Material Characteristics, Manufacturing Processes and Product Performance: A Review of Some Experimental Studies

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Abstract
The paper reviews the influence of material characteristics on the manufacturing process and product performance. Results of some previous experimental studies on hot machining, plasma surface coating and laser surface treatment, semi solid heat treatment and clean steel production are compiled, analyzed and discussed. In each case, a correlation is observed between the material characteristics and its response to the manufacturing process.

1. Introduction

Material characteristics often influence the manufacturing process. Similarity, the manufacturing process may also influence the performance of a material in service. In the past, there have been many attempts to establish the relationship amongst material characteristics and manufacturing process and service performance of the products. Some of these are aptly summarized in a recent e-book [1]. The characteristics of specific materials during machining, grinding, surface coating and sliding wear tests were experimentally investigated by one of the present authors and his co-workers. The principal results of the experimental investigations are revisited in this review paper and are discussed with reference to the other relevant published work. The main objective of this review article is to emphasize the need to study the characteristics of specific materials for optimizing the manufacturing processes and product performance for specific applications. In this article the focus is on the characteristics of the steels which has a high percentage of manganese, chromium and titanium and other alloying elements which impart poor machinability to steel.

High manganese steel bars (Fe-32 Mn-2.381-0.55C-5Al) are difficult to machine at room temperature even with carbide tipped tools. Therefore, hot machining is more appropriate. A. Prodhan et al. [2] carried out an experimental investigation with Fe-32 Mn-2.381-0.55C-5Al steel in which a bar of steel was heated to 600-700 0C by a flame torch just prior to turning by a carbide tool. The preheated bar could be machined conveniently. Cutting forces required for machining at room temperature as well as at the elevated temperature were measured by a strain gauge – dynamometer assembly. The hardness of the chips formed at different cutting speeds was measured. The corresponding chip reduction coefficients were also determined.

In the rolling of steels high in manganese, chromium and titanium, such as continuously cast 409 stainless steel slabs, normally the surfaces of such slabs are conditioned by grinding, using an alumina grinding wheel, prior to rolling, in order to remove defects on the surface of the cast slabs. However, occasionally the ground surfaces of slabs have been observed to be rougher than expected. This problem was investigated by examining in SEM the morphology, surface texture and surface chemical analysis of the chips formed [3].

Another interesting aspect is surface engineering on manganese steel. In order to improve the abrasive wear performance of a Mn-Steel an experimental investigation was carried out in which it was coated with alumina particles by means of a plasma torch with and without an intermediate Ni-Ti bond coat. A mild steel sample was also similarly coated for comparison. Each sample was a cube of size 10mm × 10mm × 10mm approximately. Argon was the plasma-gen gas. The coated samples were subjected to abrasive wear test under load. A coarse grade emery paper fitted on a rotating wheel served as the abrasive surface. A suitable fixture was designed for holding the samples and applying load on them. The worn surfaces were examined visually as well as in a SEM. The EDAX analysis of the transverse sections was also carried out [4].

In a second experiment the effect of surface modification by laser treatment on material characteristics is investigated. In this study, the surfaces of 304L, 304LN and 316 stainless steels containing high manganese and high chromium were modified by laser surface treatment to improve their corrosion resistance. The variables studied were lasing power and scan rates. The thickness of the lased layer was measured in each ease and the microstructures of the lased surfaces were also examined [5].

An investigation was carried out to investigate the influence of heat treatment on material characteristics due to change in microstructure and tribological properties. An attempt was made to modify the microstructure of a cast Al-Si-Cu alloy by heat treating samples of the alloy above its eutectic temperature. The samples were quenched from the

