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Experimental Study on Cutting Tool Wear Behavior of Sintered/Extruded P/M Alloy Steels

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Abstract: In the present scenario, Powder metallurgy (P/M) manufacturing process is one of the fastest growing fields which involves the processing of metal powders for the production of steels and has replaced all traditional methods of metal forming operations because of its low relative material wastage, low capital cost and maximum material utilization. Producing steels through the P/M route has immense potential for industrial applications in making components for machine parts, in the fields of automobiles such as fasteners, bearings, rollers, in manufacturing field such as tools, cutters, and also in the field of aerospace, defense etc. The microstructures and mechanical properties mainly depend on the final obtained density of sintered P/M alloy steels which will determine the component characteristics. The present study has been made to investigate the cutting tool wear behaviour of sintered/hot extruded P/M alloy steels with Fe-1% C as base material, W (Tungsten) and Ti (Titanium) as alloying elements. The cutting tool wear behavior was analyzed with the help of tool bits grounded from the head portion of extruded preforms with standard tool parameters for machining the non-ferrous materials by varying the cutting speed, whereas the feed and depth of cut was kept constant, and also the dry sliding wear behavior were studied on pin-on-disc (ASTM G99) arrangement. By using the optical microscopy (OM), the microstructure of extruded P/M alloy steels has been characterized to understand the structure-property relationships. The presence of WTi Carbide in both the extruded P/M alloy steels significantly enhances the tool wear resistance. Widmanstatten type ferrite-cementite matrix (alternate lamellas) microstructure is revealed on both the extruded P/M alloy steels.
Keywords: P/M alloy steels; Sliding distance; Frictional Coefficient; Cutting tool wear behavior; Sintered/Extruded.

1. Introduction

Powder metallurgy (P/M) is an established manufacturing process which has the ability to shape powders directly into final components. High quality and complex parts may be economically fabricated by using P/M techniques. Sintered low alloy tool steels have been used for over a century for cutting and forming operations. The Properties and microstructures obtained from P/M cannot be obtained by alternative metal working techniques. The presence of voids or porosity in compacted alloy is one of the major factors which cause reduction in mechanical properties of P/M alloys. The component properties and characteristics mainly depend on the final density of the sintered P/M steels. The formation of hard phases in the microstructure due to the addition of W to P/M alloys has been reported to enhance the wear resistance. The hardened carbide based P/M alloy steels could be the best choice for replacing the HSS in view of the economics of production[1]. The carbide containing titanium and tungsten which is extremely hard, has been investigated and its great value and utility as a material for use, in accordance with the customary principles of powder metallurgy, in the production of hard compositions of matter, in order to attain great hardness combined with great strength, along with a low thermal conductivity and other characteristics, has been highlighted[2]. The sintering processes of preforms have been compared by varying the variables such as initial density, sintering temperature and design used for fabrication of steel parts for various powder forging processes and it has been investigated that the type of wear evident in most of the P/M alloyed sintered steel might be adhesive wear, abrasive wear, oxidation wear and melt wear depending on the wear conditions[3.] The wear behaviour of sintered steel under both dry sliding and abrasive conditions has been investigated and it has been concluded that the better wear resistance is observed for the more hardenable steel, under dry sliding conditions giving rise to bainitic microstructures and also the sintering temperature along with compacting pressure plays a determining role in improvement of the resistance to sliding wear. Alloying the steel with W increases strength by forming second-phase carbides (Tungsten forms carbides if there is enough carbon and in absence of stronger carbide forming element), and it also increases the melting point. Ti is a strong carbide forming element; it fixes carbon in inert particles[4]. The dry sliding wear behaviour of sintered/extruded tungsten and titanium alloyed plain carbon steel has been investigated and it was resulted that the wear resistance of the titanium alloyed steel gets significantly enhanced. The mixed microstructure of Widmanstatten ferrite and ferrite-cementite matrix (alternate lamellas) was observed in the extruded Fe-1%C-1%W alloy steels whereas Fe-1%C-1%Ti extruded alloy steel showed a combination of Widmanstatten type ferrite, pearlite and bainite, which plays the vital role in the P/M alloy steels to enhance the wear resistance and results in minimum mass loss compared to W based extruded alloy steel for a particular applied load. In view of the potential applications of low alloy P/M steels as wear resistant components, it becomes significant to study the wear behaviour in order to evaluate their suitability for frictional wear applications[5]. Also the final density of the sintered P/M parts plays a vital role in determining the component properties and characteristics. It has been observed that the mechanical properties such as hardness, impact strength along with wear resistance increase because of the formation of bainitic and martensitic microstructures in the Fe-C-Cr-Mo alloy system[6]. The suitability of sintered iron-based alloys for severe sliding wear conditions has been investigated and it has been reported that oxidative wear mechanism is found to be predominant on Fe based alloy material due to the formation of solid film oxides of Fe at the relatively higher temperatures between the interface materials. The addition of copper as alloying element to iron based alloys has been reported to significantly improve the wear resistance of the alloy steels due to predominant delamination wear process[7]. It has been found that the addition of molybdenum di sulphide to the Fe-C-Cu and Fe-C-Cu-Ni P/M alloy systems improves mechanical strength, hardness and the wear resistance of the alloy steel and also observed that the coefficient of friction of the alloy steel is increased during wear test[8]. The tool-chip interference temperature and pressure for varying cutting speeds has been measured and it has been inferred that cutting speed strongly influences the cutting temperatures which in turn affects material removal rate[9]. While machining the AISI H13 hardened steel, it has been found that the contact friction between the tool–workpiece and tool–chip interfaces generates high temperatures on the cutting tool. Two main types of tool wear gradually occurred on the top rake face and the flank, i.e. crater wear and flank wear. Crater wear was formed due to the sliding of the chips against the rake surface, and the flank wear resulted from the friction between the newly generated workpiece surface and the flank face adjacent to the cutting edge[10].

