

Some Aspects of Machining Cast Al-SiCp Composites with Conventional High Speed Steel and Tungsten Carbide Tools

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An attempt was made to evaluate machining of eutectic Al-Si (LM6) and hypoeutectic Al-Si (LM25) alloys reinforced with 10, 15, and 20% SiCp of two particle sizes using conventional high-speed steel (HSS) and tungsten carbide (WC) tools by varying cutting speed, feed, depth of cut, and environment. Machining of metal matrix composites (MMCs) is a difficult task using HSS and WC tools. The tool life of both these conventional tools was observed to decrease with increasing percentage and coarseness of SiCp in the composites. Tungsten carbide tools had a longer tool life than HSS under all the different conditions studied. Contrary to the known phenomenon of enhanced tool life in machining monolithic alloys with the use of cutting fluid, the tool life of WC/HSS tool in machining composites with cutting fluid was only 10 to 20% of that without cutting fluid.

Keywords aluminum-silicon carbide particle composite, machinability, metal matrix composites

1. Introduction

Today, among various metal matrix composites (MMCs) synthesized, aluminum metal matrix composites in general and discontinuously reinforced aluminum metal matrix composites, such as Al-SiCp/Al_2O_3 in particular, have emerged as the forerunner for a variety of general and special applications. This trend has been attributed to their superior specific strength and specific stiffness, high temperature capability, lower coefficient of thermal expansion, better wear resistance, improved dimensional stability, and amenability to conventional metal forming techniques (Ref 1-4). In addition, development of stir casting route for synthesis has brought down their cost to an acceptable level compared to those processed by powder metallurgy and spray casting. The presence of hard reinforcements, like particulates of silicon carbide (SiCp) and alumina (Al_2O_3p), makes machining, one of the shaping routes, very tedious with conventional tools currently used for the matrix alloys and warrants use of special expensive tools like polycrystalline diamond (PCD).

Conversely, most aluminum alloys are quite soft relative to cast iron and steel and are commonly machined by high speed steel (HSS) tools. The exception to this are the aluminum-silicon alloys. Hypoeutectic and eutectic aluminum-silicon alloys (≤12% Si) are machined with tungsten carbide (WC) tools, while hypereutectic alloys (>12% Si) need PCD tools. This is because the silicon phase present is almost ten times harder than base aluminum. The most commonly used discontinuous reinforcement in aluminum metal matrix composites, namely SiCp and Al_2O_3p, are more than twice as hard as primary silicon. Further, aluminum-silicon alloys are also widely chosen as the matrix material because of their higher fluidity as well as lesser reaction with the reinforcement. Thus, machining of Al-SiCp composites needs special care both during selection of tool and actual operation.

Machinability, an ill-defined term, encompassing such diverse properties as surface finish of the product, rate of tool wear, chip formation, and cutting forces required in machining, is the relative ease or difficulty of removing material in transforming a raw material into a finished component. Machinability testing aims at evaluation of the comparative machining performance of work piece, cutting tools, cutting fluids, and establishment of machining conditions producing a satisfactory part meeting desired dimensional surface finish and functional integrity economically.

Machinability of a particular material can be evaluated by assessing any one of the following five parameters: (a) tool life or wear, (b) surface finish of test piece, (c) cutting force requirement, (d) power requirement, and (e) cutting temperature. Both the amount and shape of SiCp contribute to the tool wear (Ref 5, 6) while machining Al-SiCp composites. During machining with carbide tools, low cutting speed and high feed rates are recommended. Moreover, sucking of chips produced while dry cutting is found to be effective in improving tool life. Conversely, these chips lead to increased tool wear during wet cutting, wherein, higher SiCp size results in very poor surface roughness, while higher amounts of SiCp improve surface roughness (Ref 6). Machining of Al-SiCp hydraulic components has shown that while WC cutters are able to cut, they deteriorate rapidly. High-speed steel tools deteriorate almost instantly and, hence, should not be used for any production use and can be limited to special cutters and for a minimum metal removal (Ref 5). Because HSS tools cannot withstand the extremely abrasive conditions encountered during drilling Al-SiCp, experiments conducted with WC drills have revealed that (a) the presence of SiCp accelerates tool wear, (b) coolant prevents seizure and drill breakage, and (c) abrasion by SiCp is the mechanism causing wear of drills (Ref 7).

