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Can higher cutting speeds and temperatures improve the microstructural surface integrity of advanced Ni-base superalloys?

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ABSTRACT

Future Ni-base superalloys are designed to deliver outstanding mechanical behaviour at high temperatures, which may translate in significant machining challenges. In this work, a paradigm is presented by which is proven how machining of these materials could benefit from increased cutting speeds and temperatures provided that they are able to promote shear localisation and thermal softening in the chip deformation zones, whilst retaining high-temperature strength within the machined surface. In this way, thermal control of chip formation leads to both lower cutting forces and energies, as well as enhanced surface integrity with lower levels of microstructural reconfiguration.
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1. Introduction

New polycrystalline Ni-base superalloys have been designed to achieve optimal combination of yield strength, resistance to creep, low cycle fatigue, crack growth and environmental damage through optimisation of composition, precipitation strengthening (of gamma prime, γ'), and control of grain boundary phases [1,2]. When machining safety-critical superalloy components, such as high-pressure aeroengine discs, excellent microstructural surface integrity is required to ensure in-service part performance [3,4], which is quite challenging by the low machinability of these materials [5]. In fact, intensive thermo-mechanical fields can locally arise during cutting (Fig. 1a, b) [6], potentially leading to undesirable levels of machining-induced metallurgical reconfiguration [7]. In particular, high cutting temperatures may have undesirable effects when machining advanced Ni superalloys, which can display increasing mechanical strength (see highlighted zone in Fig. 1c) up to relatively high temperatures, e.g. in the range of 700−800 °C for 40−60% γ' volume fractions [8]. Specifically, compositions with increased high-temperature strength can promote severe thermo-mechanical cutting conditions leading to formation of microstructural surface anomalies [9]. Nevertheless, solutions with higher γ' content can be less sensitive to surface anomalies if machined under high temperature strengthening conditions, albeit at the expense of a lower machinability [10]. However, excessive cutting temperatures can ultimately result in thermal softening (Fig. 1c), which might appear convenient from a chip formation perspective, but it risks producing excessive surface deformation. Moreover, when machining advanced Ni-base superalloys, high cutting temperatures (> 1000 °C) are often associated with excessive cutting rates [11], under which rapid tool deterioration can further compromise the machined surface quality. As such, it appears to be a set of conflicting requirements: with either the option of cutting these superalloys under relatively low speeds and moderate temperatures for optimal surface integrity, or significantly increasing cutting rates to reach softening temperatures, but with the risk of affecting surface quality.

Differently, a new concept is here proposed to attain the best of both worlds. In fact, controlled workpiece pre-heating (Fig. 1a, b) is employed with the scope of promoting softening in the chip shear zones while exploiting temperature-strengthening conditions in the machined surface region (Fig. 1d). This concept is thus applied to a next-generation Ni-base superalloy, bringing a new perspective on the relationship between cutting speed range, chip formation mechanism, cutting temperature and surface integrity in this class of materials.

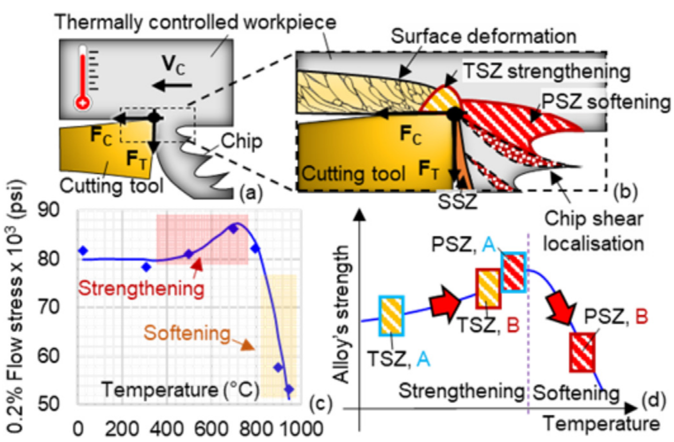

Fig. 1. (a) Chip formation and (b) shear zone detail for a pre-heated workpiece. (c) Flow stress of a Ni superalloy with 40% γ' content [8]. (d) Cutting strategy with softening in PSZ and strengthening in TSZ.

