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EFFECT OF THERMO MECHANICAL PROCESSING ON MICROSTRUCTURE AND WEAR BEHAVIOR OF FREE-CARBIDE STEEL CONTAINING DIFFERENT ALUMINUM

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ABSTRACT

This paper studies the effect of addition different Al contents (0.1 and 0.5%Al) and different post cooling rates after hot forging on the tensile properties and wear resistance of free-carbide steel. Dry sliding wear tests were carried out using experimental design technique (pin on disc) at different pressures of 1, 2 and 3MPa versus different velocities range of 1 to 10m/s. The worn surface was observed. Relationship between different work hardening due to different cooling rates and wear rates were plotted using **Lorentzian equation**. Addition of Al remarkably enhances the wear resistance of steel.

KEYWORDS: Al Content, Dry Sliding Wear Resistance, Hot Forging

INTRODUCTION

Free-carbide bainitic steels can offer high strength and high toughness and exhibit good wear-resistance. However, there are relatively few examinations of the wear properties of such steels **[1,2].** Addition of Al and Si suppresses and delay the formation of carbides (cementite) and consequently inhibits voids formation and delay crack initiation. Effect of Al on the wear resistance was not studied in details before. Microstructure constituents of the steels were related to their wear resistance.

There is a contradiction about the pearlitic and bainitic wear resistance **[3-5]**. Some papers concluded that wear resistance of pearlitic steels was found superior than bainitic steels **[6-10]**. However, in other studies some researchers showed that bainitic steels exhibited enhanced wear resistance when compared to pearlitic steels **[11-13]**. Therefore, this paper is a trial to understand the effect of different phases due to different cooling rates in existence of Al contents.

EXPERIMENTAL WORK

Material Preparation: A 100 kg of carbon steel scrap was alloyed with Al in open air induction furnace. Fe–Mn, Fe-Si and C were added to adjust the materials balance. The steel after re-melting was poured in Y-block sand mould. The chemical composition was determined using spectrometer as listed in **Table 1**.

Dilatation Test: To choose the proper thermo-mechanical zones, it was necessary to determine the critical transformation temperatures through dilation experiments and expectation of transformation temperature using empirical formulas. Dilatation test was carried using quench type dilatometer and the dilatation curves are shown in **Figure 1**.

Another helpful method is to predict the transformation temperatures from empirical formulas Kasatkin and Vinokur (1984), as demonstrated in equations 1 and 2. The transformation temperatures calculated and measured temperatures are listed in **Table 2**.

Table 1: Chemical Composition, wt%

Alloy	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb
0.1Al	0.285	0.495	1.56	0.0293	0.0194	0.217	0.238	0.534	0.0899	0.300	0.103
0.5Al	0.289	0.505	1.63	0.0310	0.0225	0.206	0.236	0.533	0.549	0.308	0.045

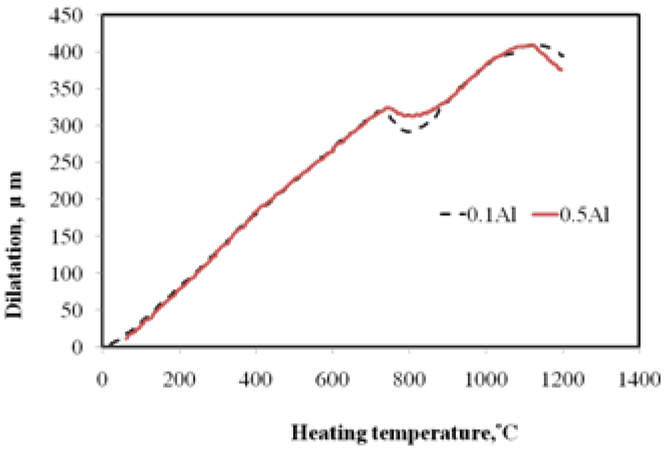

Figure 1: Dilatation Curves of Different Alloy Steels

Ac1 = 723 – 7.08 Mn + 37.7 Si + 18.1 Cr + 44.2 Mo + 8.95 Ni + 50.1 V + 21.7 Al + 3.18 W + 297 S – 830 N – 11.5 C*Si – 14 Mn*Si + 3.10 Si*Cr – 57.9 C*Mo – 15.5 Mn*Mo – 5.28 C*Ni – 6 Mn*Ni (1)