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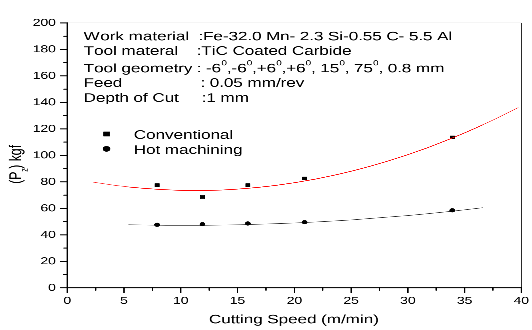
heat treatment temperature. The temperature and time of treatment were varied. The microstructures of cast samples and heat treated samples were examined. After such examination the heat treatment schedule for a 10 mm diameter cast rod was optimized at 600 0C for 20 minutes. After completion of heat treatment, 5mm diameter × 30mm length pin samples were machined out for pin-on-disc adhesive wear test. The steel disc hardness was RC62. The pins were pressed against the wheel under varying loads. The change in the length of pin samples due to wear was continuously recorded by suitable sensor arrangement [6].

Another interesting study is the role of steel cleanliness on tribological properties. In this experiment, an attempt was made to reduce the inclusion contents in an open hearth furnace melted 0.24% C steel by NaCl flux addition to the liquid steel inside the ingot mould. The ingots were subsequently hot rolled to 30mm core diameter ribbed rods. The inclusion volume fractions in the rods were determined by image analysis of metallographic samples of both untreated and NaCl steels, prepared from the same heat. The 5mm × 30mm length pins were machined from the rolled steel rods and pin-on-disc wear test was carried out. During this test the change in length of the pin samples was recorded by a data logging system [7].

2. Results and Discussion

Machining Mn Steel. The benefits of hot machining, particularly for difficult to machine metals, have been illustrated in the past [8]. Electric hot machining may improve cutting performance through heating resistance which softens the materials in the deformation zone. The present illustration is based on heating with a simple flame torch prior to turning operation [2]. The variation of feed force (Px) and thrust face (Pz) with cutting speed is shown in Figure 1 (a) and 1 (b). It may be noted from the figures that the cutting forces dropped appreciably during hot machining. It is well known that Mn-Steel suffers rapid hardening during any form of working. At room temperature, such strain hardening of the surface layer render machining difficult. During hot machining, the phenomenon of dynamic re-crystallization becomes operative. Cutting forces drop and machining becomes easier [9, 10]. This is also evident from the data on hardness values of the chips formed during room temperature machining and hot machining (Fig. 2). Hardness values of the chips dropped rapidly with cutting speed, obviously because of faster re-crystallization.



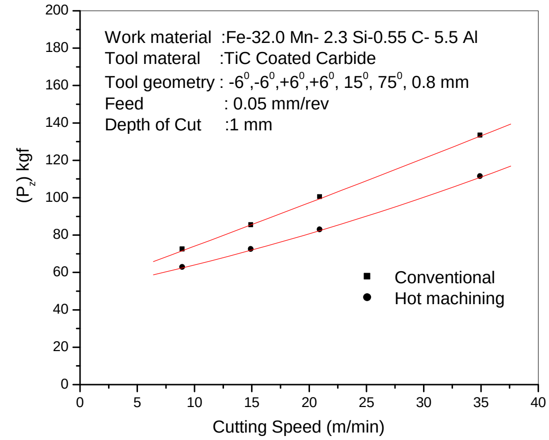


Fig: 1. Variation of cutting forces with cutting speed. [2]

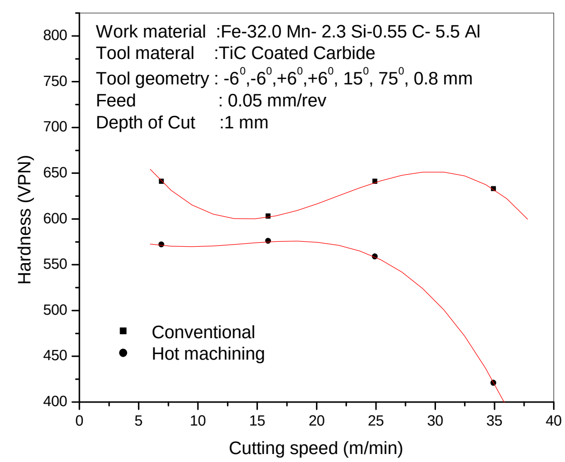


Fig: 2. Variation of chip hardness with cutting speed [2]