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2. Tuning temperature-dependant material response and machining-induced shear localisation

If one could choose, what would be the most convenient material behaviour to experience during chip formation?

Ideally, it would be desirable to encounter lower strength where most of the chip plastic deformation occurs, i.e. in the primary

(PSZ) and secondary (SSZ) shear zones (Fig. 1a, b), whilst retaining high strength in the tertiary shear zone (TSZ), where deformations should be minimised to optimise surface integrity.

However, cutting temperature distributions normally depend on the heat dissipation patterns at the tool-chip/tool-workpiece interfaces. In machining, most of the cutting heat flows in the chip, whilst only ~2% is generally dissipated in TSZ with a very limited portion flowing into the workpiece surface [12]. On one hand, this can be beneficial when cutting low-temperature materials (e.g. steels or Al alloys), as it can promote softening in the chip shear zones while inducing lower cutting temperatures. However, this condition may instead be disadvantageous when cutting Ni superalloys, as temperature rise in PSZ can undesirably lead to strengthening conditions in the chip (PSZ, A – Fig. 1d), while leaving the machined surface under lower temperature strength (TSZ, A – Fig. 1d). Instead, it would be more convenient to cut under strengthening temperatures in TSZ and softening in PSZ.

A possible way to achieve this is by pre-heating the workpiece prior to cutting to an intermediate temperature level such that, with reference to Fig. 1d, the conditions of surface deformation "TSZ, A" are shifted towards the alloy's strengthening region, in the range "TSZ, B", while shifting the chip deformation conditions away from the strengthening zone "PSZ, A" towards softening conditions in the range "PSZ, B". To experimentally explore this possibility, a next-generation Ni-base superalloy is machined under controlled pre-heating temperatures at different speed ranges, showing how a technical paradigm can be achieved: The tuning of softening effects in PSZ and strengthening in TSZ can be exploited to simultaneously enhance surface integrity and decrease cutting forces when machining advanced Ni-base superalloys, even more so at higher cutting speeds where increased chip shear localisation can further promote PSZ thermal softening.

3. Experimental details

To investigate the role of thermal fields on machining of new superalloys, the pendulum-based set-up first described in [13] originally purposed for room temperature orthogonal cutting has been upgraded with high-temperature testing capability through the addition of a PID-controlled conductive heating system, allowing to reach desired workpiece surface temperatures through an N-type thermocouple feedback, as shown in Fig. 2. Under these conditions, cutting speeds are recorded for each test through high-speed imaging at 4.5 kHz, and a Kistler dynamometer is used for cutting forces measurement. Thus, the experimental plan (Table 1) has been designed to understand the role of workpiece pre-heating temperature (T_0) on the alloy's machinability and surface integrity up to 600 °C, under different cutting speeds (V_C), uncut chip thickness (t_0) and advanced cutting tools in fresh condition (Coated carbide for lower speeds and pCBN for higher speeds).

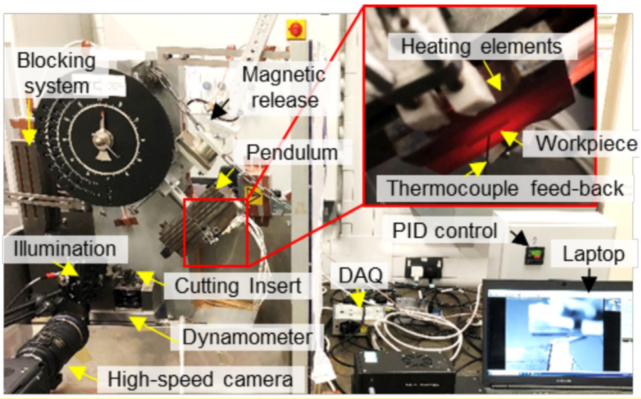

Fig. 2. Experimental set-up for orthogonal cutting experiments under controlled pre-heating temperatures.