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Even in the case of PCD tools, the amount of SiCp present in an Al-SiCp composite has a significant effect on their cutting performance, and generation of rapid initial flank wear warrants use of cutting fluid. However, particle size of reinforcement is predicted (Ref 8, 9) to be a substantially more important factor than its population due to the geometric relation between its diameter and kinetic energy transferred to the tool edge. Rotary tools made up of carbide exhibiting superior wear resistance seem to be a high performance cutting tool for machining Al-SiCp composite (Ref 10) due to its 30 to 40% lower radial thrust cutting force compared to a fixed circular insert.

Despite the availability of some data on the machining performances of conventional tools, such as HSS and WC on Al-SiCp composites, no detailed study has been reported for a given composite system, and this investigation aims at fulfilling this gap.

2. Experimental Details

Eutectic (LM6) and hypoeutectic (LM25-Al7Si0.3Mg) aluminum-silicon alloy-based composites dispersed with silicon carbide particulates of two sizes (23 and 42 μm average particle size, or APS) and amounts (10, 15, and 20 wt%) by stir casting route and cast into 75 mm diameter cylindrical ingots of 170 to 270 mm length (Fig. 1) in mild steel molds were used as the work pieces. Two types of cutting tools, HSS and WC (K10), were chosen for machining the composites in a center lathe both in wet and dry conditions. Soluble cutting oil (20:1) was used as the cutting fluid. Keeping feed and depth of cut (DOC) constant at 0.5 mm/rev and 0.5 mm, respectively, the speed was varied from 40 to 90 m/min.

In addition, to understand the influence of feed and DOC on machinability, they were varied from 0.05 to 0.20 mm/rev and 0.5 to 1.5 mm, respectively, for a given speed and environment. As the amount of wear determines the tool life, chips were collected until a flank wear of 0.3 and 0.38 mm (Ref 11) was reached in HSS and WC, respectively, and the lengths of chips were measured. The loss in weight of tool due to wear was also computed. Right hand turning was adopted, and care was exercised to collect all chips produced. The machine was stopped at regular intervals during the machinability experiment to measure the tool wear. For comparison, all the previous machinabil-

Fig. 1 LM6/LM25-SiCp composites cylinders (75 mm diam by 170 to 270 mm long) used as work pieces

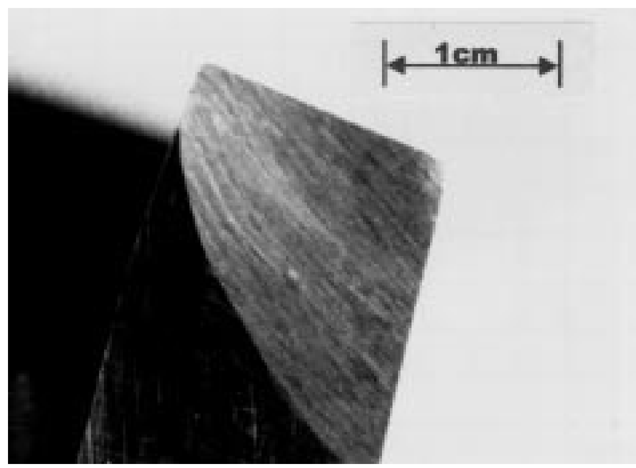

Fig 2 Well ground high-speed steel tool

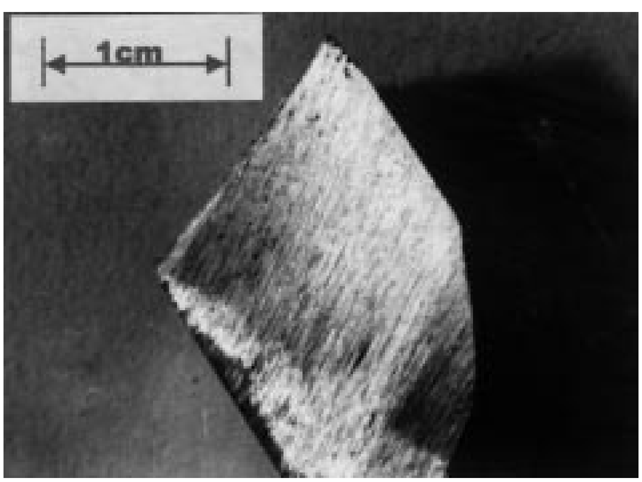

Fig 3 Formation of pores on the flank due to excess heat generation in high-speed steel tool

