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EXPERIMENTAL STUDY ON NOTCH SHAPE AND LIQUID CARBONITRIDING SPECIMENS UNDER BENDING LOADING

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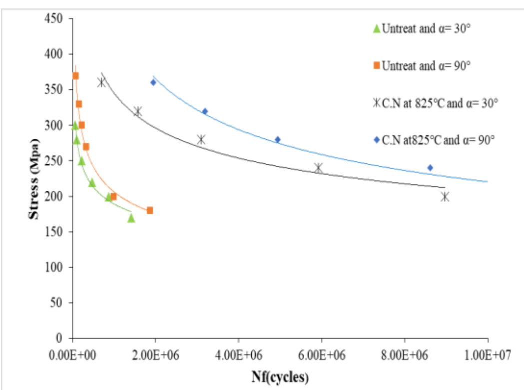
Graphical abstract



Abstract

The current work includes studying the effect of heat treatment using liquid carbon nitriding technology on steel notched (DIN17100) at two angles of 30° and 90 °, with a depth of 0.5 mm. samples were soaked for a continuous 1.5 hr in a molten salt bath at 750°C, 800°C, and 825°C. After that, samples were quenched in heated oil at 60°C and tempered at 180°C. Mechanical testing is part of the process; include tests for surface microhardness, fatigue before and after treatment,tensile testing and chemical analysis of the material. Before treatments, fatigue testing was done on the notched specimens at room temperature under full reverse bending stress. Obusirved that V-notching the specimen reduced strength and fatigue life of steel. The results showed that heat treatments significantly increased strength and fatigue life; in comparison to untreated samples, heat treatments increased fatigue life by 12.5% and 20%, respectively. Finding that the carbonitriding method of hardening produced a surface hardness of 868.71HV, which was 73% higher than the non-hardened samples.The fatigue strength increased to 338.55 MPa and 455.56 MPa at 30° and 90 °, respectively, at the highest temperature due to saturation of the surface with carbon and nitrogen atoms.