In the present study, the cutting tool wear behavior of sintered/hot extruded P/M alloy steels with Fe-1% C as base material, W and Ti as alloying elements were studied. The tool bits were grounded from the head portion of extruded preforms with standard tool parameters for machining the Non-ferrous materials (Copper, Aluminium & Brass) by varying the cutting speed, whereas the feed and depth of cut was kept constant. Also the extruded steel pin were subjected to dry sliding wear behavior under dry conditions on the computer assisted Pin-on-disk tribometer against EN 38 steel disc of Hardness HRC 60 with a constant sliding speed of 2 m/s and at a normal load of 30, 40, 50 & 60 N with 3 different sliding distances. Frictional Coefficient was measured from the tribometer during the dry sliding wear test for 3 different sliding distances.

2. Experimental Details

Elemental powders of Iron (Fe) particle size of 150μm, Graphite (C) particle size of 5μm, Tungsten (W) and Titanium (Ti) particle size of 100 μm were precisely weighed and mixed thoroughly in a pot mill for

10 hrs to yield the alloy compositions of Fe-1%C-2%W-1%Ti and Fe-1%C-4%W-1%Ti respectively. By using standard testing methods the physical properties of elemental alloy powder has been carried out and exhibited in Table 1. The elementary blended powder was then compacted into cylindrical billets of aspect ratio 1.5 (Ø25X33mm). The dried compacts were sintered to increase its strength by bonding together of the particles in muffle furnace at 1100 ± 10^{o}C, for a period of 120min, in nitrogen purged inert atmosphere to avoid oxidation. Further the sintered preforms were extruded at a temperature of 1050˚C to get cylindrical pin of 10 mm diameter as shown in the figure 1. Subsequently the hot extruded specimens were machined off to obtain the standard size of 6mm diameter. The tool bits were grounded from the head portion of extruded preforms with standard tool parameters for machining the Non-ferrous materials by varying the cutting speed, whereas the feed and depth of cut is kept constant to analyse the cutting behaviour of P/M alloy steels. Mass removal rate of the tool was measured in gm/min during the turning operation against Copper, Aluminium and Brass. Before the dry sliding wear test, the initial weight of the steel pin was measured using an electronic weighing balance of 0.01 mg accuracy. The dry sliding wear tests of P/M alloy were conducted at a normal load of 30, 40, 50 & 60N with a constant sliding speed of 2m/s with 3 different sliding distances on the computer assisted Pin-on-disk tribometer. The material mass loss was determined as the change in weight of the sintered/extruded steel pin measured accurately before and after the wear test. Frictional Coefficient was measured during the wear test from the tribometer.