Ac3 = 912 – 370 C -27.4 Mn + 27.3 Si – 6.35 Cr – 37.7 Ni +95.2 V+ 190 Ti + 72 Al + 64.5 Nb + 5.57 W + 332 S + 276 P + 485 N- 900 B +16.2 C*Mn + 32.3 C*Ni + 15.4 C*Cr + 48 C*Ni + 4.32 Si*Cr – 17.3 Si*Mo – 18.6 Si*Ni + 4.8 Mn*Ni + 40.5 Mo*V (2)

Hot Forging

From dilatation results, the hot forging heating temperature was determined. Steel parts were heated up to 1200°C for 30 minutes and then hot forged as shown in **Figure 2**, the final shape after hot forging was bar with diameter of 15 mm (85% reduction in cross-sectional area).

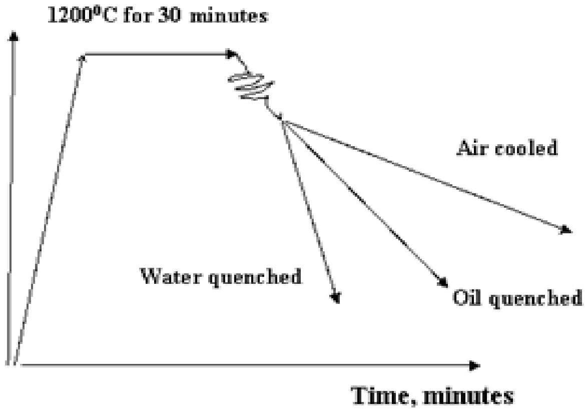

Figure 2: Thermo-Mechanical Processing Schematic Diagram

Wear Test: Dry sliding wear tests (pin on disc) were carried out using experimental design technique at different pressures of 1, 2 and 3MPa, versus different linear velocities range of 1 to 10m/s were been used. The worn surface was observed. Relationship between elapsed time and weight loss was constructed giving the wear rate. Relationships between wear pressures, linear velocities of wear test and wear rates (mg/hr) were plotted. Relationship between different work hardening due to different cooling rates after forging and wear rates were plotted. Empirical formulas were produced to explain the previous relationships.

RESULTS AND DISCUSSIONS

Dilatation Test: From dilatation results listed in **Table 2**, it is clear that Al content increases the transformation temperatures Ac_1 and Ac_3, respectively. Therefore, it is considerable to depend on the dilatation measurements instead of empirical formulas calculations. It is clear that the transformation temperature increases with increasing Aluminum content (Aluminum is ferrite former element).

Table 2: Expected and Measured Ac1 and Ac3

Alloy	Ac1, °C		Ac3, °C	
	Expected	Measured	Expected	Measured
0.1Al	715.4	720	823.1	870
0.5Al	714.7	736	822.8	924

Hot Forged Microstructure of 0.1Al Steel: Figure 3 shows the SEM microstructure of 0.1Al steel after thermo-mechanical treatment followed by post different cooling rates.

The as-cast steel (0.1wt%Al) exhibits relatively coarse ferrite matrix containing fine degenerated pearlite due to slow cooling after casting as shown in **Figure 3-a.** The effect of post cooling after hot forging leads to refining the microstructure and different morphologies as shown in **Figure 3b-d.**

The steel of air cooling shows fine bainite (see **Figure 3-b**). The moderate cooling due to oil quenching provides upper martensite as shown in **Figure 3-c**, while drastic cooling rate due to water quenching produces lower fine martensite as shown in **Figure 3-d**.