409 stainless Steel Surface Grinding. Surface grinding of stainless steel slabs is routinely carried out in reputed stainless steel plants to remove any possible surface defects. Surface examination is generally carried out visually. A neural network approach has also been tried to predict surface quality of cast slabs in order to avoid surface grinding of slabs having good surface quality [3]. However, occasionally inadequate surface finish may be encountered even after surface grinding. Examination of chips collected from a stainless steel plant provided a clue to the genesis of roughness at the ground surface. An examination of the morphology of the tiny chips in SEM, clearly revealed the presence of some saw tooth type chips (Fig. 3). Such saw tooth chips indicate a stick and slip phenomenon operating during grinding. The chips were found to have a rough surface (Fig. 4). EDS analysis of the surface layer of such a chip was therefore carried out. It was observed that the nodules formed on the surface were rich in iron and oxygen (Table 1). Chromium contents in the nodules were pretty low. Stainless steels acquire their stainless property from the impervious chromium oxide layer formed on the surface. It is apparent that this layer is ruptured during grinding. In addition a high temperature (above 1000 0C) is developed at the point of contact of the grinding tool and the job. Rapid diffusion of iron atoms from the substrate to the oxide layer may occur under such favorable condition. Some grains in the chip in Figure 3 had grown quite large in size while most under grains are very small. It clearly indicates that an adiabatic heat transfer condition prevailed at the tool-job interface. Such a thermal regime further enhanced the scope for localized oxidation and growth of oxide nodules.

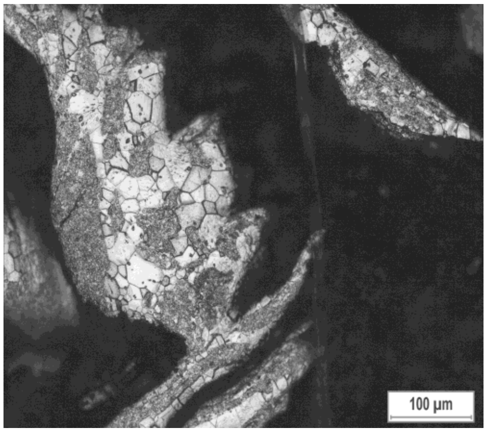


Fig: 3. Non-uniform Growth of Grains in a saw Tooth Chip

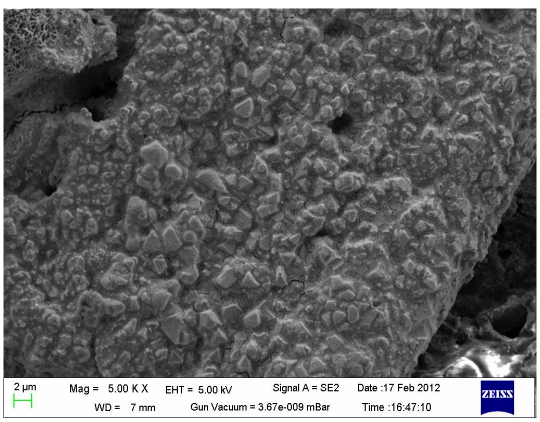
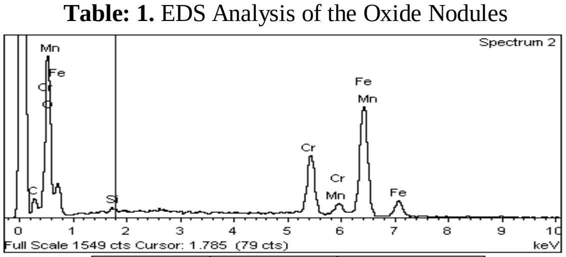


Fig: 4. Growth of Oxide Nodules on Chips Tooth Chip

Table: 1. EDS Analysis of the Oxide Nodules



Element	Weight%	Atomic%
C K	9.90	20.24
O K	36.03	55.33
Si K	0.48	0.42
Cr K	13.16	6.22
Mn K	1.03	0.46
Fe K	39.40	17.33
Totals	100.00	