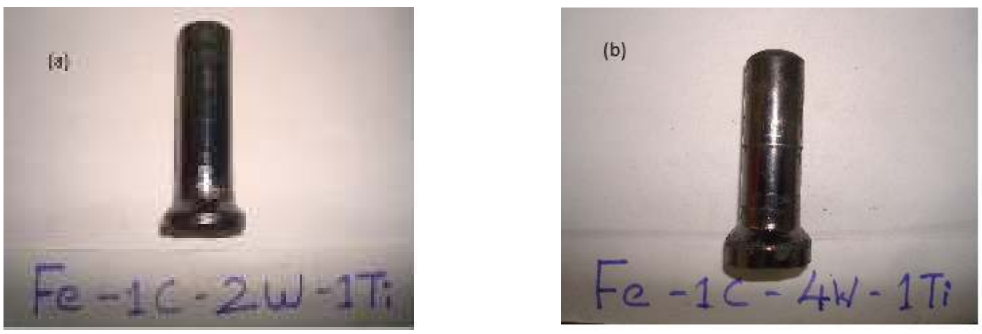


Figure- 1 Extruded P/M alloy steels (a) Fe-1%C-2%W-1%Ti; (b) Fe-1%C-4%W-1%Ti

Table -1 Physical properties of elemental alloy powder

Composition	Theoretical Density (g/cc)	Apparent Density (g/cc)	Tap Density (g/cc)	Flowability (s/g)
Fe-1C-2W-1Ti	7.74	3.08	3.43	0.52
Fe-1C-4W-1Ti	7.80	3.12	3.47	0.53

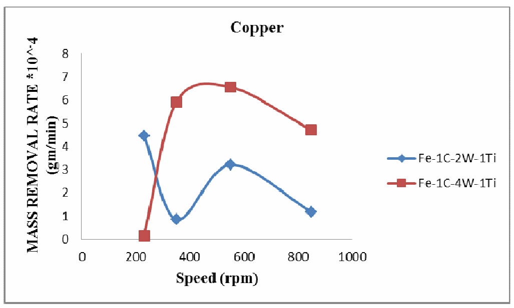
3. Results and Discussions

Basic cutting tool wear behaviour curves (Mass removal rate of tool Vs speed) of sintered/hot extruded tungsten and titanium alloyed plain carbon steel (Fe-1%C-2%W-1Ti and Fe-1%C-4%W-1%Ti) for 3 different materials (Copper, Aluminium and Brass) and also the dry sliding wear curve (Frictional coefficient versus load) at constant sliding velocity of 2m/s for 3 different sliding distance with a normal load of 30, 40, 50 & 60N respectively were obtained.

3.1 Cutting tool wear behaviour of sintered/extruded Tungsten and Titanium alloyed steels

The cutting tool wear behaviour has been investigated in dry machining of Non-ferrous materials like Copper, Aluminium and Brass. Figure 2(a) and 2(b) depicts mass removal rate of extruded P/M alloy steels at different speeds for 3 different materials respectively. Tool wear is mainly caused because the cutting face is subjected to a high temperature and a great pressure. At low cutting speeds, the tool–chip interface temperature (cutting temperature) is relatively low and abrasion wear dominates. Adhesion wear is caused by the mechanical removal of the tool material when the adhesive junctions are broken. This attrition process can dramatically deteriorate the tool rake face.

