Effect of Workpiece Microstructure and Cutting Speed on Tool Life, Surface Roughness, and Chip Formation During Dry Turning of Hypereutectic Al–Si Alloy with PCD Tools

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Abstract:

Hypereutectic aluminium–silicon (Al–Si) alloys offer high wear resistance and low thermal expansion, but their primary silicon particles can make machining difficult because of their hardness and abrasive action. This paper re-examines experimental dry-turning results for an AlSi18/A390-type hypereutectic alloy machined with polycrystalline diamond (PCD) inserts. The source study compared an unmodified alloy with a strontium-modified condition at cutting speeds of 500, 600, and 700 m/min, while feed and depth of cut were held at 0.1 mm/rev and 1 mm, respectively. Tool life was evaluated using a maximum flank-wear limit of 0.30 mm; surface quality was assessed using arithmetic mean roughness (Ra), and chip morphology was described qualitatively. Re-analysis of the tabulated results indicates that tool life decreased with increasing cutting speed in both material conditions. At 500 m/min, the reported tool lives were 38 min for the unmodified alloy and 40 min for the Sr-modified alloy; at 700 m/min, they were 15 and 18 min, respectively. The mean of the tabulated Ra measurements increased from approximately 0.806 to 1.025 µm for the unmodified alloy and from 0.795 to 0.995 µm for the Sr-modified alloy as speed increased from 500 to 700 m/min. The modest life advantage associated with Sr modification is consistent with the limited influence of Sr on primary silicon compared with modifiers specifically used to refine that phase. Because the source experiment does not report independent replicated cutting trials or inferential statistics, the observed differences should be interpreted descriptively rather than as statistically significant effects. The paper identifies practical implications and data-verification requirements for a submission-ready follow-up study.

Keywords: Hypereutectic Al–Si alloy; Dry turning; Polycrystalline diamond; Tool life; Surface roughness.

1. Introduction

Hypereutectic Al–Si alloys contain silicon above the eutectic composition and are used where low density, wear resistance, and low thermal expansion are important. A390/B390-type alloys, with silicon contents near 18–20 wt% depending on specification, are used in components such as engine blocks, cylinder liners, pistons, and compressor parts. Their machinability is nevertheless challenging because hard primary-Si particles interact with the cutting edge, promote abrasive wear, and can fracture during chip formation (Liu and Chou, 2007).

The resulting tool–workpiece interaction is controlled by more than the nominal alloy composition. Primary-Si size, morphology, and distribution influence local contact conditions and the way the material fractures and deforms during cutting. Reviews of hypereutectic Al–Si alloys emphasize the importance of microstructure and solidification control in determining performance (Vijeesh and Prabhu, 2014; Zhang et al., 2025). Experimental work has also shown that microstructural modification can change the roughness generated during machining, although the effect depends on the modifier and on which silicon phase is altered (Jiandon and Talangkun, 2022).

Strontium is commonly used to modify eutectic silicon in Al–Si alloys, but it is not necessarily the most effective route for refining primary silicon. Phosphorus-based treatments are widely reported as effective primary-Si refiners, while the response to other additions depends on alloy chemistry and processing conditions (Jiandon and Talangkun, 2022; Zhang et al., 2025). Accordingly, the machining response of an Sr-modified hypereutectic alloy should not be assumed to improve uniformly across tool life, surface finish, and chip morphology.

The experimental work examined here (Saeid, 2007) compared dry turning of unmodified and Sr-modified AlSi18 using PCD inserts at 500, 600, and 700 m/min. Although the original study provides a useful comparative dataset, it dates from 2007 and does not report independent replicate trials or statistical tests. The present manuscript therefore has two purposes: (i) to consolidate and quantitatively summarize the reported measurements in a journal-style format, and (ii) to discuss the trends against relevant literature while clearly identifying limits that must be addressed before journal submission.

1.1 Literature Review

1.1.1 Machinability of Hypereutectic Al–Si Alloys

Primary silicon improves the wear-related properties of hypereutectic Al–Si alloys, but the same hard phase can be detrimental during cutting. Fracture and abrasion of Si particles may produce local damage at the tool edge; adhered work material and micro-chipping can also contribute to flank wear. Liu and Chou (2007) investigated machining A390 alloy and showed that the relationship between temperature and tool wear is not simple: reduced temperature does not automatically produce a proportional reduction in wear under all cutting conditions. More recent studies continue to examine the trade-off between tool life, cutting conditions, and surface finish in hypereutectic Al–Si machining. Othman et al. (2020) used a factorial design for dry face milling of A390 and reported cutting speed as the most influential factor for tool life, whereas feed rate was most influential for roughness. Kobaru et al. (2020) examined tool wear in A390–T6 machining with DLC-coated carbide tools, providing a complementary perspective on the relation between cutting force and wear-land growth. Their tool materials and machining operations differ from the PCD turning conditions examined here, so their results are contextual rather than directly comparable.