3. Surface Engineering

Plasma surface spraying. The transverse section and top views of a coated steel sample is in Figure 5 (a) and 5(b). The hardness and roughness values of the coated manganese steel and the reference mild steel are given in Table 2. A comparison of Figure 5 (a) and (b) show that the top surface of the coating had formed by sintering of the plasma sprayed particles. The coated layer was quite adherent. An intermediate bond coat of Ni-Ti alloy was found necessary. However, on wear test, the coated layer on the Mn steel suffered rapid wear. In order to investigate the reasons, the hardness values of the coated steels were measured.

Fig: 5 (a). Al2O3-2TiO2 on Mn steel with Ni-Al bond coat (transverse section). [4]

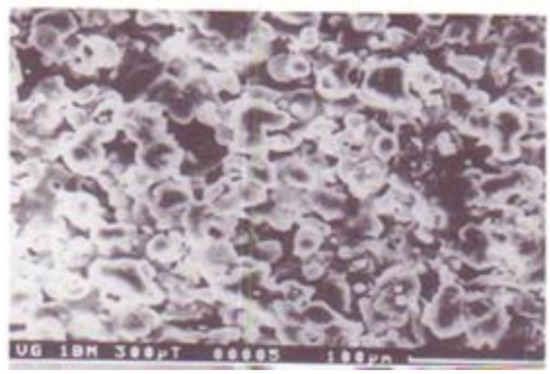


Fig: 5 (b). Al2O3-2TiO2 with Ni-Al bond (top view). [4]

Table: 2. Hardness and Roughness of the Coated Surface

Coating	Substrate	Hardness, Rc	Roughness, $\mu m.m^{-1}$
Al_2O_3	Manganese steel	33	12.2
Al_2O_3-$2TiO_2$	Manganese steel	27	7.9

Table: 3. Result of SEM-EDAX elemental analysis for Al2O3-2TiO2 coating on manganese steel substrates: for interfacial location first term indicates side of interface on which analysis was conducted

Elemental content, wt-%						
Analysis location	**Fe**	**Mn**	**Si**	**Al**	**Ni**	**Ti**
Ni-Al bond coat	60.349	4.347	5.764	5.167	24.251	0.036
Top coat surface	1.502	0.198	2.617	95.019	0.095	0.569

Top coat/bond coat interface	3.637	0.240	2.942	91.309	0.184	1.687
Bond coat/top coat interface	1.225	…	1.785	93.596	0.325	3.071
Bond coat/substrate coat interface*	1.683	…	1.956	92.696	0.211	3.457
Bond coat/substrate coat interface*	60.915	5.642	1.670	16.888	14.165	0.725
Substrate/bond coat interface*	68.523	5.672	1.044	16.498	14.163	0.099
Substrate*	68.915	5.672	1.670	10.496	14.163	0.725
No bond coat						
Top coat surface	24.656	0.715	0.585	74.076	…	…†
Top coat surface*	3.463	0.128	0.157	95.898	0.352	…†
Top coat/substrate interface*	4.487	…	0.753	94.031	0.753	…†
Substrate/top coat interface*	87.973	7.202	…	3.952	0.893	…†

*Analyses through parallel transverse section
†Other elemental contents normalized without Ti

Table 2 shows that the hardness of the coated layer was very low. The concentration of different elements at different locations was measured by SEM-EDAX system. It is apparent from Table-3 that considerable diffusion of Fe & Mn into the alumina layer takes place during plasma coating. Application of a bond coat does not prevent such diffusion appreciably. As a result, the coated layer actually belongs to the FeO-MnO-Al2O3 system. The hardness of such a layer is very low. Figure 5(a) further illustrated that pores existed in the coated layer. Consequently rapid abrasive wear loss occurred. This conclusion is also confirmed by previous observations that change in porosity and elemental composition of the friction surface appreciably increases the wear rate [11].