For Fe-1C-2W-1Ti tool material, at lower speeds, when soft materials such as aluminium and brass are machined, the work piece material bonds to the cutting tool, due to the higher thermal softening. Fragments of the materials can act as third-body abrasives.The tool wear is mainly caused by the formation of an adhesive layer and a built-up edge formation which sticks to the surface of the tool and deteriorate the tool rake face[9]. The formation of this one appears like the main damage mechanism under low cutting conditions. This was evident for the Fe-1C-4W-1Ti tool bit used for brass material at moderate cutting speed of 500rpm there could be seen thick adhesion of work pieces materials, indicating amazing adhesive wear leading to maximum mass removal rate of tool[10]. As the cutting speed further increases, the tool-work piece interface temperature also rises up, and the adhesion layer peel off from the tool face resulting in decreasing of tool mass removal rate. For copper due to the higher thermal conductivity and lower thermal softening, irrespective of the cutting speed, there is no stick-slip between the tool and work piece, resulting in low uniform tool wear. In general, for both the tool materials decreasing trend was observed in the mass removal rate with an increase in cutting speed.



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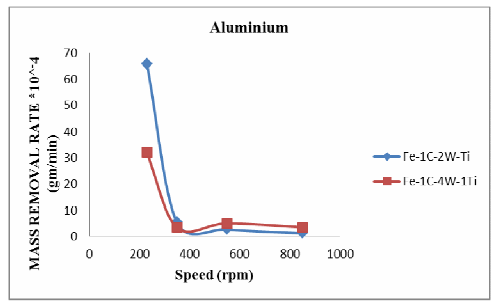

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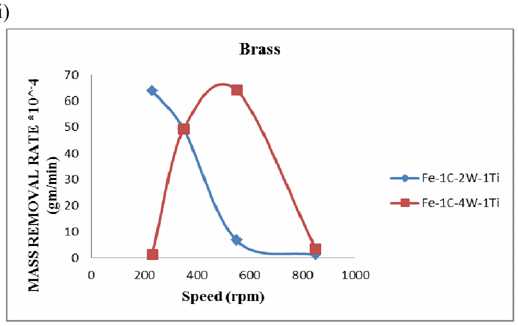
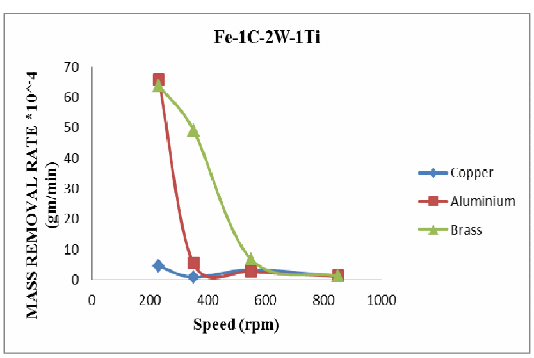


(iii)

Figure 2(a) Mass removal rate of extruded P/M alloy steels at different speed (i) copper; (ii) Aluminum; (iii) Brass