Keywords: Liquid carbonitriding, fatigue test, hardness, shape notch, FLIF

1.0 INTRODUCTION

The material (steel structures, shafts, gear teeth, screws, etc.) frequently undergoes gradual structural deformation when it is repeatedly and cyclically subjected to load, and the maximum stress values will typically be less than the normal tensile stress limit as well as possibly the yield stress limit. A component's fatigue life is expressed as the number of loading cycles needed to start a fatigue crack and allow it to grow to a critical size [1]. The phenomenon of metal fatigue is intricate, with various elements influencing its fatigue life, including the type of material used, its structure, form, and temperature changes. Through more types of fatigue, lives are estimated with a load cycle number, which means that objects or materials can be handled before failure. Usually, the fatigue life of un-notched (plain) specimens is much longer than that of notched specimens [2]. There are many studies that talk about the effect of cracks on fatigue behaviour due to the concentration of stresses in those areas. Fatigue failures of machine components remain a issue of relevant importance in the manufacturing world. Typically, they result from geometrical elements like grooves, notches, corners, and holes, the true impact of which is sometimes underestimated during the design stage. Due to its intricate microstructure and complex geometries, gray cast iron cast parts are common examples of components that are challenging to design for fatigue [3]. As a result, it is imperative to increase the fatigue life and mechanical qualities of steel, and there are numerous ways to do so, including nitrocarburizing [4], cyanide salt bath [5–6], Rf plasma carbonitriding [7], and gas carbonitriding [8]. Carbonitriding process gives bright finishing on the product. Distortion can be easily avoided and fatigue limit can be increased[9]. The fundamental characteristic of steel is its hardening ability, or the capacity to undergo a partial or total transformation from austenite to martensite in a given amount of time and under a given set of circumstances [10]. One type of heat treatment known as liquid carbonitriding involves saturating the steel surface with diffusive elements (carbon and nitrogen) in their atomic state. These elements are produced when certain compounds develop and come into contact with the steel surface, forming bonds. Chemical by the process of absorption and then penetration into the steel by the process of diffusion. Nitrogen stabilises austenite, and as much as 70% mass-% of austenite can be kept depending on the amount of carbon and nitrogen content attained [11-12]. Zhang *et al*. [13] studied nitrocarburized in gas and salt bath effict on medium carbon steel was , forming three layers (oxide layer, compound layer and diffusion layer) on the surface of the specimen. The results show that fatigue limits of the specimens treated in gas and salt bath are improved by 120% and 100%, respectively, compared to that of the untreated specimens after the very high cycle fatigue (VHCF) test peformed. Poppy *et al.* [14] employed a novel technique called pack carbonitriding to treat low-carbon steel specimens. Pack carbonitriding temperatures ranged from 700 to 800 degrees Celsius, with holding times of one and two hours, respectively. The outcome demonstrated how steel's mechanical properties are impacted by temperature differences caused by carbonitriding. When holding times were shortened from two hours to one hour, steel toughness rose. Sajjad *et al*. [15] studied the effect of surface treatments on LCS under rotating bending fatigue behaviour and found that the fatigue life of steel was significantly improved compared to the metal before treatments. Jifa Chen *et al*. [16] carried out a fatigue test on the specimen whose diaphragm segments had curved notches. Arc-shaped notched plate steel specimens with corresponding notch radii of 10, 20, and 30 mm have been employed. concluded that as the notch radius grows, fatigue life increases as well. The right increase in notch radius during the design of the curved notch in steel box girder cross-sections is advantageous to extending the structure's fatigue life. Dazhen et a. [17] investigated the effect of post-ion carbonitriding treatment on mechanical properties and tribological properties of the carburized and quenched 18Cr2Ni4WA steel. According to the data, the wear rate of ion carbonitriding samples dropped by more than 99% under two conditions: a 6 N light load and a 60 N heavy load. The friction coefficient stayed essentially unaltered. The results have shown that careful selection of carburizing and ionic nitro hardening temperatures significantly improves surface hardness and wear resistance. After treatment, the material's surface hardness increased by 50%, but its core hardness only decreased by less than 20%. The aim of this paper is to study the effect of shape notch before and after treatment with liquid carbonitriding on the fatigue behaviour of low-carbon steel at a variable temperature, which was not implemented in the previous works mentioned above. Study the effect of liquid carbonitriding on the improvement percentage of fatigue life and fatigue property. The material used is DIN17100 low carbon steel. Two types of V-shaped notched samples at angles of 30° and 90 °, were produced. The samples were immersed in a salt bath inside a stainless steel box designed for this purpose. The fatigue properties and surface hardness were measured experimentally before and after treatment.

2.0 METHODOLOGY

2.1 Metal Seliction and Tensile Test

In this research, a low-carbon steel alloy (St-44) was used, whose chemical composition (wt%) is C: 0.22, Cr: 0.138, Mn: 0.499, Si: 0.136, and Fe: Ball. As a result of its wide use in engineering projects and applications. Tensile testing was performed using a WAW-200-1180kN machine. The tensile specimens were designed according to ASTM-A 370, so they were valuable in terms of yield strength (380 MPa) and ultimate strength (530 MPa).

2.2 Preparation of Sample

According to the standards for ASTM 606-80 cylindrical specimens, fatigue test specimens were produced as shown in Figure 1. For the purpose of testing it on a fatigue device (WP 140). A CNC machine was used. Two categories were established for the designed fatigue specimens. First category of specimens included notch at an angle of 30°, while the second category of specimens also included a notch but at a 90-degree angle. Samples with notches have a depth of 0.5 mm. The notch is situated 10 mm from the mounting side. Figure 2 illustrating the specifics of the research samples.