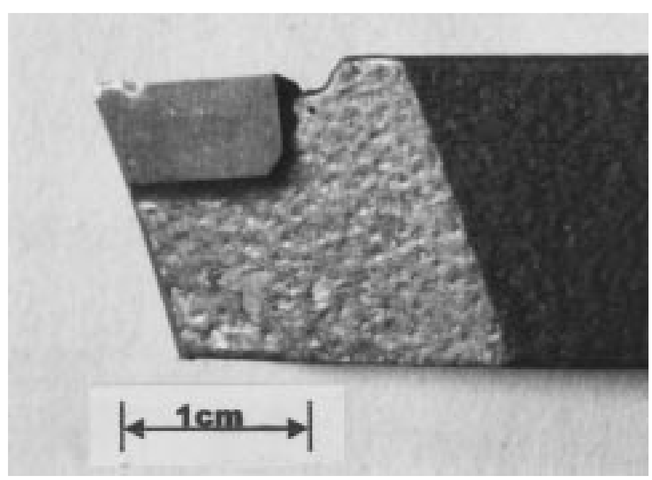

Fig 4 Flank wear, builtup edge, and local wear on flank land of tungsten carbide tool

ity studies were repeated for both matrix alloys containing no reinforcement. Chipping or breaking of cutting edge (Fig. 2-4) indicates end of tool life.

3. Results and Discussion

Table 1 lists some of the machining characteristics measured while machining LM6-15/20%SiCp (23 μm APS) composites and unreinforced matrix alloy under different conditions. The tool life of HSS for LM6-15SiCp was between 0.75 and 1.80 min, and its wear was instantaneous. Conversely, the tool life of WC for LM6-15SiCp was 18.5 min at 50 m/s and reduced to half, that is, 9.65 min with an enhanced speed of 90 m/s. In addition, tool life of WC reduced with increasing feed at a constant speed of 70 m/s. The chip length in all the previous cases increased with either increasing speed at a constant feed or increasing feed at a constant speed. Figure 5 shows a comparison of HSS and WC tool life while machining LM6-15SiCp composites under varying speeds. Tool life of HSS and WC tools with LM6-20% SiCp composite was around 1 and 9 to 12 min, respectively, under the chosen experimental conditions. Figure 6 compares the tool life of WC and HSS tools while machining LM6-20SiCp composite at varying speeds. Overall, these composites could be more easily machined with WC than a HSS tool, and its tool life was reduced to approximately 25% of that for unreinforced LM6 alloy.

Table 2 gives all the machining parameters studied and measured with respect to unreinforced LM25 alloy and its composites with 10, 15, and 20 wt% SiCp of 23 and 43 μm APS.

Table 1 Machining characteristics of LM6 alloy without and with SiCp reinforcement using tungsten carbide and high-speed steel tools in dry and wet conditions

Tool	Speed, m/min	Feed, mm/rev	Tool life, min	Chip length, mm
LM6				
WC	60.00	0.05	36	55.00
WC	80.00	0.05	31	65.00
LM6-15 SiCp, 23 μm APS				
WC	50.00	0.05	18.5, 3.0(a)	10.00
WC	70	0.05	11.25, 1.5(a)	13.00
WC	70	0.10	8.00	30.00
WC	70	0.15	5.00	47.00
WC	70	0.20	8.00	50.00
WC	90.00	0.05	9.65, 1.0(a)	15.00
HSS	50.00	0.05	1.80	5.00
HSS	70.00	0.05	1.35	6.00
HSS	90.00	0.05	0.75	7.00
LM6-20 SiCp, 23 μm APS				
WC	50.00	0.05	11.4, 2.0(a)	28.0
WC	60.00	0.05	10.80	35.0
WC	70.00	0.05	1.00(a)	…
WC	85.00	0.05	8.55	45.0
WC	90.00	0.05	0.05(a)	…
HSS	85.00	0.05	1.38	7.50
HSS	145.00	0.05	1.20	12.50
HSS	250.00	0.05	0.72	17.50