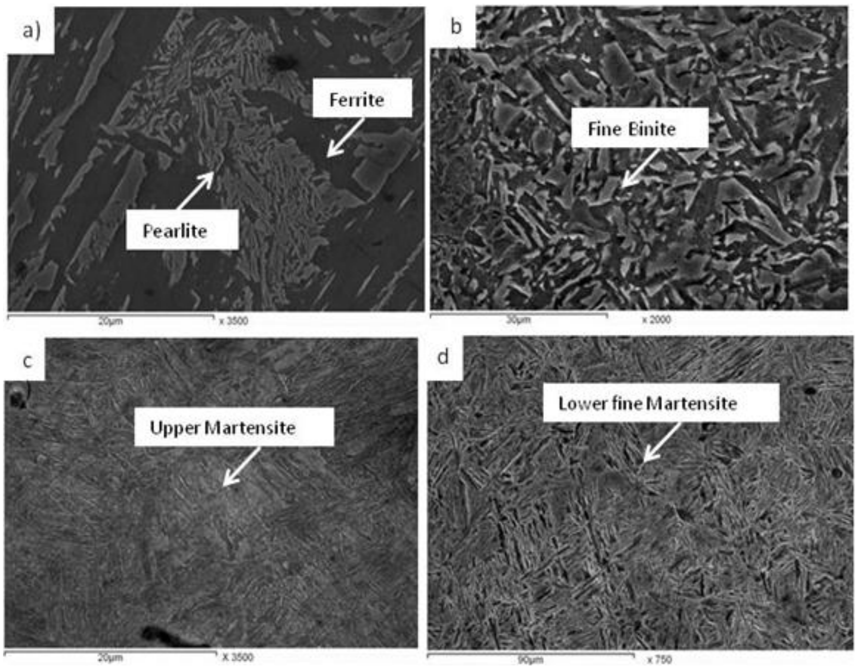

Figure 3: SEM Microstructure of 0.1Al Steel after Thermo-Mechanical Treatment followed by Post Different Cooling Rates, (a) As-Cast, (b) Air Cooled, (c) Oil Quenched and (d) Water Quenched

Hot Forged Microstructure of 0.5Al Steel: Figure 4 shows the effect of hot forging and different post cooling on the microstructure of 0.5Al steel. The as-cast structure of 0.5wt% Al steel shows highly refined ferrite-pearlite structure (**see Figure 4-a**) due to slow cooling and the Al content of 0.5wt%. Using of air cooling after hot forging, the steel exhibits upper martensite as shown in **Figure 4-b**, while moderate cooling rate due to oil quenching produces lower martensite (see **Figure 4-c**). The water quenched steel provides lower aggregates martensite as shown in **Figure 4-d**

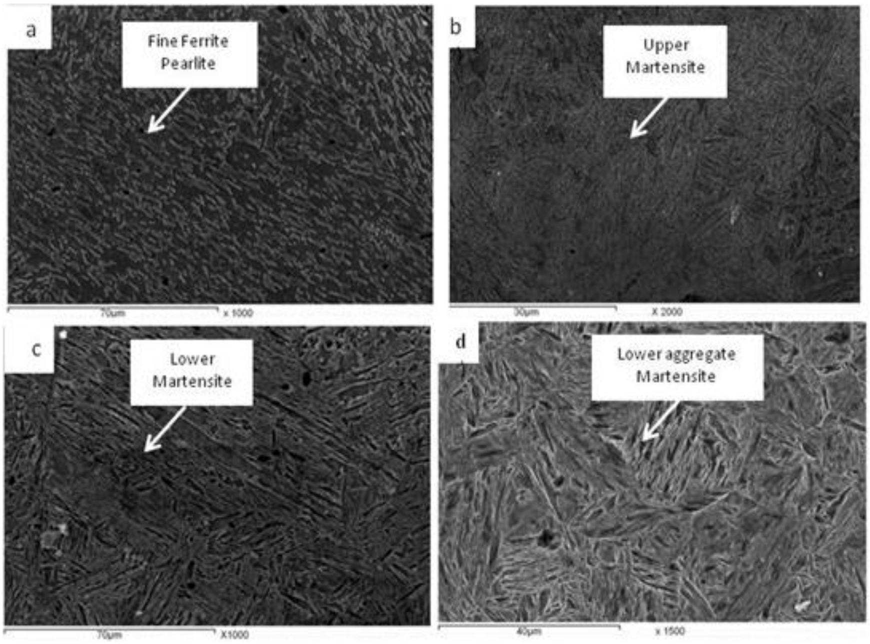

Figure 4: SEM Microstructure of 0.5Al Steel after Thermo-Mechanical Treatment followed by Post Different Cooling Rates, (a) As-Cast, (b) Air Cooled, (c) Oil Quenched and (d) Water Quenched

Hardness: Figure 5 shows hardness for both alloys of steel(0.1&0.5wt%Al). It is clear that both hot forging and post different cooling rate highly increase hardness due to high refining of microstructure and hard phase formation such as martensite in existence of Al.