1.1.2 Microstructural Modification

The effectiveness of a modifier depends on the phase it acts upon. Jiandon and Talangkun (2022) reported that phosphorus can refine primary silicon in B390 alloy, while bismuth affects eutectic silicon and surface roughness; their results illustrate that primary and eutectic Si need to be considered separately. The recent review by Zhang et al. (2025) surveys conventional, rare-earth, and particle-based approaches for primary-Si refinement and notes that particle size, shape, and distribution remain central variables. These findings provide context for interpreting the modest difference between the Sr-modified and unmodified cases in the source dataset.

1.1.3 Surface Roughness and Chip Formation

Arithmetic mean roughness (Ra) is a common indicator of the surface profile generated by machining, but it is affected by feed, tool geometry, built-up edge, vibration, material heterogeneity, and tool wear. Othman et al. (2020) likewise found roughness to depend strongly on feed rate in dry face milling of A390, illustrating why results from different operations and feed definitions should not be pooled without normalization. Recent PCD studies on much higher-silicon Al–Si composites have directly characterized abrasive, adhesive, and oxidation-related wear, but those materials and assisted-machining conditions differ substantially from the AlSi18 alloy and conventional dry turning in the present source (Liu et al., 2025). The source study used three roughness readings at each observation point and reported their average. In this manuscript, the speed-level value is calculated as the arithmetic mean of the tabulated point averages; it is not an independently replicated experimental mean. Chip morphology is discussed qualitatively because the source provides images and descriptions rather than quantitative chip segmentation or chip-thickness measurements.

2. Methodology

2.1 Workpiece and Cutting Tool

The source thesis describes a hypereutectic AlSi18 alloy in two conditions: unmodified and Sr-modified. The original report associates the material with the A390/AlSi18 family. Exact chemical composition, Sr addition level, casting route, heat treatment, hardness, and primary-Si particle-size statistics were not

consistently available in the tabulated experimental record reviewed for this manuscript; these details should be recovered from laboratory records before submission.

Turning was performed on an ALPHA 1350S two-axis CNC lathe using polycrystalline diamond (PCD) inserts. The reported tests were dry, with no cutting fluid. The original thesis discusses flank wear, tool life, surface roughness, and chip morphology as the principal response measures.

2.2 Cutting Conditions and Response Measures

Table (1): Cutting conditions and response measures

Parameter	Reported setting
Cutting speeds, Vc	500, 600, and 700 m/min
Feed rate, f	0.1 mm/rev
Depth of cut, ap	1.0 mm
Cutting environment	Dry turning
Tool material	Polycrystalline diamond (PCD)
Tool-life endpoint	VBmax = 0.30 mm, as used in the source thesis
Surface quality	Arithmetic mean roughness, Ra (μm), three readings per observation point
Chip assessment	Qualitative visual/micrographic observations

The source thesis reports that tool wear was monitored at time intervals until the maximum flank-wear criterion reached 0.30 mm. The present paper retains that endpoint to make the two material conditions comparable. ISO 3685:1993 provides a recognized framework for single-point turning tool-life testing, but the standard's stated scope focuses on high-speed steel, cemented carbide, and ceramic tools used on steel and cast iron; therefore, this study should not be described as fully ISO-compliant for PCD machining of Al–Si unless the relevant procedure is independently verified (ISO, 1993).

2.3 Data Treatment

For each speed/material condition, tool life was taken as the cumulative cutting time at which the tabulated maximum flank wear reached 0.30 mm. The speed-level roughness value was calculated by averaging the "Average" Ra column across the observation points in the corresponding source table. The relative tool-life difference was calculated as 100 × (T_Sr − T_unmodified)/T_unmodified. No inferential statistical tests were performed because the source does not establish independent repeated tool-life trials. Values are therefore reported descriptively, and no p-values or confidence intervals are claimed.

3. Results and Discussion

3.1 Tool Life and Flank Wear

Tool life decreased as cutting speed increased for both workpiece conditions. The unmodified alloy reached the 0.30 mm flank-wear limit after 38, 31, and 15 min at 500, 600, and 700 m/min, respectively. The Sr-modified alloy reached the same limit after 40, 34, and 18 min. Thus, the Sr-modified condition showed a descriptive tool-life increase of approximately 5.3%, 9.7%, and 20.0% at the three respective speeds. These percentages are based on single reported tool-life endpoints and should not be interpreted as statistically significant improvements.

