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Effect of Heat Treatment on Fatigue Behavior of Carbon Steel

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ABSTRACT
This research comprises a study of the effect of heat treatment on fatigue behavior carbon steel, and it was concluded that the increase of fatigue strength is directly proportional to the increase in tensile strength. The best results were obtained for the specimen tempered at comparatively low temperature (200°C). These specimens have also shown the highest endurance limit; this is perhaps due to the fact that these specimens possess vary high strength with significant ductility.

Keywords: carbon steel, endurance limit and ductility, tensile strength

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INTROUCTION

All materials have different properties that result in advantages and disadvantages. The study and understanding of these properties are critical to the design of a mechanical system and the selection of the correct materials for a given part. One crucial failure mode is fatigue. Fatigue is the weakening or failure of a material resulting from prolonged stress. However, it is understood that when a mass is repeatedly cyclically loaded at a location on the material, cracks begin to form. These cracks spread enough to eventually cause failure and break the piece at the location. Consequently, when designing a mechanical system, it is important to know these limits [1].

Carbon steel is an alloy of iron and carbon. This steel type may also include traces of other elements like manganese, up to a 1.65% maximum; silicon, with a 0.6% maximum; and copper, up to 0.6%. High carbon steel contains 0.6–1.4% carbon [2]. Carbon steel is probably the most widely used engineering material. It is extensively used for high-temperature applications in power plants, chemical and petrochemical processing, oil refining, and in many other industries. Boiler tubes in power plants, reactor vessels in process industries, heat-treating fixtures, and exhaust train piping [3].

Generally, with an increase in the carbon content from 0.01% to 1.5% in the alloy, its strength and hardness increase, but still such an increase beyond 1.5% causes appreciable reduction in the ductility and malleability of the steel [4].

Experimentation Design

The experimental techniques for the project work are listed as follows:

- Heat treatment
- Study of mechanical properties
- Fatigue life estimation

The specimen preparation was the first and foremost job for the experiment. The sample was taken from medium carbon steel from a trader. It is a medium carbon steel having high hardness with moderate ductility and high strength as specified in Table 1.

Table 1. *Chemical composition of the specimen.*

C	Mn	Si	Mo	S	P	Fe
0.54	0.72	0.18	0.06	0.037	0.03	Balance

The objective was to carry out the heat treatment of medium carbon steel at different temperatures according to heat treatment process [5], and then to compare the mechanical properties. There are various types of heat treatment processes we had adapted.

Annealing

- The specimen was heated to an annealed temperature of 800°C.
- At 800°C, the specimen was held for 1 hour.
- After soaking for 1 hour, the furnace was switched off so that the specimen temperature will decrease with the same rate as that of the furnace.

Normalizing

- First, the specimen was heated to the temperature of 800°C.
- There the specimen was kept for 1 hour.
- After soaking for desired time, the furnace was switched off and the specimen was taken out.
- Now the specimen is allowed to cool in the ordinary environment, i.e. the specimen is air-cooled to room temperature.

Quenching and Tempering

- First, some of the specimens were heated to 800°C for 1 hour and then quenched in the water bath maintained at room temperature.
- Among them, some of the specimens were heated to 200°C but for a different time period of 1, 1 1⁄2 and 2 hours, respectively.
- Now some more specimens were heated to 400°C for the same time periods

After the specimens got heated to different temperatures for different time periods, they were air-cooled. The heat treatment of tempering at different temperatures for different time periods develops a variety of properties within them.

RESULTS AND DISCUSSION

Fatigue Life Estimation Results and Analysis

The results showed the variation of life cycles with respect to stress where load was applied and calculated by Moore testing machine. Here all the dimensional values were considered according to the dimension of the specimen. From these life cycles, different heat treatments are estimated and tabulated in Tables 2–6.

Table 2. *Life estimation for normalizing.*

Serial no.	**Stress (MPa)**	**No. of cycles to failure, *N***	**Value of Log *N***
1	432 (YS)	1.6×10^5	5.1
2	416 (0.95 YS)	3.2×10^5	5.2
3	392 (0.90 YS)	$6.3{\times}10^5$	5.4
4	370 (0.85 YS)	1.2×10^6	6.0
5	347 (0.80 YS)	2.5×10^6	6.3
6	343 (0.80 YS)	5.0×10^6	6.6
7	346 (0.80 YS)	1.0×10^7	7.0
8	342 (0.80 YS)	2.0×10^7	7.3
9	341 (0.80 YS)	4.5×10^7	7.8
10	348 (0.80 YS)	9×10^7	8.0

Table 3. *Life estimation for annealing.*

Serial no.	**Stress (MPa)**	**No. of cycles to failure, *N***	**Value of Log *N***
1	425 (YS)	3.2×10^5	5.5
2	403 (0.95 YS)	6.3×10^5	5.8
3	382 (0.9 YS)	1.2×10^6	6.1
4	361(0.85 YS)	2.5×10^6	6.4
5	340 (0.80 YS)	5.0×10^6	6.7
6	318 (0.75 YS)	1.0×10^7	7.0
7	318 (0.75 YS)	1.9×10^7	7.3
8	318 (0.75 YS)	3.9×10^7	7.6
9	318 (0.75 YS)	7.9×10^7	7.9
10	318 (0.75 YS)	1.5×10^8	8.2