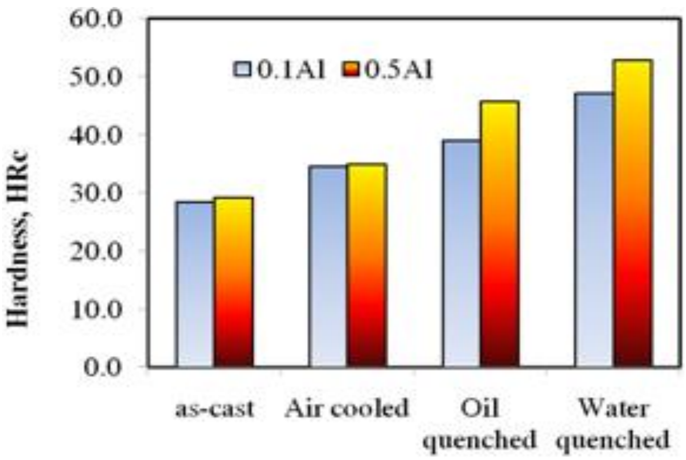

Figure 5: Comparison of Hardness after Hot Forging and Different Post Cooling

Wear Results, Air Cooled

Figure 6 (a) and **(b)** show the wear characteristics of both steel alloys 0.1 and 0.5wt%Al respectively, (where they were subjected to hot forging followed by air cooling). It is clear that the weight loss increases as the tribological parameters increase. Therefore, the need to explain and understand the relationship between wear rate and tribological parameters leads to construct a wear map and to deduce the governing empirical formula.

The equation coincides with wear data is **Lorentzian type.** From empirical formulas, it is clear that the main parameter controlling the wear rate is the linear velocity. The wear maps represent the most critical zone of severe wear where the wear rate reaches its maximum values and sometime shows catastrophic conditions. The empirical formulas are presented as equations 3 and 4.

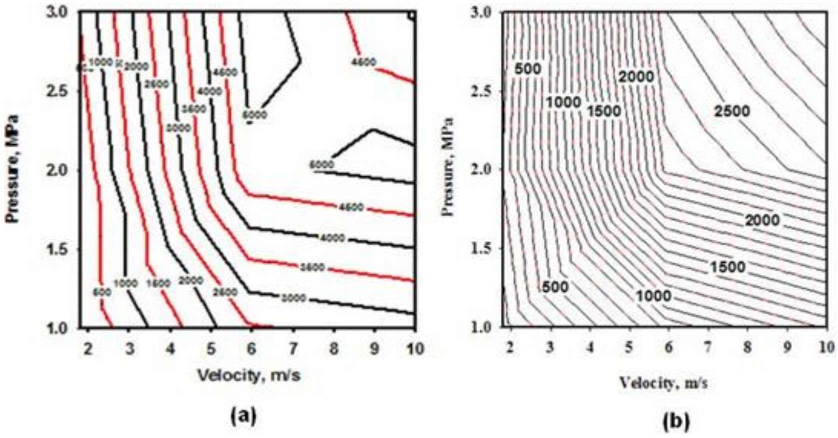

Figure 6: Effect of Tribological Wear Parameters (Pressure and Velocity) on Wear Rate of Air Cooled Steel after Hot Forging. (a) 0.1 Al Steel, (b) 0.5Al Steel

It is also clear that increasing the Al content moves the maximum wear rate to the right side corner and decreases the wear rates (see **Figures 6** and **7**).

$$WearRate\left(\frac{mg}{hr}\right) = 7722.8162 * e^{-0.5*\left(\left(\frac{X-7.9677}{2.2544}\right)^2+\left(\frac{Y-2.1723}{1.0077}\right)^2\right)} \quad (3)$$

$$WearRate\left(\frac{mg}{hr}\right) = 3870.8902 * e^{-0.5*\left(\left(\frac{X-8.2612}{2.6231}\right)^2+\left(\frac{Y-2.6842}{1.1801}\right)^2\right)} \quad (4)$$

Wear Results, Oil Quenched: Figure 7 (a) and (**b**) show the wear characteristics of alloys 0.1 and 0.5wt%Al (where they were subjected to hot forging and oil quenching). It seems clear that the weight loss increases as the wear parameters increase. The equation coincides with wear data is **Lorentzian type.** The wear map shows that the main parameter affecting the wear test of oil quenched steel is the linear velocity. The empirical formulas are stated equations 3 and 4. However, in case of oil quenching, the wear rates highly decrease (24%) than of air cooling as shown in **Figures 6–a** and **7-a** for 0.1Al steel. On the other hand for 0.5Al steel, the wear rate of oil quenching decreases (36%) due to Al content as shown in **Figures 6-b** and **7-b**.