APS, average particle size; WC, tungsten carbide; HSS, high-speed steel.
(a) With cutting fluid or under wet condition

Tool life of HSS and WC in machining a LM25-10SiCp (23 μm) composite was 9 and 22 min, respectively, under a feed of 0.05 mm/rev and a speed of 40 m/min. In addition to longer chip length, as well as lesser builtup edge (BUE) formation, changing the size of SiCp to 42 μm, has reduced the tool life of both the tools (less than 1 and 7 min, respectively). Figure 7 shows a comparison of WC and HSS tool life while machining different LM25-SiCp composites at a speed of 40 m/min and a feed of 0.05 mm/rev. Conversely, Fig. 8 shows similar comparison for a speed of 50 m/min and a feed of 0.05 mm/rev. Varying the feed from 0.05 to 0.14 mm/rev under a constant speed of 50 m/min while machining LM25-10SiCp (23 μm) with WC tool has reduced its tool life from 6.5 to 3 min, but increases the chip length (35 to 85 mm). Increasing the amount of SiCp (23 μm) from 10 to 15% in the composite resulted in reduced tool life in both HSS and WC tools. A further increase in SiCp content to 20% led to further reduction in tool life because of excessive nose wear (Fig. 9). It is interesting to note that tool life of a WC tool while machining LM25-10/15 SiCp (23 μm) reduces to 50

Table 2 Machining characteristics of LM25 alloy without and with SiCp reinforcement using tungsten carbide and high-speed steel tools under dry and wet conditions

Tool	Speed, m/min	Feed, mm/rev	Tool life, min	Chip length, mm
LM25				
WC	60	0.05	41.5	70
WC	75	0.05	37.0	80
LM25-10%SiCp, 23 μm APS				
WC	40	0.05	22.0	12
WC	50	0.05	20.0	15
WC	65	0.05	15.40	14
HSS	40	0.05	9.40	20
HSS	50	0.05	7.0	25
HSS	65	0.05	6.30	23
LM25-10%SiCp, 42 μm APS				
WC	40	0.05	6.80	37
WC	50	0.05	6.50	35
WC	50	0.07	4.90	55
WC	50	0.10	4.10	75
WC	50	0.14	3.0	85
WC	70	0.05	2.70	37.5
HSS	40	0.05	0.60	12.5
HSS	50	0.05	0.35	18.0
HSS	70	0.05	0.30	30.0
LM25-15%SiCp, 23 μm APS				
WC	40	0.05	20.00	10.0
WC	50	0.05	17.00	10.0
WC	50	1.00	18.00	14.0
WC	50	1.50	20.00	15.0
HSS	40	0.05	9.00	12.0
HSS	50	0.05	7.50	12.0
HSS	70	0.05	6.00	9.0
LM25-20%SiCp, 23 μm APS				
WC	40	0.05	5.0, 1.0(a)	4.0
WC	50	0.05	4.50	4.0
WC	70	0.05	4.0	5.0
HSS	40	0.05	0.30	3.0
HSS	50	0.05	0.30	4.0

APS, average particle size; WC, tungsten carbide; HSS, high-speed steel.
(a) With cutting fluid or under wet condition

to 70% of that of unreinforced LM25 alloy. The LM25 alloy with 10% SiCp could be more easily machined than one with 20% SiCp, wherein tool life of both tools was decreased by manifold. Nevertheless, a WC tool is many times better than a HSS tool in machining these composites as well.

