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EFFECT OF HEAT-TREATMENT UNDER CHANGEABLE APPLIED LOAD ON WEAR RESPONSE OF AGRICULTURAL GRADE MEDIUM CARBON STEEL: A MULTIPLE RANGE ANALYSIS

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Abstract: Low alloy medium carbon steels have tremendous potential for agricultural application because of its low cost and obtaining excellent combination of various properties after heat treatment. In the present study abrasive wear response of medium carbon steel used for soil working components of agricultural implements i.e. rotavator blade, cultivator sweep, plough share etc. was studied under three heat treatment processes and three load conditions. Micro structural, mechanical, and tribological properties of medium carbon SAE-6150 steel were altered by annealing, inter-critical annealing and quenching and tempering heat-treatment processes. A rotating rubber wheel type test apparatus was used to measure the wear rate of heat-treated and control specimen at 75, 200 and 375 N loads. This technique of wear measurement is very similar to working condition of soil working components of agricultural implements. The study revealed that under low load (75 N) condition, both the inter-critically annealed and quenched and tempered SAE-6150 medium carbon steels gave identical wear resistance. However, inter-critically annealed material under medium load (200 N) condition and quenched and tempered material under high load (375 N) condition exhibited supremacy in terms of abrasive wear resistance.

***Key words**: soil working components, mechanical properties**,** heat-treatment cycle, abrasive wear, DMRT*

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INTRODUCTION

Most of the fast wearing components of agricultural machines like plough share, cultivator sweep, rotavator blade, weeder blade, thresher pegs are made up of various grades of medium carbon steel. High strength and abrasive wear resistance is primary requirement for these components to overcome abrasive wear, fatigue and chemical reaction during operation. Micro-structural examination of various working components of agricultural machines revealed that most of these components were not properly heat-treated [10]. Formation of ferrito-martensitic structure and tempered martensitic structure in the steel during heat-treatment process provides extremely excellent combination mechanical as well as tribological properties [7-9]. Heat-treatment process especially quenching and tempering is a commonly used popular method to improve the wear resistance and hardness of agricultural implements [7,9]. Apart from different heat-treatment processes, various surface modification technologies such as diffusion processes like carburising, nitriding, boriding [2], coatings [4] as well as hard facing [1,3] and shot peening [6,7] have been tried by various researchers to alter the properties of the materials. All above-mentioned treatment changes the micro-structural constituents of the material, which leads to change in hardness that follows a linear relationship with the wear rate in most of the cases. Some of these surface modification techniques, used to overcome the wear situation in agricultural engineering application, are cheaper but these are effective up to a certain depth. As the effective depth is worn out, the specimen behaves like the parent specimen [7]. The medium carbon steel like SAE-6150 after application of heat-treatment gave better wear resistance in rotavator blades among other steels used for agricultural application in India which was also techno-economically viable [11]. Wear rate at the same time is highly influenced by the applied load and sand particle size used to induce abrasive wear on the specimen [5]. Soil working components of various agricultural machineries usually work under different soil conditions having variable soil resistance or draft. Hence, evaluation of influence of heat-treatment processes in medium carbon low-alloyed agricultural grade steel under different system of applied load is very crucial. This will be helpful to determine the appropriate heat treatment process to be given to the material of these components engaged in different farm operations exerting distinct load on them so that the cost incurred for heat treatment can be minimized.

MATERIAL AND METHODS

Present study was conducted at Central Institute of Agricultural Engineering (CIAE), Bhopal, India during 2009-10. In this study a low alloyed medium carbon steel (SAE-6150) most common used for fast wearing components of agricultural machinery containing 0.52% C, 0.22% Si, 0.70% Mn, 1.0% Cr, 0.17% V, 0.025% S and balance Fe was used. This steel was undergone three heat-treatment process at Indo-German tool room Indore. German made double chamber furnace was used for austening the specimen at 870^0C for two hours. In case of inter-critical annealing the specimens after socking two hours were shifted to second chamber at 777^0C for 30 minutes. For annealing the specimen were allowed furnace cooling and others were quenched in circulating water and 8% NaCl solution for uniform heat flow. Tempering of these specimens was carried out at 250^{0}C for two hours in German made fluidized bed furnace for maintaining the uniformity of properties in the steel specimen. The hardness and mechanical properties of control and heat-treated specimens were measured using Vicker's hardness tester and universal testing machine. The control and treated specimens were examined for their micro-structural characterization using Scanning Electron Microscope (SEM) at Advanced Materials and Processes Research Institute, Bhopal as per standard procedure. Rotating rubber wheel (having 12.7 mm thickness and 177.8 mm diameter) type dry sand apparatus was used to study the wear behaviour of control and treated specimens of 76.2 mm X 25.4 mm X 8 mm size as per ASTM G-65 standard. Initially polished specimens were used and subsequent tests were conducted on pre worn surfaces of the specimens. This process was repeated to obtain steady state value of the wear rate. The specimens were tested using dry crushed silica sand particles of 212-300 μm at the rate of 370 g/min for abrasion on the stationary specimen's surface pressed against the rotating rubber wheel as depicted in Fig.1. During the testing the speed of rotating rubber wheel was maintained at 100 rpm (1.86 m·s^{-1} linear velocity) with three loads (75, 200 and 375 N). This test methodology is very similar to the working condition of soil engaging components of agricultural machinery.