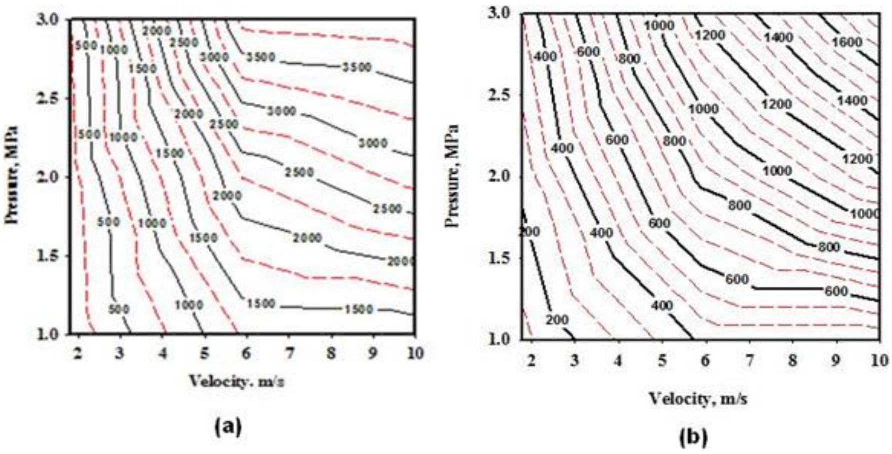

Figure 7: Effect of Tribological Wear Parameters (Pressure and Velocity) on Wear Rate of Oil Quenched Steel after Hot Forging. (A) 0.1 Al Steel, (B) 0.5Al Steel

Wear Results, Water Quenched: Figure 8 (a) and **(b)** exhibit the wear characteristics of both alloys 0.1 and 0.5wt%Al (where they were subjected to hot forging followed by water quenching). It is apparent that the weight loss increases as the wear parameters increase. The empirical equation which coincides with wear data is also **Lorentzian type.** The empirical parameters values indicate that the wear velocity is highly affecting wear rate than wear pressure. Furthermore, the 0.5Al highly decreases the wear rate of metal about 50%. The effect of post cooling rates on toughness is clear in **Figure 10** where the oil quenched steel of both 0.1 and 0.5Al have the lowest values of wear rates. The empirical formulas are presented as equations 5 and 6.

$$\boldsymbol{WearRate}\left(\frac{mg}{hr}\right) = \mathbf{6252.8071} * \mathbf{e}^{-0.5*\left(\left(\frac{X-8.0783}{2.4879}\right)^{2}+\left(\frac{Y-3.9941}{1.9040}\right)^{2}\right)} \tag{5}$$

$$\boldsymbol{WearRate}\left(\frac{mg}{hr}\right) = \mathbf{1829.9542} * \mathbf{e}^{-0.5*\left(\left(\frac{X-9.4660}{4.1860}\right)^{2}+\left(\frac{Y-3.2737}{1.3854}\right)^{2}\right)} \tag{6}$$

Effect of Toughness on Wear Rate and Optical Worn Surfaces: Figure 9 shows the effect of maximum wear parameters on the worn surface. It seems clear that colors of air cooled samples are not dark blue, see **Figure 9-a**. Contrarily, the water quenched worn surface exhibits dark blue color due severe wear conditions (absorbed oxygen from atmosphere) as shown in **Figure 9-b**. The wear rate of 0.5Al steel (water quenched steel) is lower than 0.1Al steel wear rate (Wear rate $_{0.5Al}$ = 0.45%Wear rate $_{0.1Al}$). Aluminum enhances the wear resistance and oil quenching produces relatively high toughness and consequently increases the wear resistance (see **Figure 10**). The empirical formulas are presented as equations 7 and 8.

