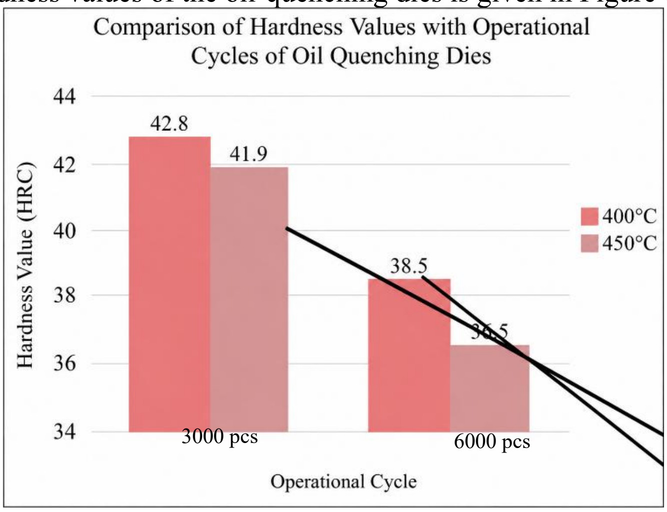

Figure 6. Comparison Graph of Oil Quenched Dies

Figure 6 shows that the comparative graph of oil-quenching dies also represents a decrease in hardness for every tempering temperature variation after forging 6000 pieces. The 450°C tempering temperature resulted in a hardness value of 41.9 HRC after forging 3000 pieces, decreasing to 36.5 HRC after forging 6000 pieces, at a reduction of 5.4 HRC. The 400°C tempering temperature had a hardness value of 42.9 HRC after forging 3000 pieces, reducing to 38.5 HRC after forging 6000 pieces, a reduction of 4.4 HRC. Consequently, the tempering temperature variation of 450°C had a greater decrease in hardness compared to the variation at 400°C.

Based on the explanation above, it is clear that the dies with the variation of salt bath quenching at a tempering temperature of 400°C produced the highest hardness value and the smallest reduction after forging 6000 pieces. This directly affected the condition of the undercarriage link PC200 SKD NEW product, where no defects appeared in the pin and bush areas. According to [8], the use of the salt bath quenching method followed by tempering results in high hardness combined with good toughness. This is because the salt bath quenching process produces a predominantly tempered martensitic microstructure that is more homogeneous from the surface to the core, reducing the risk of distortion and residual stress due to its more homogeneous cooling characteristics. Salt bath quenching has a uniform cooling effect because there is no vapor blanket when the hot surface contacts the salt bath. This is due to its liquid phase, which can conduct full convection immediately. Therefore, temperature reduction begins with consistent cooling across the whole surface with minimal fluctuation, resulting in a more uniform temperature distribution and minimal distortion [9].

3.3 Results of Wear Testing

The results of the wear test for each variation are given in Table 2.

Table 2. Wear Test Results

Variation			**Wear Specific (Ws) (mm^3/kg.m)**
Cooling Medium	**Tempering Temperature**	**Operational Cycle**	
Salt Bath Quenching	400°C	3000 pcs	6,9777x10^{-5}
		6000 pcs	8,1242x10^{-5}
	450°C	3000 pcs	6,9994x10^{-5}
		6000 pcs	10,2118x10^{-5}
Oil Quenching	400°C	3000 pcs	9,0830x10^{-5}
		6000 pcs	11,3554x10^{-5}
	450°C	3000 pcs	9,7105x10^{-5}
		6000 pcs	21,5262x10^{-5}

According to Table 2, the wear values of each variation have been obtained. The smallest value of wear rate of each variation was 6.9777×10^{-5} mm^3/kg·m for the salt bath quenching variation at a tempering temperature of 400°C after 3000 operational cycles, while the largest value of wear rate belonged to the oil quenching variation at the tempering temperature of 450°C after 6000 operational cycles, showing the value of 21.5262×10^{-5} mm^3/kg·m.

Linking the data to the hardness values of each variation [10], mentioned that the higher the hardness value of a material is, the better it will be in terms of wear resistance and the lower the specific wear rate (Ws). According to [11], from the relationship between the tempering temperature and hardness value, it can be obtained that the higher the tempering temperature used, the lower the hardness value compared with the lower tempering temperature. This is because the higher tempering temperature that is used, the faster the decomposition of martensite and the growth of carbides will occur, so that the structure becomes softer. Thus, the influence of tempering temperature, hardness value, and the specific wear rate is interconnected. Based on that, it can be obtained that the salt bath quenching variation with the use of a tempering temperature of 400°C had the highest hardness value and lowest value of specific wear rate compared to all the variations.