Table (2): Effect of strontium modification on tool life at different cutting speeds

Cutting speed (m/min)	Unmodified tool life (min)	Sr-modified tool life (min)	Difference (%)
500	38	40	5.3
600	31	34	9.7
700	15	18	20.0

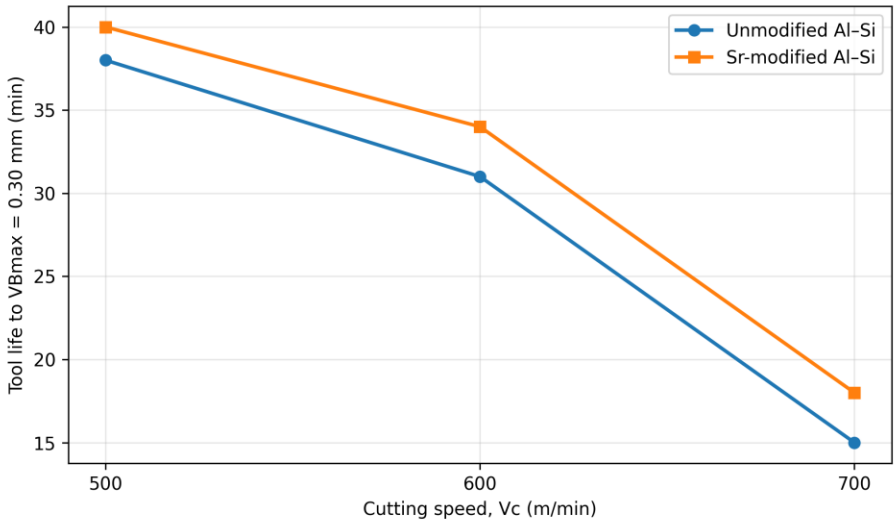


Figure (1): Reported tool life to the 0.30 mm maximum flank-wear criterion at the three cutting speeds

The reduction in tool life with speed is consistent with more severe cutting conditions at higher speeds, where thermal and mechanical loading can intensify. However, the source did not directly measure tool temperature, cutting force, or wear-mechanism fractions, so the relative contribution of thermal effects, abrasion, adhesion, and edge chipping cannot be isolated from these data.

3.2 Surface Roughness

The mean of the tabulated Ra point averages increased with cutting speed in both conditions. For the unmodified alloy, the calculated means were 0.806, 0.902, and 1.025 µm at 500, 600, and 700 m/min. For the Sr-modified alloy, corresponding values were 0.795, 0.900, and 0.995 µm. Across 500 to 700 m/min, the speed-level mean increased by about 27.0% for the unmodified condition and 25.1% for the Sr-modified condition. These derived means summarize the tabulated observations and do not represent averages across independent machining replicates.

Table (3): Comparison of mean surface roughness (Ra) between unmodified and Sr-modified Al–Si alloys at different cutting speeds

Cutting speed (m/min)	Unmodified mean Ra (µm)	Sr-modified mean Ra (µm)
500	0.806	0.795
600	0.902	0.900
700	1.025	0.995

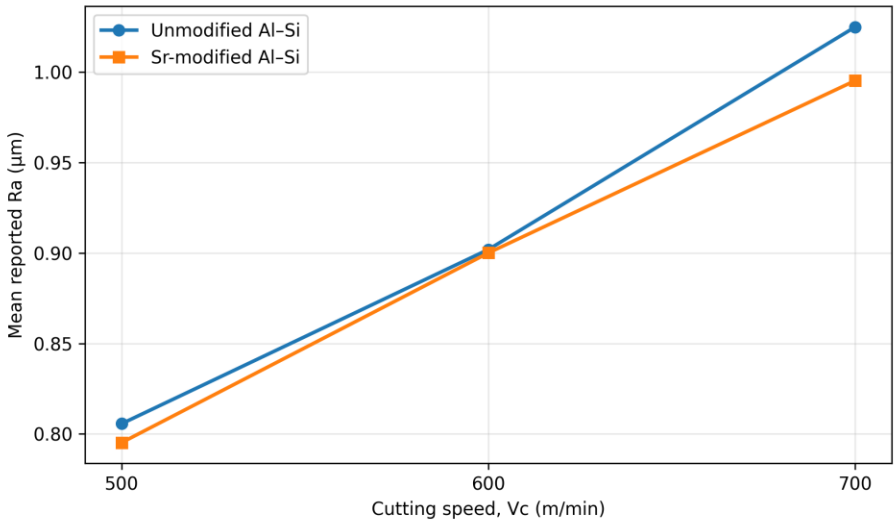


Figure (2): Mean Ra calculated from the point-average values listed in the source thesis tables

The difference between the two material conditions is small relative to the change associated with cutting speed. This is consistent with the thesis conclusion that Sr modification did not produce a substantial reduction in primary-Si size. A definitive explanation would require quantitative microstructural measurements and replicated roughness tests. The original table for the Sr-modified condition at 600 m/min contains a value of 0.986 µm among the three readings at one observation point, while the stated point average is 0.873 µm; this appears inconsistent and should be checked against the original measurement sheet. The speed-level calculations above use the source table's stated "Average" column.