$$\boldsymbol{WearRate}\left(\frac{mg}{hr}\right) = \mathbf{7641.0649} * \mathbf{e}^{-0.5*\left(\left(X-\frac{7.7684}{2.0965}\right)^{2}+\left(\frac{Y-2.6951}{1.2866}\right)^{2}\right)} \tag{7}$$

$$\boldsymbol{WearRate}\left(\frac{mg}{hr}\right) = \mathbf{42626130.611} * \mathbf{e}^{-0.5*\left(\left(X-\frac{19.005}{0.072}\right)^{2}+\left(\frac{Y-2.6432}{0.9869}\right)^{2}\right)} \tag{8}$$

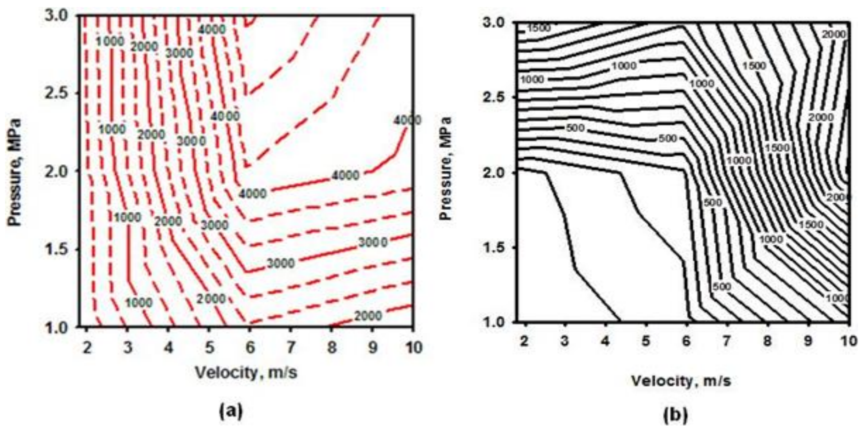

Figure 8: Effect of Tribological Wear Parameters (Pressure and Velocity) on Wear Rate of Water Quenched Steel after Hot Forging. (a) 0.1 Al Steel, (b) 0.5Al Steel

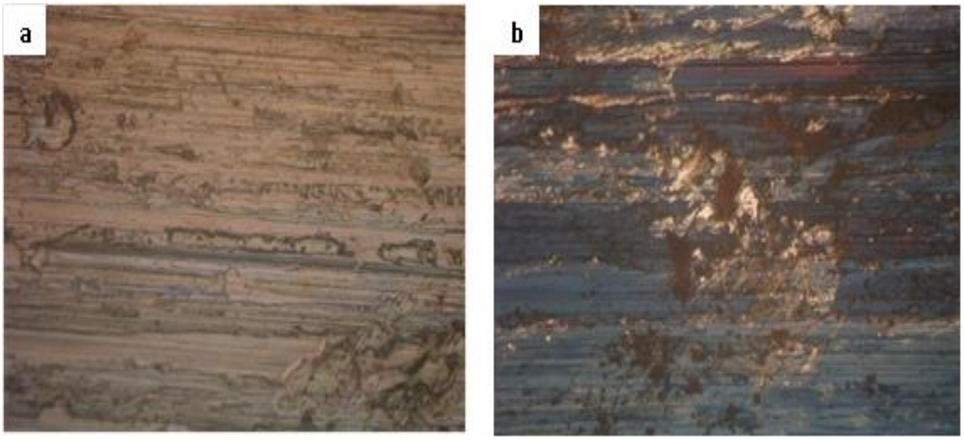

Figure 9: The Worn Surfaces, (a) Worn Surface of 0.1Al Hot Forged + Air Cooled at Velocity =5.9m/s and Pressure 2MPa, ×200, (b) Worn Surface of 0.1Al Hot Forged + Water Quenched at Velocity=1.8ms and Pressure 3MPa, ×200

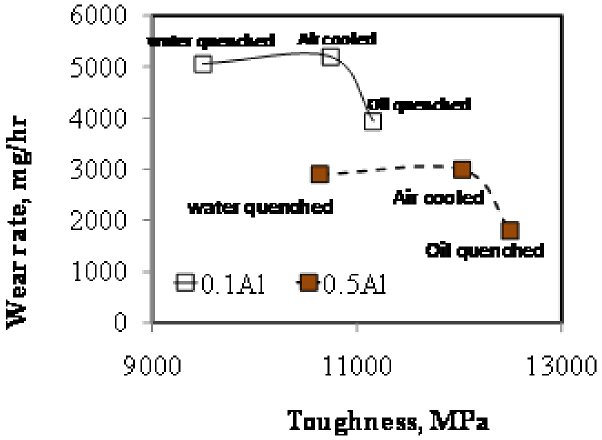

Figure 10: Relationship of Toughness and Wear Rate of Steel Alloys with 0.1 and 0.5Al% after Different Cooling Rates