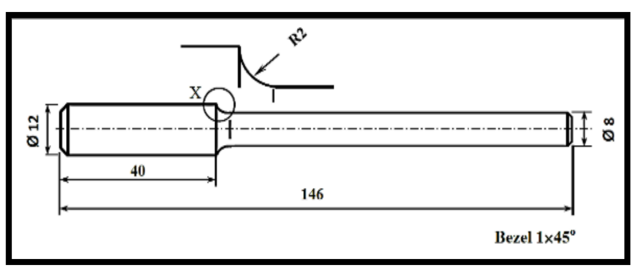


Figure 1 Schematic diagram for fatigue test specimens

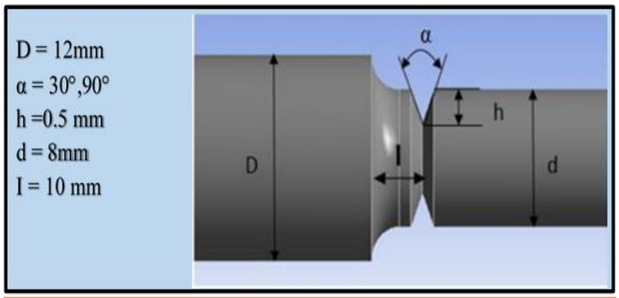


Figure 2 Dimensions of V shape notch specimens [15]

2.3 Fatigue Device

Rotating bending fatigue testing machine used, he machine type is (GUNT HUMBURG WP 140) shown in Figure 3.

Figure 3 Machine of rotating bending fatigue test

2.4 Heat Treatments

2.4.1 Stress Relieving

Stress relief is performed by heating a furnace to a temperature below the critical temperature and holding it at that temperature long enough to achieve the desired reduction in residual stresses. The temperature, duration and time kept at temperature are the basic processcycles. This process relieves internal stresses without causing any color change. Returns the material to a strength level approximately equivalent to that it was in before forming.

In this work all specimens were subjected to a temperature of 200 °C for three hours using an eclectic furnace as part of the internal stress relief process[18].

2.4.2 Liquid Carbonitriding

Preparing the saline solution medium (liquid carbonitriding(C.N)) according to weight percentages: 61% sodium cyanide, 24% sodium chloride, and 15% potassium carbonate [15]. Mixing salts in a crucible made of stainless steel. It was then placed in a furnace at a temperature of 650°C with the aim of melting the components before inserting the samples. The process of melting the components was accompanied by the process of heating the samples in another furnace at a temperature of 200°C. To get rid of stuck-on moisture and avoid popping caused by moisture, if it is placed inside molten,where it is suspended in a steel holder, then the contianer containing the molten salts was withdrawn from the furnace, and the heated samples were placed inside it (suspended in the molten substance) and returned to the furnace, where the heating process continued for 1.5 hr at temperatures of 750°C, 800°C, and 825°C, then the crucible is withdrawn, the samples are taken out, and they are placed directly in the oil heated to a temperature of 60°C to reduc deformation[19]. This process was followed by tempering at 200°C for 2 hours to remove internal stresses, reduce hardness, and increase durability, so that the steel is able to withstand shocks and vibrations. Figure 4. Illustrate the details of the treatments performed on the samples before and after liquid carbonitriding.

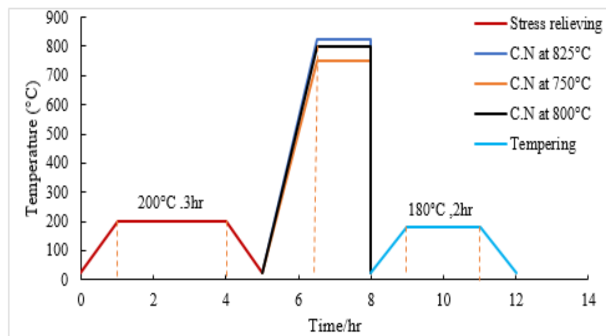


Figure 4 Heat treatment cycle

3.0 RESULTS AND DISCUSSION

In the article that follows, the fatigue test results for each temperature, form angle, and surface hardness measurement will be discuss.