3.4 Metallographic Testing Results

The following section discusses the microstructural characteristics observed for each variation.

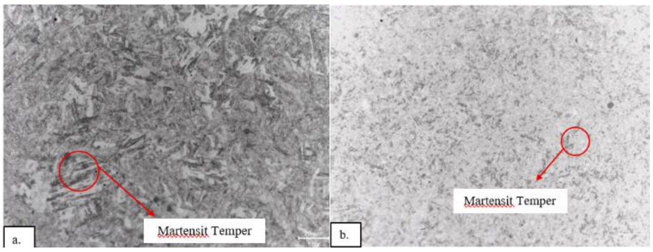

Figure 7. Microstructure of SKT4 Dies at Tempering Temperature of 400°C, Production of 3000 Pieces, 50× Magnification
(a) Oil Quenching (b) Salt Bath Quenching

Figure 7 shows a comparison of the microstructure from each variation. Image (a) shows a tempered martensitic structure where an acicular morphology is well defined. The sharp and well-defined lath formations indicate that the original martensitic structure upon oil quenching has taken place. Bright regions distributed around the darker matrix indicate the presence of carbide precipitates. Image (b) indicates a much finer, shorter, and uniform resulting tempered martensitic structure than that produced by oil quenching [12]. The lath morphology in this structure is less sharp than in the previous picture. This can be because the transformation from austenite to martensite takes place more uniformly throughout the material with less thermal gradient present within the material [13]- [15]. This greatly reduces the creation of internal stresses during cooling. Visually, the resulting structure seems smoother and less coarse compared to the oil-quenched microstructure [16]- [18].

A finer and more uniform structure due to the salt bath quenching process theoretically provides higher toughness with comparable hardness [19]. Minimal internal stress not only minimizes the likelihood of failure during the heat treatment process itself but also prolongs the service life of the dies in the forging operation. This also tallies with the hardness and wear resistance values of each variation, where image (b) exhibits higher hardness and wear resistance than image (a). According to [12], a larger grain size tends to decrease hardness by reducing the density of grain boundaries which act to impede dislocation movement [20]. This relationship is also supported by the Hall–Petch equation, which inversely relates hardness to the square root of grain size. Microstructural analysis further confirms that continuous forging progressively decreases the hardness of the die material with increased numbers of forging cycles.

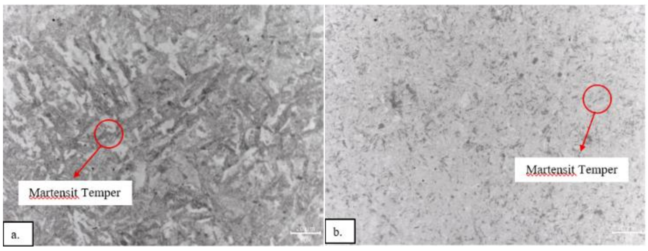

Figure 8. Microstructure of SKT4 Dies with Tempering Temperature of 400°C, 6000 Pieces, 50× Magnification (a) Oil Quenching (b) Salt Bath Quenching

Figure 8 shows the microstructures developed for each variation. Image (a) shows a clearly tempered martensitic phase, which consists of long, sharp, but relatively coarse laths. These laths are oriented in every direction, reflecting the prior austenitic grain structure. The coarse and well-defined morphology is characteristic of martensitic transformation under high thermal stress due to rapid and uneven cooling in oil. Image (b) shows that the laths of the tempered martensitic phase are much finer, shorter, and more homogeneously distributed. There are no obvious coarse and elongated laths as seen in the oil-quenched sample; thus, it appears more homogeneous [21].