The nose wear of an HSS tool while machining an LM6-15/20%SiCp (23 µm APS) composite was equivalent to the depth of cut given. Builtup edge (BUE) formation was observed to be helpful in enhancing tool life by 50 to 80% as reported by Lane (Ref 12). However, high BUE formation

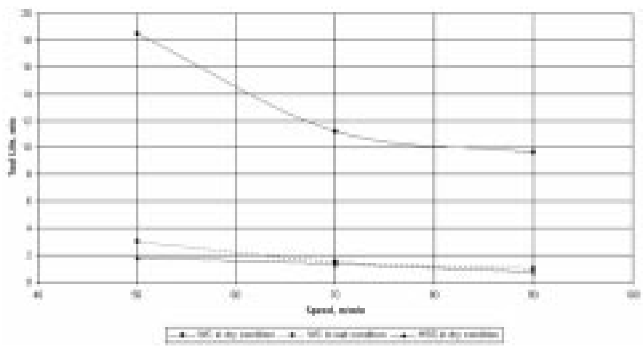

Fig 5 Comparison of tungsten carbide and high-speed steel tool life during machining LM6-15SiCp composite under dry and wet conditions. (Feed 0.05 mm/rev)

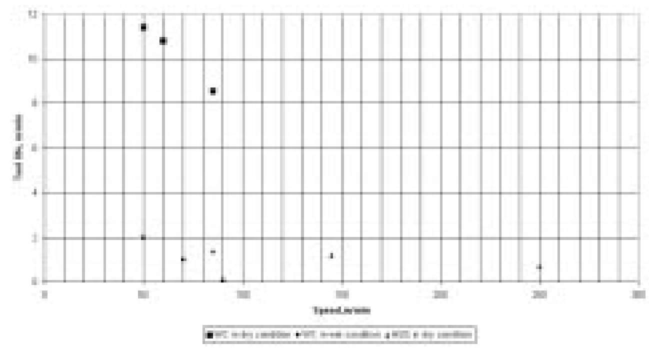

Fig. 6 Comparison of tungsten carbide and high-speed steel tool life during machining LM6-20 (23 µm). SiCp composite under dry and wet conditions. (Feed, 0.05 mm/rev)

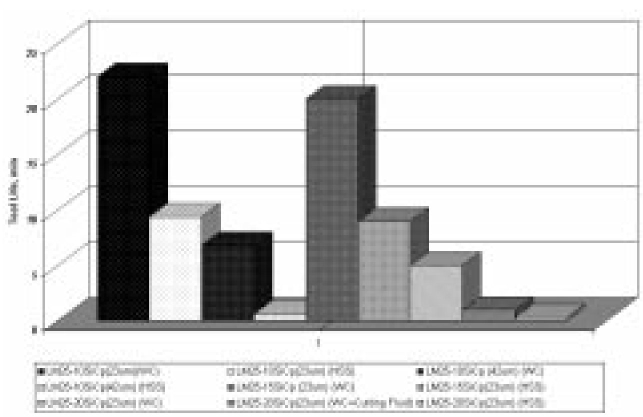

Fig. 7 Comparison of tungsten carbide and high-speed steel tool life while machining LM25-SiCp composites. (Speed, 40 m/min; feed, 0.05 mm/rev)

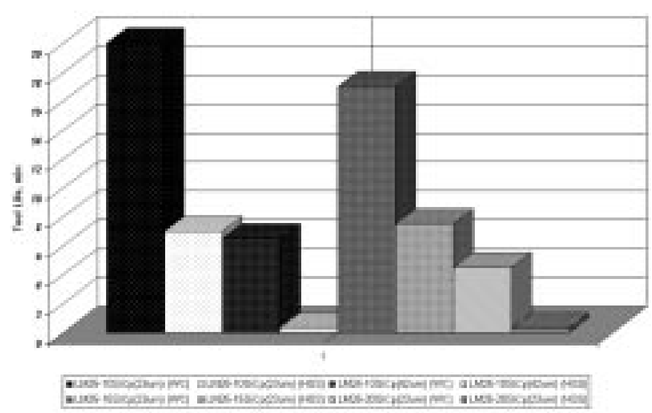

Fig. 8 Comparison of tungsten carbide and high-speed steel tool life while machining LM25-SiCp composites. (Speed, 50 m/min; feed, 0.05 mm/rev)