3.1 Hardness Measurement

The result showed that the surface hardness of low-carbon steel that is treated with a liquid carbonitreding process at a soaking time of 1.5 hours with a variation of temperature (750°C, 800°C, and 825°C) can be seen in Table 1 following:

Table 1 Results of hardness low carbon steel due to liquid carbonitriding

Heat treatment	Time/ hr	VH, hardness No.specimens 1	2	3	Average HV	Improvement hardness %
Base metal	----	234	234.9	235.3	234.7	------
750°C	1.5	713	716	716.7	715.23	67
800°C	1.5	840.07	845.13	847.18	844.12	72
825°C	1.5	866.15	868.78	871.2	868.71	73

The hardness tests were carried out using Vickers method with the type of device (HVS-1000) , Three replicated tests were performed on samples of each liquid carbonitriding temperature.

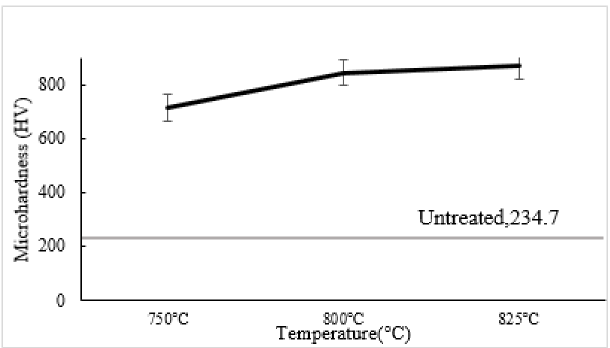


Figure 5 Surface microhardness vs. treatment temperature

Figure 5 illustrates the liquid carbonitride's microhardness as a function of treatment temperature. On the sample surface, a significant rise in microhardness was observed. Steel that has undergone the liquid carbonitriding process contains additional elements, such as Cr, which has a strong affinity for nitrogen due to the high processing temperature. Some fine iron nitride (Fe_4N) and iron carbide (Fe_3C) precipitates formed inside the diffusion layer, which led to an increase in hardness [9]. The hard layer that impedes plastic flow is what makes the surface hardness improve fatigue strength. Observed that the increase in temperature leads to an increase in the surface hardening by 67%, 72%, and 73% for 750°C, 800°C, and 825°C, respectively. The obtained results show that the hardening achieved a higher surface hardness of 868.71 HV relative to unhardened samples.

3.2 Fatigue Test Results

Figure 6 and Figure 7 show the S-N curves of liquid carbonitriding. These figures show fatigue behaviour after surface thermal treatments at variable temperatures (750°C, 800°C,and 825°C) with constant soaking time. observed a significant change in fatigue behaviour after surface hardening with liquid carbonitriding compared with samples untreated. It is observed that the increase in temperatures and constant soaking time (sample retention time in the salt bath medium inside the furnace at high temperatures) results in an enhancement of each hardening process' fatigue performance. The improvement in fatigue performance (life and strength) of the surface-hardened samples comes from using surface heat treatments that create a protective layer (hardened layer). Because of the difference in concentrations from high concentrations (carbon medium) to low concentrations (steel surface with low carbon content), carbon and nitrogen atoms diffused together inside the metal surface, resulting in this layer [20], where the steel's surface hardens and becomes smoother as carbon and iron combine to form iron carbide Fe_3C (cementite), which is what gives steel its high stress resistance. The nitrogen atom that results from this process is also more able to penetrate farther because of its small size. Inside the surface of the mineral with deformation of the crystal structure, which leads to delayed crack initiation and growth. The experimental data from fatigue testing is fitted to create these curves. It is noted that the best enhancement in the (S-N) curve is at a temperature of 825°C at an angle of 90 degrees and an angle of 30 degrees compared to the temperatures of 750°C and 800°C, as shown in Figure 8.