Table 4. *Life estimation for tempering at 200°C, 1 hour.*

Serial no.	Stress (MPa)	No. of cycles to failure, *N*	Value of Log *N*
1	817 (YS)	4.9×10^4	4.7
2	772 (0.95 YS)	1.26×10^5	5.0
3	737 (0.90 YS)	1.9×10^5	5.2
4	693 (0.85 YS)	3.16×10^5	5.4
5	659 (0.80 YS)	5.01×10^5	5.6
6	610 (0.75 YS)	7.94×10^5	5.8
7	572 (0.70 YS)	1.26×10^6	6.0
8	577 (0.70 YS)	1.99×10^6	6.2
9	570 (0.70 YS)	3.1×10^6	6.3
10	577 (0.70 YS)	5.01×10^6	6.5

Table 5. *Life estimation for tempering at 200°C, 2 hours.*

Serial no.	Stress (MPa)	No. of cycles to failure, *N*	Value of Log *N*
1	725 (YS)	1.9×10^5	5.2
2	693 (0.95 YS)	3.16×10^5	5.4
3	653 (0.90 YS)	5.01×10^5	5.7
4	618 (0.85 YS)	7.94×10^5	5.7
5	581 (0.80 YS)	1.26×10^6	6.0
6	545 (0.75 YS)	1.99×10^6	6.5
7	511 (0.70 YS)	3.1×10^6	6.6
8	474 (0.65 YS)	5.01×10^6	6.7
9	475 (0.65 YS)	7.9×10^6	6.8
10	472 (0.65 YS)	1.2×10^7	7.0

Table 6. *Life estimation for tempering at 400°C, 1 hour.*

Serial no.	Stress (MPa)	No. of cycles to failure, *N*	Value of Log *N*
1	619 (YS)	2.51×10^5	5.3
2	588 (0.95 YS)	3.98×10^5	5.5
3	557 (0.90 YS)	6.3×10^5	5.7
4	557 (0.90 YS)	1×10^6	6.1
5	557 (0.90 YS)	1.58×10^6	6.3
6	557 (0.90 YS)	2.51×10^6	6.5
7	557 (0.90 YS)	3.98×10^6	6.6
8	557 (0.90 YS)	6.3×10^6	6.9
9	557 (0.90 YS)	1×10^7	7.1
10	557 (0.90 YS)	1.58×10^7	7.3

CONCLUSION

From the Tables 1–6, we came to the conclusion that the variation of fatigue limit and also the respective cycles are significantly visible for 400°C. Fatigue limit of 400°C, 1 hour, is much higher than that of the 1 1⁄2 and 2 hours. For 400°C, 1 hour, the fatigue limit comes around 557 MPa at 6.0×10^5 number of cycles. But for 1 1⁄2 hours, it comes around 430 MPa which is less than that of the 1-hour tempering at 400°C but from 1 1⁄2 hours, when the time period changed to 2 hours, there is a slight decrement in the fatigue limit from 430 to 395 MPa. At 2-hour tempering for the same temperature, the fatigue limit comes at 1.6×10^6 number of cycles slightly more than that of the 1-hour tempering.

Life estimation by Moore's fatigue testing machine is based upon the yield stress (YS) of the specimen. Application of various loads as calculated and tabulated in the Tables 1–6 gives different fatigue limits for different heat-treated samples. From these results we come to the following conclusions:

Endurance limit increases with increases in tensile strength. It has been the highest 573 MPa for low-temperature (200°C) tempering. As tensile strength decreases with tempering time, endurance limit also decreases. Endurance limit of normalized steel is higher than that of annealed ones, but at a particular stress level (above the endurance limit 346 MPa), cycles cause less fatigue failure for normalized steel. As far as tempered specimens are concerned, it has been seen that at a particular temperature the endurance limit decreases with the increase tempering time, the highest for 200°C at 1 hour, i.e. 573 MPa, and the lowest for 200°C at 2 hours, i.e. 473 MPa. For the other two tempering temperatures also, the variation of endurance limit will be the same as that of 200°C. It has also been found after 1 1⁄2 hours, the effect of time becomes practically insignificant (the endurance limit remains constant). At the intermediate temperature (400°C), the effect of time is more significant. There is a sharp fall in the values of endurance limit from 1 1⁄2 to 2 hours of tempering. From the above study, it may be concluded that the increase of fatigue strength is directly proportional to the increase in tensile strength. The best results were obtained for the specimen tempered at comparatively low temperature (200°C). These specimens have also shown the highest endurance limit. This is perhaps due to the fact that these specimen possess very high strength with significant ductility. So, as far as fatigue strength is concerned, the low-temperature tempering may be regarded as the best possible heat treatment operation. From the above discussions, it can be concluded that the micro-structural changes may have a greater impact on fatigue properties.

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