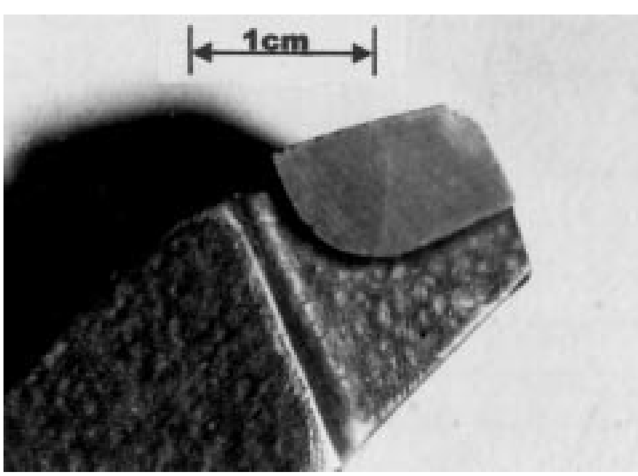

Fig. 9 Excessive nose wear and nose groove formation while machining LM25-20% SiCp (42µm) with tungsten carbide tool

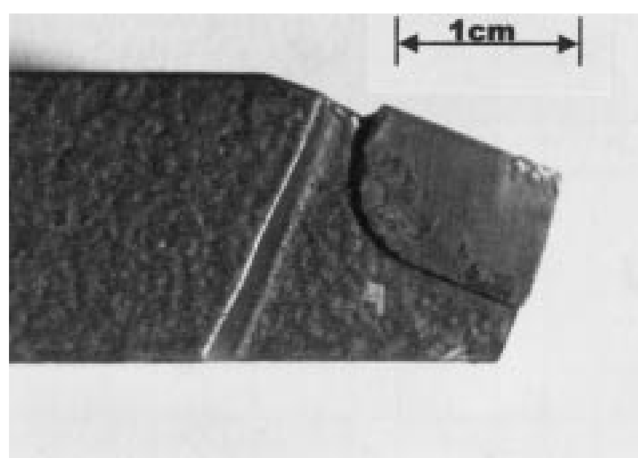

Fig 10 Formation of large builtup edge on tungsten carbide tool while machining LM25-10SiCp (23µm) composite under dry environment

resulted in poor surface finish. Because an increase in feed rate led to increased BUE formation, rough turning in dry environment of aluminum MMCs can be carried out at high feed rate where ever surface finish is not a criteria. As in LM6 base composites, formation of BUE increased tool life considerably at higher speeds at which the surface finish of the LM25-SiCp composites was poor. Hence, to achieve a good finish at higher speeds, very low feed as well as removal of BUE should be adopted.

The formation of a builtup edge is a common phenomenon observed while working at higher speed, feed, and depth of cut in dry environment (Fig. 10), which is responsible for the enhanced tool life observed. Formation of BUE is purely thermochemical (Ref 11). While working at higher cutting conditions, temperature at the tool tip goes up to 600 °C. The chips and minute particles of the work piece existing on the top rake of the tool become welded to the tool tip eliminating its wear on the flank or nose.

The use of cutting fluid is always expected to enhance tool life. Contrary to this known fact, lower tool life was experienced in machining aluminum MMCs in the presence of cutting fluid, that is, 10 to 20% of that under dry condition. The cutting fluid, by eliminating BUE formation on the rake of the tool, makes the tool incapable of withstanding the abrasive wear leading to lower tool life. It was also noticed that the tool life with cutting fluid was near to the time taken for BUE formation without cutting fluid. Hence, aluminum MMCs with SiCp reinforcement need to be machined with WC/HSS tools under dry conditions for rough and semifinished machining.

4. Conclusions

Tungsten carbide tools have exhibited higher tool life than HSS for all the conditions studied, and builtup edge formation may be a possible additional reason under dry condition. Use of cutting fluid was found to decrease tool life of both composites to 10 to 20% of that without cutting fluid. Increasing coarseness and the amount of SiCp reduce tool life of both HSS and WC tools. Tungsten carbide tools can be used for jobs requiring lesser machining. Judicious selection of speed (<100 m/min), feed (<0.1 mm/rev), and depth of cut (<1.0 mm) can enable extended WC tool life as well as help attain a good surface finish. Tool life of WC tool while machining LM6-SiCp and LM25-SiCp composites is reduced by 25% and 50 to 70% of that of unreinforced matrix LM6 and LM25 alloys.

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