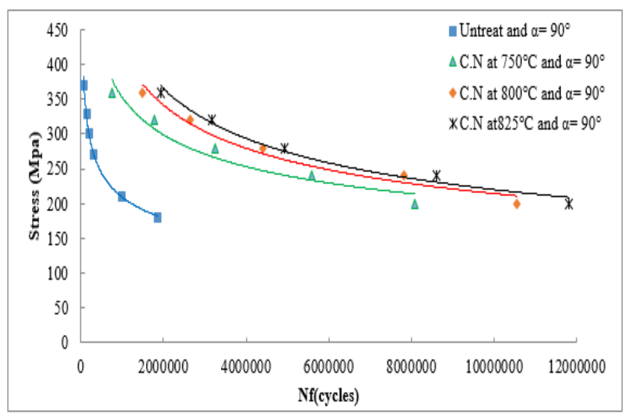


Figure 6 S-N curve of fatigue test samples at variable temperatures with an angle of 90 degrees after and before carbonitreding

The component's shape and the manufacturing method have an effect on the stress concentration. For the test specimens used to evaluate the fatigue strength of engineering materials, the stress concentration of the circumferential notch in the circular bar is significant. Observed in this work that the stress concentration factor for the notched specimens of the selected materials under reverse bending is that the shape of the 30° degree angle significantly affected the fatigue resistance compared to the 90° degree angle as a result of the concentration stress. The stress concentration decreased at the 90-degree angle due to the angular shape of the notch. Whenever the angle notch is greater than 30°, stress concentration decreases and fatigue resistance increases.

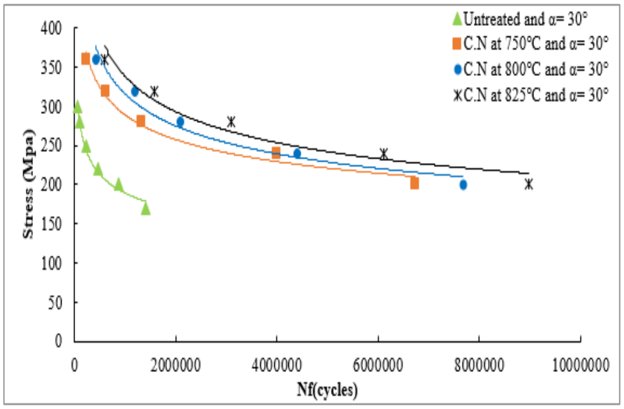


Figure 7 S-N curve of fatigue test samples at variable temperatures with an angle of 30 degrees after and before carbonitriding

Figure 9 show the enhancement of the fatigue behaviour of low-carbon steel 17100 at stress 200 MPa after and before treatment with liquid carbonation, as the number of cycles increased from 981668 RPM at point A to 11807744 RPM at point D. Table 2 shows the improvement in fatigue life at an applied stress of 200 MPa at different degrees of heat treatment.

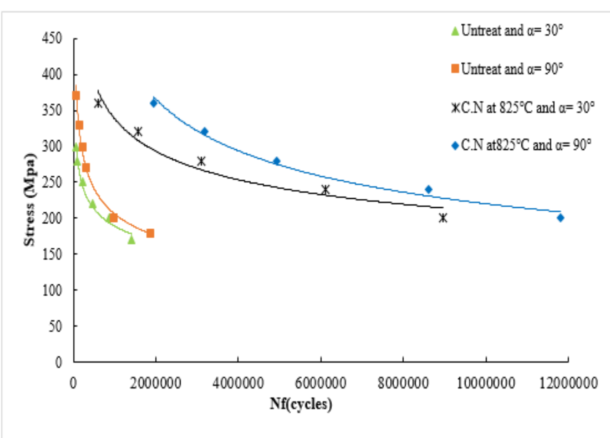


Figure 8 S-N Curve of fatigue test samples at variables angle (30 and 90 degree) temperature 825°C after and before carbonitreding

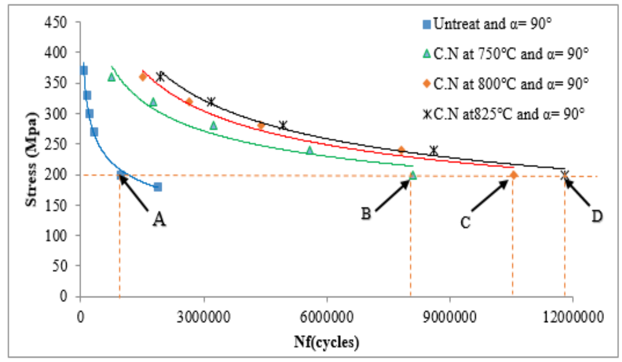


Figure 9 S-N curve of fatigue test samples at variable temperatures with an angle of 90 degrees after and before carbonitreding at stress 200 MPa