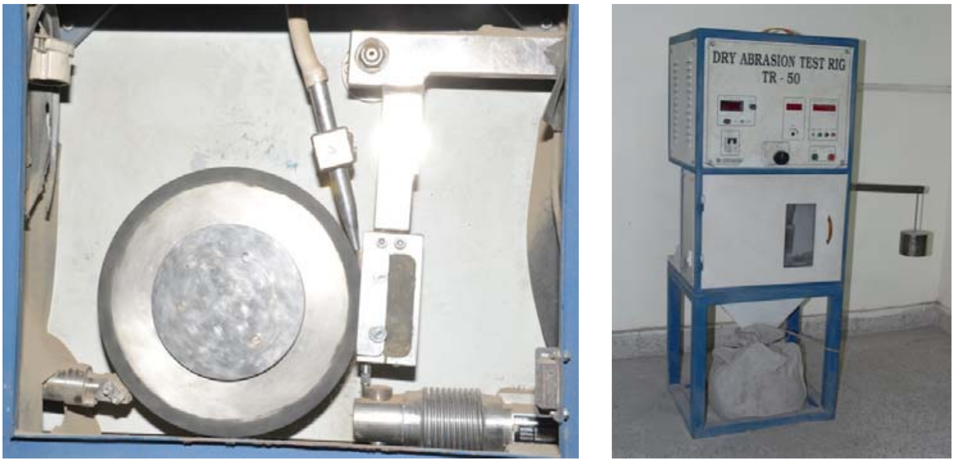

Figure 1. Rubber wheel /dry sand abrasion test apparatus

The experiment was laid out by following factorial completely randomized design with two factors namely, heat treatment process with four levels and applied load with three levels to find out the effect of heat treatment processes and applied load as well as their interaction on wear response of medium carbon steel for indicating the most suitable heat treatment process under different load regimes so as to minimize the cost incurred for heat treatment. Similar multi-factor analysis of variance technique to work out the least significant difference (LSD) was also adopted by [5] for finding the effect of individual as well as interacting factors influencing the grain yield of winter wheat. However, moving a step further we applied Duncan's Multiple Range Tests (DMRT) to the means to critically scrutinize the behaviour of different heat treated materials under varying load applied on them.

RESULTS AND DISCUSSION

The average hardness, ultimate tensile strength, percentage elongation and volume fraction of micro constituents of the examined steel i.e. Control and heat-treated is depicted in Tab. 1. These results indicate that the control and annealed specimen; inter-critically annealed and quenched & tempered steels have almost identical mechanical properties and microstructural constituents.

Table 1. Properties of SAE-6150 steel undergone various heat-treatment processes

Heat-treatment	*Phase %*	*Hardness (HV)*	*Ultimate tensile strength [N·mm^{-2}]*	*Percentage elongation*
Control	*86% pearlite and remaining ferrite*	*150*	*858*	*7*
Annealed	*80 % pearlite and remaining ferrite*	*130*	*785*	*11*
Inter-critical annealing	*85% tempered martensite and remaining ferrite*	*471*	*1390*	*6*
Quenching & tempering	*96 % Tempered martensites and remaining retained austenite*	*498*	*1450*	*4*