A next-generation powder Ni-base superalloy for future aero-engine applications has been selected for this study, with a 51−53% γ' volume fraction and ASTM 8 to 7 average grain size. Further details on this material can be found in the patent [14]. On the microscale, the alloy displays γ matrix grains and small secondary γ' strengthening precipitates (Fig. 3a, b). For metallurgical inspection, samples are mounted in resin, polished and etched with Kalling's n°2 reagent as needed.

Table 1
Experimental plan for the analysis of chip formation under different thermo-mechanical conditions.

Test #	V_C [m/min]	T_0 [°C]	t_0 [mm]	Insert Grade
1	80	RT	0.1	PVD Coated Carbide
2		200		
3		400		
4		600		
5		600	0.2	
6	140	RT	0.1	pCBN
7		200		
8		400		
9		600		
10		600	0.2	

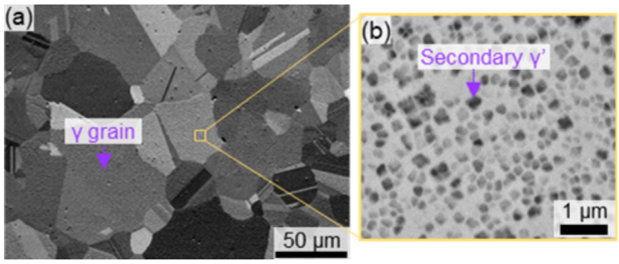

Fig. 3. Microstructure of the selected Ni-base superalloy. (a) γ matrix grains (Electron channelling contrast imaging) and (b) secondary γ' strengthening precipitates (Backscatter electron imaging).

Field-emission gun scanning electron microscopy (FEG-SEM) and electron backscatter diffraction (EBSD) techniques were employed to reveal the influence of different thermo-mechanical conditions on the cutting-induced microstructural reconfiguration and integrity.

4. Machinability and chip formation analysis

Before delving into small scale surface integrity analysis, chip formation (Fig. 4), cutting forces (Fig. 5a, b) and cutting energies (Fig. 5c) were first examined for the selected thermal conditions and speed ranges (Table 1). Increasing pre-heating temperatures from RT to 600 °C at constant cutting depth (t_0 = 0.1), produced a decrease in cutting forces both at low (Fig. 5a – V_C = 80 m/min) and high speeds (Fig. 5b – V_C = 140 m/min). Interpretation of this trend is provided by chip formation analysis in Fig. 4. In fact, it can be observed how an increasingly serrated chip morphology is produced when progressively increasing T_0 from RT to 200 °C, 400 °C and 600 °C, at both low and high cutting speeds. Specifically, it can be noted how the effect of pre-heating appears to have a predominant role on chip serration at low speeds, while at higher speeds shear localisation is additionally promoted by the increased cutting rates, where chip serration starts occurring from an advanced stage even at RT. Hence, greater chip serration is associated to a change in chip formation mechanism towards increasing levels of shear localisation. As a result, the energy consumed for primary chip shear is dissipated over smaller chip volumes in PSZ, promoting localised softening conditions, greater serration and lower cutting forces. An analogous tendency is observed also in the high speed range (140 m/min), where higher levels of serration are associated to higher pre-heating temperatures activating the combined onset of shear localisation and thermal softening in PSZ. Furthermore, this is even more easily achieved in such higher speed range as shear localisation is additionally aided by the imposition of higher rates of deformation. Differently, an increase in cutting depth at high temperatures (t_0 = 0.2, T_0 = 600 °C) produced an increase in cutting forces (Fig. 5a, b) compared with lower cutting depths at high temperatures (t_0 = 0.1, T_0 = 600 °C), but interestingly without exceeding the RT levels (t_0 = 0.1, T0=RT). Thus, the expected rise in forces at greater uncut chip thicknesses is mitigated by higher pre-heating temperatures through promotion of shear localisation, as indicated by the very high levels of serration displayed in Fig. 4. Thus, although higher pre-heating temperatures required lower amounts of cutting energy overall (Fig. 5c), they are favourably associated to much higher energy densities in PSZ as the microscale chip deformation increasingly localises into narrower shear regions responsible for higher serration degrees. In addition, this behaviour is further promoted by higher cutting speeds, especially in the higher temperature range of T_0 = 600 °C where combination of these effects leads to lowest energy consumption (Fig. 5c).