Table 2 Results life cycles of specimens experimentally for liquid carbonitriding at variable temperatures and constant soaking time at stress 200 Mpa

Stress(Mpa)	Cycles			
	A	B	C	D
200	981668	8085524	10542629	11807744

3.3 Basquin Equation

The experimental S-N equations (Basquin's equations) and the experimental fatigue strength (fatigue limit) for liquid carbonitriding are shown in Table 3 and Table 4. Equation 1 provides Basquin's equation, which is a power law regression [21].

$$\sigma = a\, N^{\,b} \tag{1}$$

a and b curve fitting constant.

Remarkably, the highest fatigue strength at 10^6 cycles is 455.56 MPa and 338.55 MPa for shape angles 90° and 30° degrees at 825°C, and the minimum fatigue strength at 10^6 cycles is 351.56 MPa and 289.48 MPa for shape angles 90° and 30° degrees, respectively, at 750°C with a constant soaking time of 1.5 hours.

- FSIF can be calculated from the flow equation 2 [9], [22].

$$FSIF\% = \frac{\sigma_e - \sigma_{ref}}{\sigma_{ref}} x100\% \tag{2}$$

Where σe refers to the fatigue strength of hardened steel after 10^6 cycles, and σ_{ref}. denotes the fatigue strength of an untreated specimen after 10^6 cycles. 10^6 cycles is the value of fatigue strength for alternating stress of steel. After 10^6 cycles, the standard considers the fatigue life to be infinite.

- FLIF can be calculated from the following equation 3 [9].

$$FLIF\% = \frac{\sum |\log N_f - \log N_{ref}}{\log \sum N_{ref}} \quad (3)$$

Where N_f is the number of surface-hardened metal failure cycles, and N_{ref} is the number of untreated reference material failure cycles, In contrast to samples that had been surface-treated, the untreated reference material had the fewest cycles to failure.

Table 3 Results S-N equation of LCS notched shape angle 30 degree

Heat treatments	S-N equation	Fatigue strength (MPa)	Fatige ratio σ_e/σ_{ult}	FSIF %	FLIF %
Untreated	$\sigma_a = 2023N^{-0.172}$	187.92	0.35	----	----
750°C	$\sigma_a = 2868.3N^{-0.166}$	289.48	0.54	54	9.46
800°C	$\sigma_a = 5007.1N^{-0.2}$	315.92	0.59	68	10.8
825°C	$\sigma_a = 5992.8N^{-0.208}$	338.55	0.63	80	12.5

Table 4 Results S-N equation of LCS notched shape angle 90 degree

Heat treatments	S-N equation	Fatigue strength (MPa)	Fatigue ratio σ_e/σ_{ult}	FSIF%	FLIF%
Untreated	$\sigma_a = 4485.1N^{-0.222}$	208.82	0.39	---	----
750°C	$\sigma_a = 9683.3N^{-0.24}$	351.56	0.66	68	16.85
800°C	$\sigma_a = 22679N^{-0.289}$	418.43	0.78	100	19.11
825°C	$\sigma_a = 34878N^{-0.314}$	455.56	0.85	118	20

It was observed that as the temperature rose and the constant soaking time increased, the chosen material's fatigue strength increased due to the diffusion of more carbon and netrogin atoms through the surface at a certain depth towards the core, where carbon with iron forms iron carbide Fe3C (cementite) and nentrogin with iron forms Fe4N on the surface of the metal, which is responsible for the high resistance of steel to stresses. Thus, these atoms of carbon and nitrogen fill the voids and scratches and obstruct the initiation and growth of cracks. Figure10 shows the effect of surface heat treatment on FSIF%. The figure shows that the FSIF% increases with an increase in temperature. It is concluded that in the liquid carbonitriding process, FSIF% increases by about 54%, 68%, and 80% at 750°C, 800°C, and 825°C, respectively, during V shape angle 30°, while in the same process, FSIF% increases by about 68%, 100%, and 118% at V shape angle 90° degrees. It is concluded that the maximum improvement percentage of fatigue strength is 80% and 118% for v-shaped angles of 30° and 90° degrees, respectively, at a temperature of 825°C.