Laser surface treated stainless steel. The corrosion and wear resistance of AISI 304 and 316 stainless steel are reported to be enhanced by laser surface treatment [12, 13]. However these reports do not state how the lasing variables may affect the thickness of the lased layer in stainless steel. In this investigation, irrespective of alloy composition, lasing power and scan rate, there was no evidence of amorphisation of the lased surface of any of the stainless steels. Examination of the microstructures of the laser surface heated steels revealed the transition from the usual polygonal structure (Fig. 6a) to dendritic structure of a cast steel (Fig. 6b).

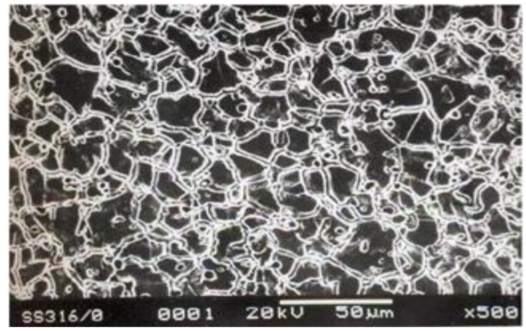


Fig: 6(a). 316 Stainless Steel Untreated [5]

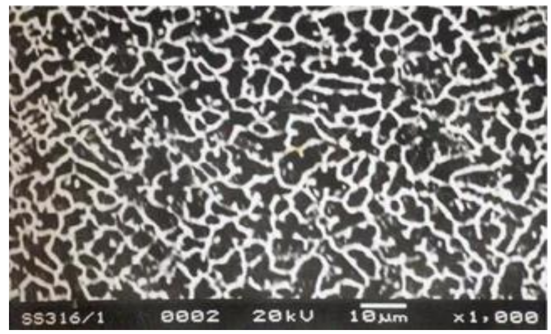


Fig: 6(b). 316 Stainless Steel Laser Treated

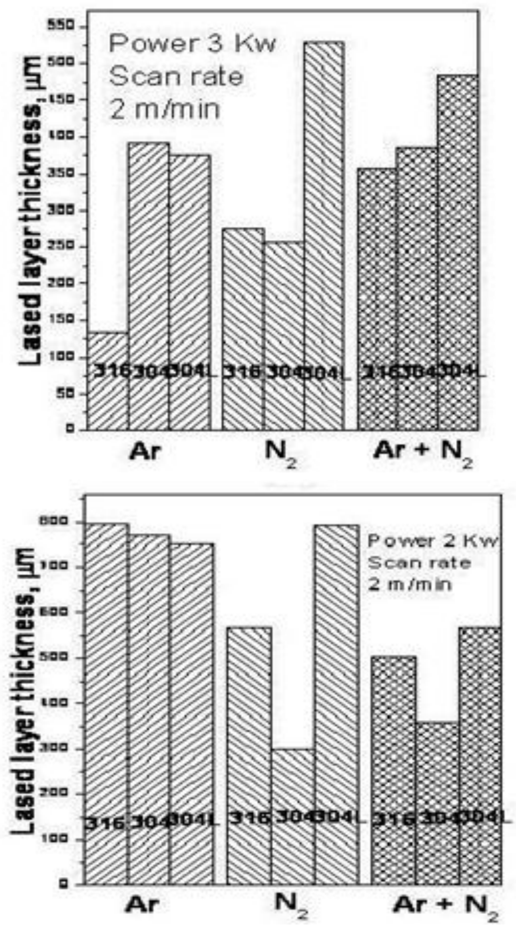


Fig: 7. Thickness of the Re-melted layer of the Surface after Laser Treatment [5]

On the contrary, the thickness of the re-solidified layer decreased with increase in lasing power and scan rate (Fig. 7a and b). It is presumed that volatilization of the molten layer started under 3 kW lasing power and 2 m/min scan rate. The trend was same in all the stainless steels investigated. Hence it is unnecessary to increase the lasing power and scan rate for surface modification beyond a certain set of operating parameters.

Heat treatment of Al-Si-Cu Alloy and Its Wear Performance. Aluminum-silicon group of alloys are traditionally used for wear resistant applications, a typical example being piston rings. An investigation was conducted to correlate the micro-structural changes during heat treatment in the semisolid state with adhesive wear performance.