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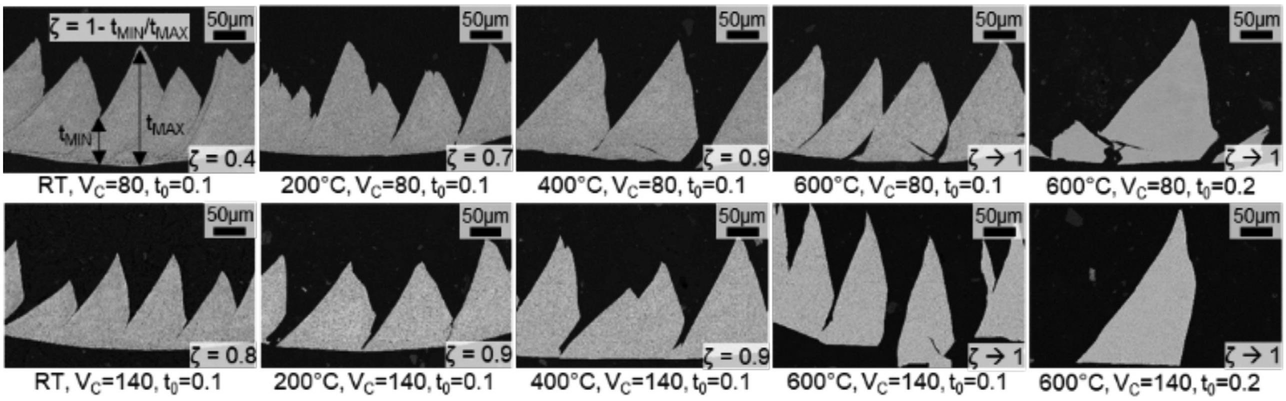

Fig. 4. Chip morphologies under different thermo-mechanical cutting conditions. Increasing temperatures (RT, 200 °C, 400 °C, and 600 °C) promote greater chip serration under fixed cutting parameters, with increasing chip serration degrees (ζ) both in the low and high speed ranges. Shear localisation is further promoted by higher cutting speeds and higher uncut chip thickness.

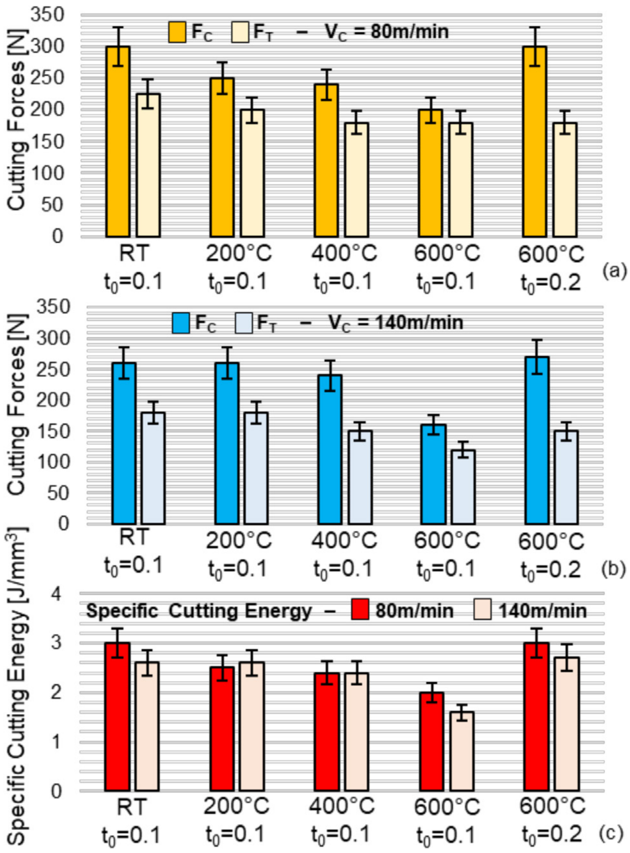

Fig. 5. Temperature-dependant cutting forces and energies. (a) Cutting forces in the low speed range. (b) Cutting forces in the high speed range. (c) Specific cutting energies at low and high speeds.