The micro-constituents of control and annealed specimens are 86% pearlite, 14 %ferrite and 80 % pearlite, 20 % ferrite respectively. These steels are almost identical only the percentage of ferrite is increased by about 6 % when the steel under gone annealed process as compared to control. Hardness of control and annealed steel is 150 HV, 130 HV respectively; the ultimate tensile strength and percentage elongation are also almost similar in these two specimens. On the other side inter-critical annealing and quenching & tempering also depict similar behaviours. The ICA steel contains 85% tempered martensite and 15 % ferrite, whereas QT condition depicted tempered martensites with 4-5% retained austenite. The martensitic structure is relatively harder in comparison to ferritic and pearlitic, so the hardness of the heat-treated specimen increases with increase the martensite content. After inter-critical annealing or quenching & tempering process the hardness of the specimen was 471 and 498 HV i.e. more than threefold of the hardness of the control specimen and ultimate tensile strength of the steel increased to three fold to the control and annealed specimen.

Effect of sliding distance, heat-treatment and applied load on abrasive wear

The wear rate of control as well as heat-treated specimen as a function of sliding distance at 375 N load is examined in Fig. 2(a). This figure depicts that the wear rate reduces in uniformity with the sliding distance due to continuous work hardening (plastic deformation) during the abrasion process and finally reaches to the stable value. Annealed steel has lower hardness but more capacity to work hardening due to releasing the residual stresses; it becomes more ductile than the control. It retains wear debris for long duration and the chips/flakes are not easily removed from the surface of the specimen. The wear rate of control and annealed are comparable irrespective of the sliding distance; it is reduced substantially 60-75 % in case of inter-critical annealing and quenching & tempering process. This reduction is due to generation of harder phase of micro-structure i.e. ferrito-martensite or tempered martensite in case of inter-critical annealing or quenching and tempering process, which controls the penetration and scratching ability of the hard abrasive on the specimen surface. There structures exhibit excellent combination of strength and toughness to control the by the sand particles from the specimen surface. Similar trend is obtained when the specimens were tested at lower loads i.e. 75 and 200 N loads. The wear rate of differently heat-treated specimen as a function of applied load is depicted in Fig. 2(b).