Table: 4. Chemical Composition of the alloy Under Investigation

Alloy	Si	Cu	Fe	Mn	Mg	Zn	Ni	Al
As received	10.0	3.22	0.569	0.164	0.603	0.841	0.481	83.0

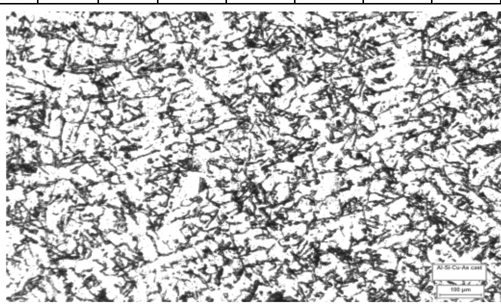


Fig: 8(a). As cast microstructure of the Al-Si-Cu alloy Hardness 54 VPN. [6]

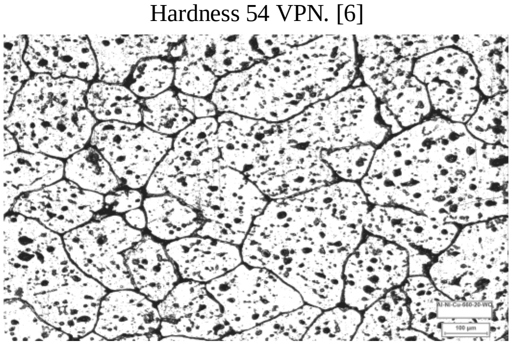


Fig: 8(b). Microstructure of the Al-Ni-Cu alloy heat treated at 6600C for 20 minutes and then air cooled. Hardness 34 VPN [6]

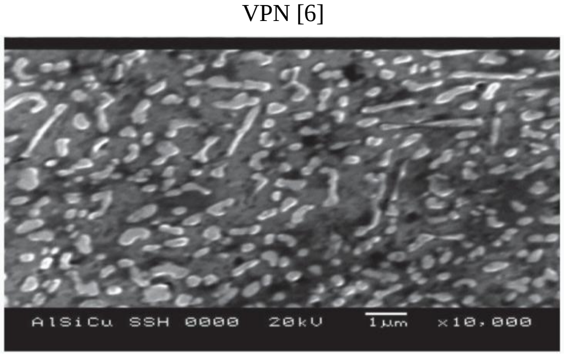
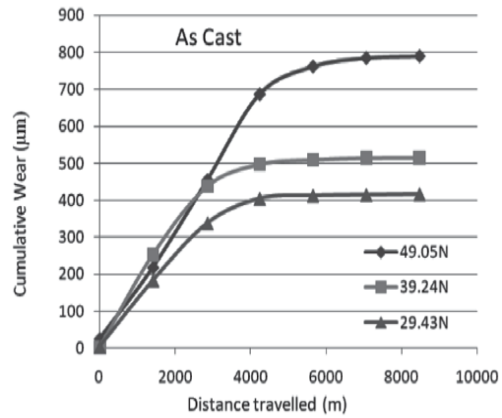
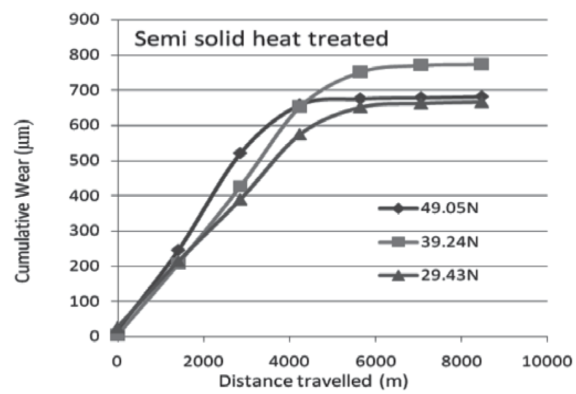


Fig: 8(c). Spheroidised Eutectic Silicon Particles [6]

The chemical composition of the alloy is given in Table 4. Figs. 8 (a, b and c) illustrate the microstructure of the alloy in the as cast state and after semisolid heat treatment at 600 0C for 20 minutes. It may be noted that the □-Al grains became rounded and silicon needles were mostly globularised after semi solid heat treatment (Fig. 8 c).