3.3 Chip Morphology

The thesis describes segmented chips in both material conditions. At 500 m/min, the reported chips were generally short and snarled, whereas higher cutting speeds were associated with more evident shear bands and deformation features. The source interprets these features as being related to increased cutting temperature and plastic deformation of the aluminium matrix, together with fracture of hard silicon particles. This interpretation is plausible but remains qualitative: chip segmentation frequency, shear angle, chip thickness, and local temperature were not quantified in the reported dataset.

3.4 Discussion

3.4.1 Influence of Cutting Speed

The clearest trend is the decline in tool life with increasing cutting speed. Between 500 and 700 m/min, reported tool life fell by 60.5% for the unmodified alloy (38 to 15 min) and by 55.0% for the Sr-modified alloy (40 to 18 min). At the same time, mean Ra rose by approximately 27.0% and 25.1%, respectively. Within the tested range and fixed feed/depth of cut, the lower speed therefore offered the best combination of longer tool life and lower roughness. This conclusion is restricted to the tested PCD tool, dry conditions, alloy conditions, and parameter range; it does not establish that 500 m/min is globally optimal for productivity, cost, or all tool geometries.

3.4.2 Effect of Sr Modification

The Sr-modified alloy produced longer reported tool life at each speed, but the absolute advantage was modest: 2 min at 500 m/min, 3 min at 600 m/min, and 3 min at 700 m/min. The relative advantage appears larger at 700 m/min because the baseline tool life is shorter. Given the absence of independent replicate trials, it is not possible to determine whether these differences exceed experimental variability. The slight reduction in mean Ra for the Sr-modified material is also descriptive rather than statistically established.

The material-science interpretation is that Sr is generally more effective at modifying eutectic silicon than refining primary silicon. Since primary Si is a principal abrasive constituent in hypereutectic Al–Si alloys, a

limited change in primary-Si morphology may yield only a limited improvement in tool life. Recent literature distinguishes primary-Si refinement from eutectic-Si modification and identifies phosphorus and combined-modifier approaches as possible routes for controlling both phases (Jiandon and Talangkun, 2022; Zhang et al., 2025). These findings suggest a testable follow-up hypothesis, not a result demonstrated by the current dataset.

3.4.3 Wear Mechanisms and Limitations of Interpretation

The source discusses abrasion by hard silicon particles and edge chipping as likely contributors to PCD wear. Literature on machining A390 also describes abrasive interactions and adhesion-related mechanisms, while cautioning that the influence of cooling and temperature depends on cutting conditions (Liu and Chou, 2007). A 2025 study of PCD tools during pulsed-laser-assisted turning of Al–50 wt% Si reported abrasive, adhesive, and oxidation-related wear, with the dominant mechanisms changing with temperature (Liu et al., 2025). Because Al–50 wt% Si is a much higher-silicon material and the process uses laser assistance, that study supports the need for direct wear characterization but cannot be used to assign the same mechanism to the present AlSi18 tests. The present source did not report SEM/EDS of worn inserts, quantitative edge-chipping measurements, cutting forces, or tool temperature. Therefore, the paper should avoid claiming that one mechanism dominates. Direct tool-surface microscopy, wear-land profiling, and replicated tests would substantially strengthen the mechanistic interpretation.

4. Conclusion

1. Under the reported dry-turning conditions (f = 0.1 mm/rev and ap = 1 mm), increasing cutting speed from 500 to 700 m/min reduced PCD tool life from 38 to 15 min for the unmodified alloy and from 40 to 18 min for the Sr-modified alloy.
2. The mean of the source-table Ra averages increased with speed: 0.806 to 1.025 µm for the unmodified alloy and 0.795 to 0.995 µm for the Sr-modified alloy.
3. The Sr-modified condition showed a descriptive tool-life advantage of 5.3–20.0% over the tested speeds, but the source data do not support a claim of statistical significance.
4. The source describes short, snarled chips at the lowest speed and more evident segmentation/shear-band features at higher speeds; these observations remain qualitative.
5. A publishable follow-up should verify the raw tables, document material chemistry and microstructure, add independent replicate trials, and characterize worn PCD inserts to distinguish abrasive, adhesive, and edge-chipping mechanisms.

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