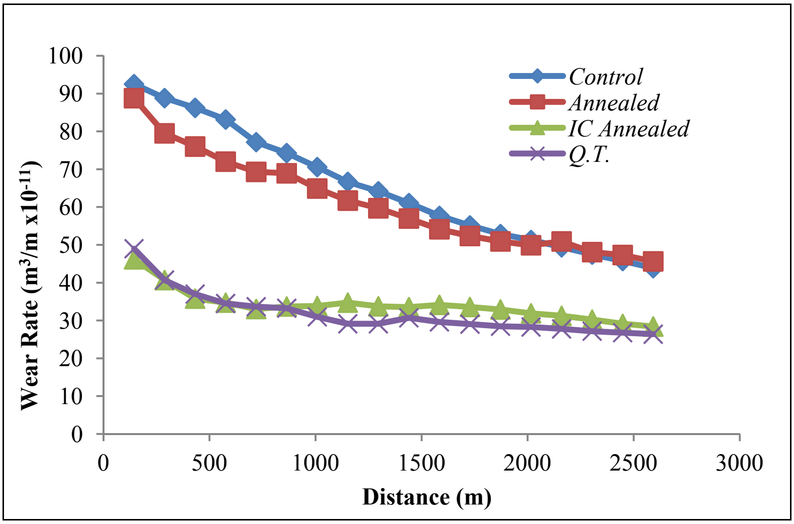

Figure 2(a). Wear rate as a function of sliding distance

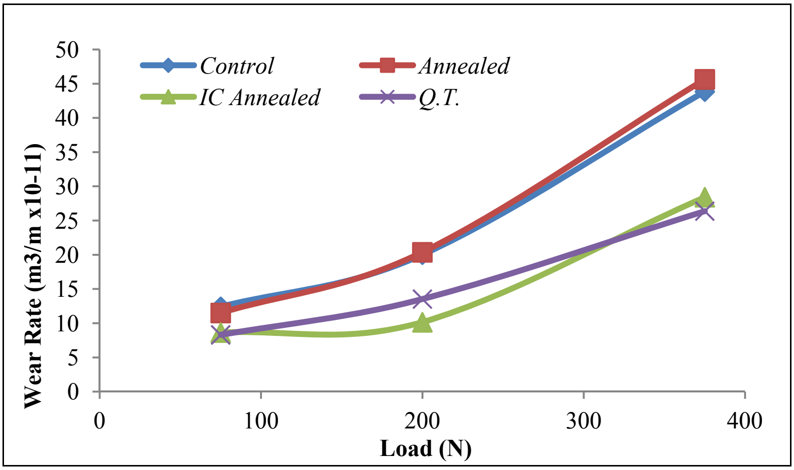

Figure 2(b.) Wear rate as a function of applied load

It is evident from this figure that wear rate increases with applied load irrespective of heat-treatment schedule. As explained earlier on the base of wear rates are these heat-treatments classified in two categories in formal category control and annealed specimen and in latter category inter critical annealed and quenching & tempering. The former category exhibits significantly higher wear rate than that of later category at all applied loads. This signifies that microstructure and mechanical properties have significant effect on wear behaviour of the steel specimens. This figure shows that at higher applied load the trend of wear rate changes i.e. the wear rate of quenched and tempered steel reduces than that of inter critical annealing because of transformation of retained austenite in to tempered martensitic structure because of generation of high heat due to fraction.

The effect of heat treatment and applied load on wear rate of medium carbon steel (SAE-6150) has been described in Tab. 2. It was observed that there was insignificant reduction in wear rate in annealed specimens as compared to control specimens. These two specimens have almost identical microstructure and mechanical properties. The hardness of annealed specimen is slightly lower than the control that is compensated by the removal of residual thermal stresses. However, the wear rate reduced significantly when the specimens were subjected to inter-critically annealing and quenching and tempering treatments, because of generation of harder phase during the heat-treatment process. But, the difference in wear rate between these two treatments was found again insignificant because in both the cases formation of ferrito-martensitic and tempered martensitic structure gives excellent combination of toughness and ductility, which reduces the penetration or scratching ability of the hard abrasives during the wear test.

Table 2. Effect of heat treatment and applied load on wear rate of SAE-6150 steel

Factors of experiment	*Wear rate*	*Least significant difference at 5% level of significance*	*Standard error of mean*
No heat treatment (Control)	*25.826*	*0.651*	*0.223*
Annealed	*25.414*		
Inter-critically annealed	*15.728*		
Quenched and tempered	*16.075*		
Under low load (75 N)	*10.213*	*0.564*	*0.193*
Under medium load (200 N)	*16.008*		
Under high load (375 N)	*36.061*		

Table 3. Analysis of variance for factorial experiment

Source of variation	*Sum of squares*	*Degree of freedom*	*Mean sum of squares*	*F-ratio*	*Coefficient of variation (%)*
Heat Treatment	*851.324*	*3*	*283.775*	*633.550****	*3.224*
Load	*4415.018*	*2*	*2207.509*	*4928.445****	
Heat Treatment x Load	*324.831*	*6*	*54.138*	*120.868****	
Residual	*10.749*	*24*	*0.448*	*-*	
Total	*5601.923*	*35*	*-*	*-*	

**** = Significant at 1% level*

The analysis of variance for different factors and their combination influencing the wear rate of medium carbon steel (SAE-6150) showed that all the factors and their combinations were significantly controlling the wear rate in the material under study (Tab. 3). As shown in earlier table, the heat treatment processes exert a distinctive and polarized effect on wear rate because after heat-treatment the steel specimens depict two categories i.e. poor combination of microstructural and mechanical properties i.e. control and annealed specimen and excellent combination such as inter-critical annealing and quenching & tempering whereas; the applied load demonstrated a linear influence on wear rate because during abrasion testing, increase in applied load increases the depth of penetration which leads to more removal of material from the specimen i.e. more wear rate.

Table 4. Duncan's multiple range test for heat treatment under different load

Load condition	*Heat treatment*	*Wear rate*	*Rank obtained*	*Least significant difference at 5% level of significance*	*Standard error of mean*
Under low load (75 N)	*No heat treatment (Control)*	*12.404*	*fg*	*1.128*	*0.387*
	Annealed	*11.500*	*g*		
	Inter-critically annealed	*8.632*	*i*		
	Quenched and tempered	*8.317*	*i*		
Under medium load (200 N)	*No heat treatment (Control)*	*20.003*	*e*		
	Annealed	*20.360*	*e*		
	Inter-critically annealed	*10.140*	*h*		
	Quenched and tempered	*13.530*	*f*		
Under high load (375 N)	*No heat treatment (Control)*	*43.835*	*b*		
	Annealed	*45.618*	*a*		
	Inter-critically annealed	*28.412*	*c*		
	Quenched and tempered	*26.378*	*d*		

Duncan's Multiple Range Test (DMRT) was applied for distinguishing the treatment combinations according to their rank to identify treatments for maximum wear resistance. It was observed that under low load condition, both inter-critically annealing and quenching and tempering emerged out as the maximum wear resistance inducing treatments for medium carbon steel (SAE-6150). Both the steel specimen have excellent combination of microstructural and mechanical properties, which reduces the penetration of hard sand particles and during low load application, the force exerted on the sand particle for penetration or scratching also low that leads to minimum wear rate or maximum wear resistance. However, under medium load condition inter-critically annealing was the most desirable treatment for reduction of wear rate for the same material showing a significant improvement in wear rate as compared to quenched and tempered steel.