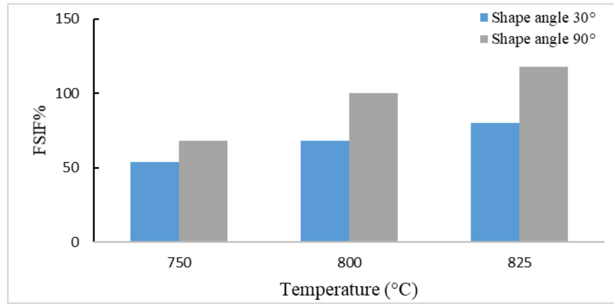


Figure 10 Fatigue Strength Improvement Factor for different temperature with constant time

Table 3 and Table 4 show the percentage fatigue life improvement factor for heat treatments (liquid carbonitrid) at variable temperatures. It was concluded that the maximum improvement percentage of fatigue life is 20% at 825 °C with a V shape angle of 90° degrees, 12.5% with a V shape angle of 30° degrees, and the minimum fatigue life at 750 °C is 9.4% at a V shape angle of 30° degrees. Figure 11 illustrate factor improving fatigue life after heat treatments with variable temperatures of molten salt bath.

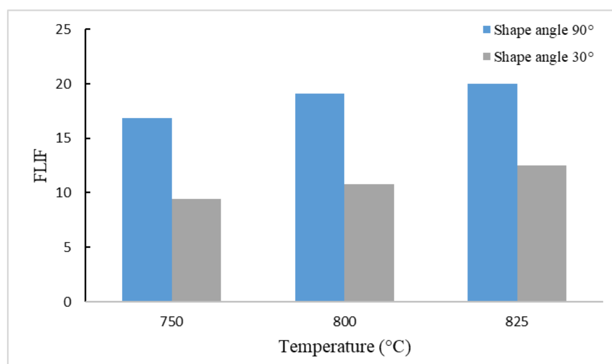


Figure 11 Fatigue life improvement factor for different temperature with constant time

4.0 CONCLUSION

The current work studied the effect of heat treatments using carbon nitriding under variable temperature conditions on notched steel. The selected material was chemically examined, tensile test, micro-surface hardness test, and fatigue test were examined. Results showed that liquid carbonitriding significantly improved both surface hardness and fatigue performance. A soaking time of 1.5 hours at 825°C enhanced fatigue life by 12.5% for 30° notched samples and 20% for 90° notched samples. Surface hardness of St44-2 DIN17100 steel increased by up to 73% compared to untreated samples. The fatigue strength increased to 455.56 MPa and 338.55 MPa compared to untreated steel 187.92 MPa and 208.82 MPa for specimens notched at 90° and 30° angles, respectively. at the standard fatigue life of 10^6 cycles, the maximum improvement in fatigue strength was 118% for 90° notched and 80% for 30° notched samples. These findings highlight the effectiveness of liquid carbonitriding in enhancing the mechanical properties of notched steel.

Nomenclatures

Symbol	Meaning	Unit
σ_e	Fatigue Strength	MPa
a, b	curve fitting constant.	
σ_{ult}	Ultimate stress	Mpa
N	Number of cycles	Cycle

Abbreviations	
HV	Hardness Vickers
RF	Radiofrequency
ASTM	American Society for Testing and Materials
C.N	Carbonitriding
Fe_3C	Iron Carbide
Fe_4N	Iron Nitride
FSIF	Fatigue Strength Improvment Factor
FLIF	Fatigue Life Improvment Factor

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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