(a)



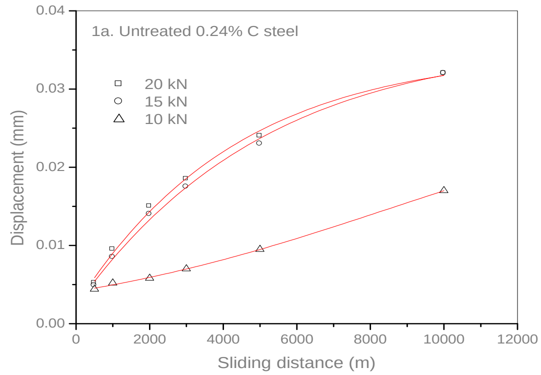
(b)

Fig: 9. Wear behaviour of the Alloy (a) As-cast (b) Semisolid Heat-Treated. [6]

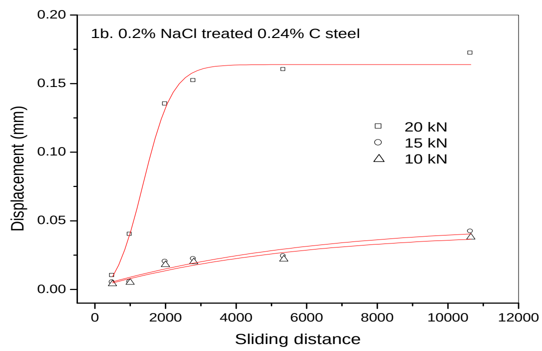
During adhesive wear test, the wear loss was more in the heat treated sample under relatively lower loads of 29.43.N and 39.24 N. The wear loss was more or less identical under a higher load of 49.05 N (Fig. 9 a and b). Silicon needles have a higher surface area to volume ratio. The needles therefore resist wear to a greater extent than the globules. At a higher load, the □-Al matrix is work hardened adequately. Thus there is hardly any difference between the wear loss in the as cast sample and the heat treatment sample under 49.05 N load. Wear characteristics of rheocast aluminium alloys with similar □-Al rounded grains had been studied in the past. Previous investigations also did not note any significant improvement of their properties [14]. The wear test results on the precast semisolid treated alloys broadly matches with those of rheocast aluminium alloys.

Table: 5. Inclusion Removal from Wrought Steel

	Vol. % inclusions
1a. Untreated 0.24 Carbon Steel	0.4725
1b. 0.2% NaCl treated 0.24 Carbon Steel (BSP sample, as rolled)	0.2309



(a) Steel 1a.



(b) Steel 1b.

Fig: 10. Cumulative Wear after Sliding against a Steel disc [7]

Relation between steel cleanliness and wear behaviour. Normally cleaner steels are preferred for engineering applications. Treatment with NaCl flux reduced the inclusion content in the treated steels (Table 5). However on adhesive wear test it was found that the clean steel suffered greater wear (Fig. 10 a and b).

It therefore appears that the hard inclusions (alumina, silicate etc.) present in a commercial steel stand proud and support wear load. When these inclusions are removed, wear loss increases.

4. Conclusions

The correlation between material characteristics and a manufacturing process or the service performance of a product is emphasized through the following conclusions drawn from the review of past research:

i. Hot machining offers an easy route for processing of difficult-to-machine manganese steel.
ii. A diffusion barrier needs to be created on the surface of the job to effectively coat alumina ceramic powder on manganese steel.
iii. Excessive lasing power density and scan rate are harmful. These two parameters need to be optimized for every material. Unless surface grinding parameters are properly managed, the operation may further damage the surface quality.
iv. Although a low inclusion content in the steels is generally desired, the presence of certain oxide inclusions may be beneficial for adhesive wear applications.

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