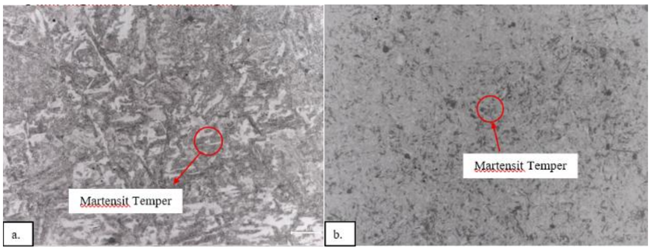

Figure 9. Microstructure of SKT4 Dies with Tempering Temperature of 450°C, 3000 Pieces, 50× Magnification (a) Oil Quenching (b) Salt Bath Quenching

Figure 9 presents a comparison of the microstructure obtained by each variation. Image (a) depicts a tempered martensitic phase with a clearly distinct, long, and somewhat coarse lath morphology. The large lath structure is indicative of the process. The result of oil quenching, this morphology develops from the severe thermal stress induced by cooling. Image (b) reveals a tempered martensitic phase which has much finer, shorter, and more evenly distributed laths throughout the matrix. The absence of any coarse dominant laths leads to an extremely homogenous appearance.

As discussed in [13], increasing the tempering temperature from 400°C to 450°C results in a hardness reduction for both samples because of additional carbide growth. Yet the basic appeal of salt bath quenching remains. The finer and more uniform structure provided by salt bath quenching will give superior toughness at a given hardness level since cracks are unlikely to propagate as effectively through a matrix with fine, evenly distributed laths compared to the coarse structure of the oil-quenched sample [14].

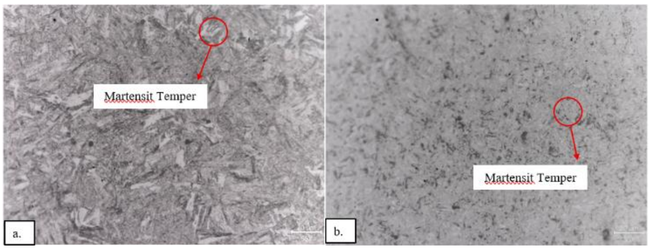

Figure 10. Microstructure of SKT4 Dies with Tempering Temperature of 450°C, 6000 Pieces, 50× Magnification (a) Oil Quenching (b) Salt Bath Quenching

Based on Figure 10, a comparison of the microstructures obtained from each variation can be observed. In image (a), a tempered martensitic structure with long, needle-like, and relatively coarse laths is evident. This coarse morphology results from martensitic transformation under high thermal stress during the oil quenching process. In image (b), the tempered martensitic phase shows finer, shorter, and more uniformly distributed laths, creating a homogeneous structure. This structure is produced by a more controlled cooling process compared to oil quenching [22].

Based on the discussion above, several differences are observed between dies subjected to oil quenching and those treated with salt bath quenching. These differences include the main morphology, structural homogeneity, and the underlying causes of these variations. According to [8], salt bath quenching provides superior cooling control compared to oil quenching. This occurs because, in salt bath quenching, no vapor blanket forms when the hot surface comes into contact with the salt bath. Instead, the salt bath remains in a liquid state, allowing immediate full convection quenching. Consequently, the temperature decreases consistently across the entire surface without large fluctuations, resulting in uniform cooling and minimal distortion. In terms of microstructural characteristics, the oil-quenched specimens exhibit a non-uniform microstructure dominated by coarse, large-lath martensite, while salt bath quenching produces a much more uniform tempered martensitic structure with finer acicular morphology [23]- [25]. The resulting grain size also differs; according to [14], oil quenching generally produces larger grain sizes compared to faster cooling media such as salt baths. Slower cooling rates lead to a coarser mixed microstructure.

4. Conclusion

In the oil-quenched dies, the tempered martensitic phase has a clear acicular morphology with sharp and well-defined laths. On the other hand, for the salt bath-quenched dies, the structure of the tempered martensite is finer, shorter, and homogeneous compared to that developed in oil-quenched dies. Salt bath–quenched dies show higher hardness compared to oil-quenched dies for temperature variations of 400°C and 450°C and operational cycles of 3000 and 6000 pieces. Among the different variations of tempering temperatures and operational cycles, the lowest specific wear value is obtained for the salt bath–quenched dies that have been tempered at 400°C with 3000 operational cycles. The salt bath-treated products and dies show excellent visual results without any defects in the pin and bush areas, with no deformation in the respective die sections for tempering temperatures of 400°C and 450°C and 3000 and 6000 cycles. On the other hand, the products and dies treated with oil quenching at tempering temperatures of 400°C and 450°C for 3000 and 6000 cycles have shown inferior visual results, with defects in the bush areas and minor deformation observed in the respective die regions.

Declaration of AI and AI assisted technologies in the writing process
No AI or AI-assisted technologies were used in the preparation of this manuscript.

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.

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