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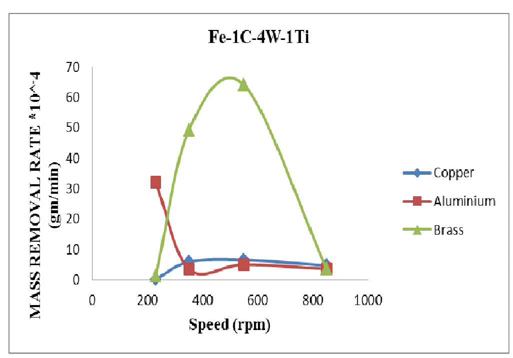
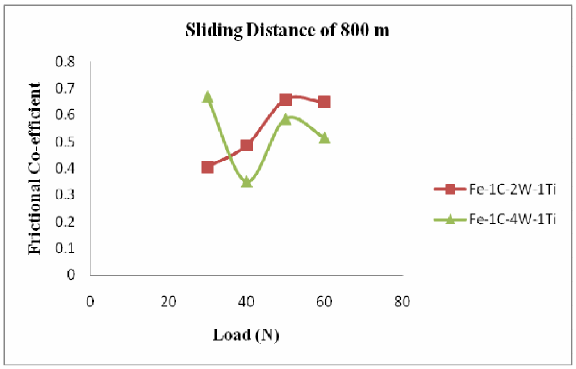


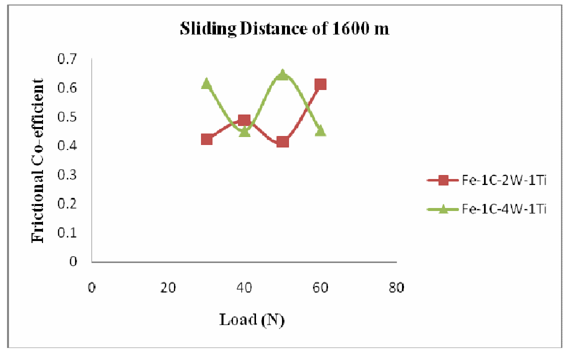
(ii)

Figure- 2(b) Mass removal rate of extruded P/M alloy steels at different speed (i) Fe-1C-2W-1Ti; (ii) Fe-1C-4W-1Ti

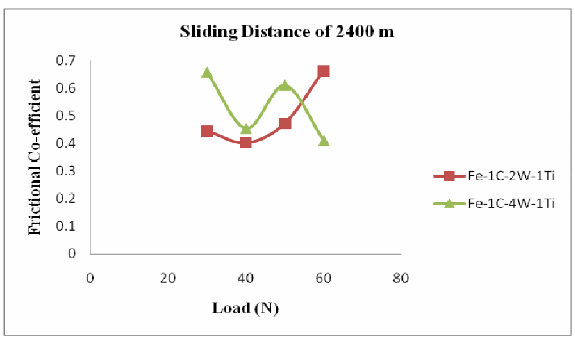
3.2 Frictional Coefficient of sintered/hot extruded Tungsten and Titanium alloyed steels

Figure-3 depicts frictional coefficient of extruded P/M alloy steels with a normal load of 30, 40, 50 & 60N at 3 different sliding distances (800, 1600 & 2400m). The frictional coefficient for Fe-1C-2W-1Ti was slightly lower at low level of applied load due to the presence of already formed oxide layer and as the load and sliding distances increases, frictional coefficient also increases because of the fracture and detachment of oxide layer causing the WTi carbide present in alloy steel contact the disc material in the interface. But for Fe-1C-4W-1Ti initially at lower loads the frictional coefficient was higher due to the increase in % of tungsten in the base metal, leading to formation of hard second phase tungsten carbide contributing to increase in frictional force after that decreases because of fracture of WTi carbide with the increase in load may be due to the delamination of carbide from the surface[11]. On further increment in applied load (50N) there was slight increase in friction coefficient because of the direct metal contact to the disc material and decreases further with increment in applied load of 60N might be due to the softening of the surface occurs, because of higher interface temperature between the specimen and the disc material[8].