Generation of ferrito-martensitic structure in intercritically annealed steel depicts excellent combination of toughness and ductility, whereas, martensitic structure of quenched and tempered steel is more brittle in comparison to ferrito-martensitic structure. This leads to more cutting and fragmentation from the specimen surface during wear. With further increase in applied load, the wear resistance behaviour in medium carbon steel showed significant transformation as the quenched and tempered steel showed the best wear resistance revealing significant improvement in reduction of wear rate as compared to inter-critically annealed steel. At higher applied load i.e. 375 N, due to higher fraction the surface temperature increases very high and its effect at the point of contact is again very high that leads to transformation of retained austenite to martensite and at high temperature the brittleness of the steel again reduces and lesser tendency for fragmentation contributes towards reduction in wear rate of quenched and tempered steel when tested at higher applied load.

Therefore, the study indicates that both the inter-critically annealed and quenched and tempered medium carbon steel can be selected as material for manufacturing the components which are subjected to soil resistance typically for conducting farm operations like deep ploughing in summer in heavy clay soils but inter-critically annealed material should be preferred for farm operations like deep trench making for irrigation. However, for farm operations involving very high draft like digging of well, using of quenched and tempered material is the only option for manufacturing of working components.

CONCLUSIONS

The process of heat-treatment applied to medium carbon steel determines its micro-structural, mechanical and tribological properties to a great extent. Treatments such as quenching and tempering as well as inter-critically annealing of medium carbon steel result into greater hardness with desirable mechanical properties which lead to superior abrasive wear resistance as compared to that of controlled and annealed steel. However, the heat-treatment process should be selected according to the load applied on the working components. Therefore, it is suggested that the soil working components of agricultural machinery may be appropriately heat treated for better resistance to abrasive wear and enhanced service life.

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UTICAJ TOPLOTNOG TRETMANA POD PROMENLJIVIM OPTEREĆENJIMA NA HABANJE RADNIH ORGANA OD SREDNJE UGLJENIČNOG ČELIKA: ANALIZA VIŠE OPSEGA

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Sažetak: Nisko legirani srednje ugljenični čelici imaju značajan potencijal za upotrebu u poljoprivredi zbog svoje niske cene i postizanja odlične kombinacije različitih svojstava posle toplotnog tretmana. U ovom istraživanju je proučavano abrazivno habanje srednje ugljeničnog čelika od koga su izrađeni radni organi priključaka za obradu zemljišta, kao što su nož roto sitnilice, motičica kultivatora, raonik pluga i sl., posle tri toplotna tretmana i u uslovima tri nivoa opterećenja. Mikro strukturne, mehaničke i tribološke osobine srednje ugljeničnog čelika SAE-6150 su izmenjene žarenjem, inter-kritičnim žarenjem sa naglim hlađenjem i toplotnim tretmanom površinskog kaljenja. Uređaj sa testiranje sa rotacionim gumenim točkom je upotrebljen za merenje stepena habanja toplotno tretiranog i kontrolnog uzorka pod opterećenjima od 75, 200 i 375 N. Ova tehnika merenja habanja je veoma slična radnim uslovima u kojima se nalaze radni organi priključaka za obradu zemljišta. Istraživanje je pokazalo da pod malim opterećenjem (75 N) i inter-kritično žaren pa naglo hlađen i pogvršinski kaljen srednje ugljenični čelik SAE-6150 daje jednak otpor habanju. Ipak, inter-kritično žareni material pod srednjim opterećenjem (200 N) i hlađeni i kaljeni material pod visokim opterećenjem (375 N) pokazali su najveće otpore abrazivnom habanju.

Ključne reči: *radni organi za obradu zemljišta, mehanička svojstva, ciklus toplotnog tretmana, abrazivno habanje, DMRT*

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