CONCLUSIONS

Results of dilatation test shows that addition of Al to steel increases the transformation temperatures. The effect of velocity and pressure on the wear rate can be presented using Lorentzian equation. Wear rates increase as the toughness increases due bainite phase. Al addition enhances the wear resistance of steel. Water quenched worn surface exhibits dark blue color due severe wear conditions.

From microstructure investigation by SEM, it is shown that microstructure of air cooling is relatively fine bainite, oil quenching is fine bainite and water quenching is coarse martensite this for 0.1Al steel. While for 0.5Al steel the microstructure for air cooling is very fine bainite, oil quenching is very fine bainite and water quenching is fine martensite .

The presence of Al revealed remarkable increase of the wear resistance of this steel especially with high cooling rates after hot forging (oil & Water). The wear rate decreases with increasing the cooling rate of the steel after forging, this due to the phases presented after quenching. The velocity and pressure during the wear test highly affect the wear rate.

Toughness of this steel shows remarkable increase with Al addition and with increasing the cooling rate after hot forging. This is in a good agreement with the wear resistance results obtained at the same conditions.

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REFERENCES

1. Xu, D.X.,Lu, G.X., 1993.Contact fatigue behavior of an austenitic bainitic ductile iron, *Wear, 169,* p.153-159.
2. Kalousek, J., Fegredoa, D.M., Laufer, E.D., 1985.The wear resistance and worn metallography of pearlitic, bainitic and tempered martensite rail steel microstructures of high hardness, Wear, 105, p.199-222.
3. Garnham, J.R., Beynon, J.H., 1992. Dry sliding wear of bainitic and pearlitic steels, Wear, 157, p.81-109.
4. Scholl, M.,*Devanathan*, *R*.,*Clayton*, *P*.,1994.Abrasive and Dry Sliding Wear Resistance, Vol*5*, ASM Handbook, ASM International, 49, p. 497–509.
5. Kasatkin, O.G.,Vinokur, B.B.,Pilyushenko, V.L.,1984. Calculation models for determining the critical points of steel, Metal Science and Heat Treatment, Volume 26, Number 1, p.27-31.

6. Clayton, P., Devanathan, R., 1992. Rolling-sliding wear behavior of chromium-molybdenum rail steel in pearlitic and bainitic conditions, wear. 156, p. 121-131.

7. Shipway, P.H.,Wood, S.J.,Dent, A.H., 1997.The hardness and sliding wear behavior of a bainitic steel, wear 203-204, 11th International Conference on Wear of Materials, Volumes 203-204, p.196-205.

8. Devanathan, R., Clayton, P., *1991*. Rolling-sliding behavior of three bainitic steels, *Wear.* 151, p.255-267.

9. Shah, S.M.,Verhoevena, J .D.,Bahadur, S. 1986. Erosion behavior of high silicon Bainitic structure; austempered ductile iron. Wear, 113, p.267-278.

10. S. Das, I. Timokhina, S.B. Singh, E. Pereloma, O.N. Mohanty, Effect of bainitic transformation on bake hardening in TRIP assisted steel, Materials Science and Engineering A 534 (2012) 485– 494

11. A. Misra, S. Sharma, S. Sangal, A. Upadhyaya, K. Mondal, Critical isothermal temperature and optimum mechanical behaviour of high Si-containing bainitic steels, Materials Science & Engineering A 558 (2012) 725–729

12. A. Karmakar a, M.Ghosh b, D.Chakrabarti, Cold-rolling and inter-critical annealing of low-carbon steel: Effect of initial microstructure and heating-rate, Materials Science & Engineering A 564 (2013) 389–399

13. T. El-Bitarv, N. Fouadb, A.I. Zakya, S.A. El-Radyb, Effect of cooling rate after controlled forging on properties of low carbon multi-microalloyed steels, Materials Science and Engineering A 534 (2012) 514– 520