(a) (b)



(c)

Figure- 3 Variation of the frictional coefficient of extruded P/M steels at different sliding distances (i) 800m; (ii) 1600m; (iii) 2400m

3.3 Microstructure of sintered/hot extruded Tungsten and Titanium alloyed steels

The figure 4 (a, b) depicts the microstructures of the hot extruded P/M alloy steels. The WTi carbides formed due to the alloying elements of W and Ti were embedded along the grain boundaries leading to enhancing the tool wear resistance of both the extruded P/M alloy steels because W and Ti are some of the well-known carbide formers. In both hot extruded alloy steels (figure 4a & 4b) a mixed microstructure of Widmanstatten ferrite and ferrite-cementite matrix (alternate lamellas) was found, it clearly indicated that might be possibly occurred at a very high temperature between AC1and AC3 (723–900°C) during hot extrusion attributes to the higher hardness. The frictional coefficient is found to be higher due to the presence of second phase hard WTi carbide in both the P/M alloy steels. Also the cutting tool wear increases for Fe-1C-2W-1Ti (figure 4a) at lower and moderate cutting speeds while used for soft materials like Aluminium and Brass which is mainly because of lower % of WTi carbide formation leading to thermal softening of both tool and work piece, which results in higher tool mass removal rate due to built-up edge formation which sticks to the surface of the tool and deteriorates the tool rake face. Whereas for (figure 4b) Fe-1C-4W-1Ti due to more % of WTi carbide formation tool wear decreases because the tool-work piece interface temperature rises up, and the adhesion layer peels off from the tool face resulting in decrease of tool mass removal rate.

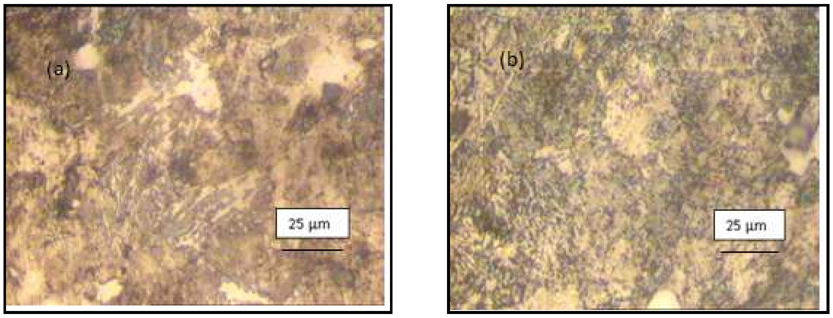


Figure- 4 Microstructures of extruded P/M alloy steels (a) Fe-1%C-2%W-1%Ti; (b) Fe-1%C-4%W-1%Ti

4. Conclusion

1. For Aluminium and Brass, at low cutting speeds, the tool–chip interface temperature (cutting temperature) is relatively low causes, the work piece material bonds to the cutting tool (a built-up edge formation which sticks to the surface of the tool) due to the higher thermal softening and deteriorates the tool rake face. As the cutting speed increases, the tool-work piece interface temperature also rises up, and the adhesion layer peels off from the tool face resulting in decrease of tool mass removal rate. For copper due to the higher thermal conductivity irrespective of the cutting speed there is no stick-slip between the tool and work piece resulting in low uniform tool wear.
2. The presence of WTi carbide can provide enhanced tool wear resistance provided the load is limited to that where fracture of the WTi carbide does not occur. Fragments of the carbides can act as third-body abrasives. A general decreasing trend was observed in the mass removal rate of tools with an increase in cutting speed irrespective of the 3 non-ferrous materials.
3. Frictional coefficient decreases with increase in % of WTi carbide content (Fe-1C-4W-1Ti) because of the brittle nature of the WTi carbide causing its fracture at higher loads. But for Fe-1C-2W-1Ti, frictional coefficient is slightly lower at low level of applied load because of the already formed oxide layer and gradually increases with respect to load leading to the fracture and detachment of oxide layer causing the WTi carbide present in alloy steel contact the disc material in the interface.
4. The mixed microstructure of Widmanstatten ferrite and ferrite-cementite matrix (alternate lamellas) was observed in the both hot extruded P/M alloy steels, the WTi carbides formed due to the alloying of elements W and Ti were embedded along the grain boundaries which plays the vital role in the alloy steels to enhance the tool wear resistance.

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