5. Microstructural surface reconfiguration and integrity

In terms of microstructural surface integrity, metallurgical analysis indicates that high speeds and high temperatures (T_0 = 600 °C) resulted in lower levels of machining-induced deformation, as plotted in Fig. 6. In fact, this outcome could already be predicted from the machinability analysis carried out in the previous section, which revealed how the higher cutting speeds and temperatures yielded the lowest cutting forces (and energy) due to softening effects in PSZ, with high-temperature strengthening conditions in TSZ. Specifically, higher temperatures produced lower levels of microstructural deformation both in the low and high speed range, while an increase in cutting depth produced an expected increase in material deformation. Nevertheless, it is interesting to notice how even under uncut chip thicknesses at high temperature (t_0 = 0.2), the resulting cutting forces, energies and surface deformations are still not exceeding the corresponding RT levels under a lower cutting depth (t_0 = 0.1), confirming the advantages of combining TSZ strengthening with PSZ softening effects. Higher cutting speeds also result in favourable effects on surface integrity, especially in the high-temperature range (as shown in Figs. 7, 8), where microstructural analysis suggests that the machining-induced surface deformation mechanism may be further influenced by rate-dependant effects. Specifically, remarkable deformation in the γ' precipitates is observed only within the subsurfaces machined at the higher speed of 140 m/min (Fig. 7b, d). Differently, surfaces machined at the lower speed of 80 m/min exhibited much less distortion of the γ' particles whilst deformation of the γ grains propagated towards greater subsurface depths (Fig. 7a, c).

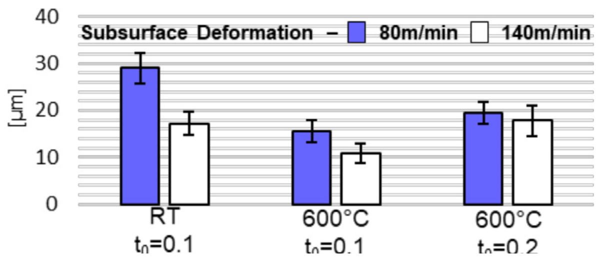

Fig. 6. Microstructural surface deformation for the selected thermal conditions, cutting speeds and cutting depths obtained from SEM inspection of the machined surfaces.

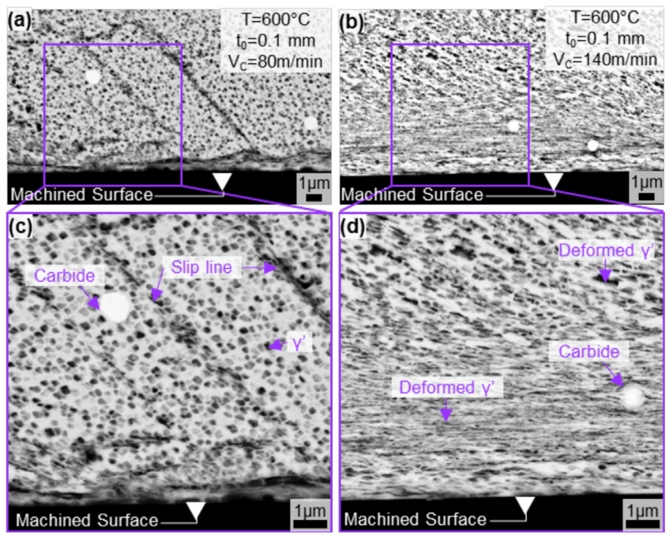

Fig. 7. High-temperature microstructural surface deformation (T_0 = 600 °C, f = 0.1) (a) Low cutting speed (80 m/min). (b) High cutting speed (140 m/min). (c) Detail of low-speed grain deformation (80 m/min) (d) Detail of high-speed deformation of γ' precipitates (140 m/min).

Additional insights on the role of temperatures and speeds on the machining-induced microstructural alteration is provided by EBSD crystallographic analysis. Specifically, surfaces machined under low-speed/low-temperature conditions (Fig. 8a, d) are characterised by more pronounced grain sweep and

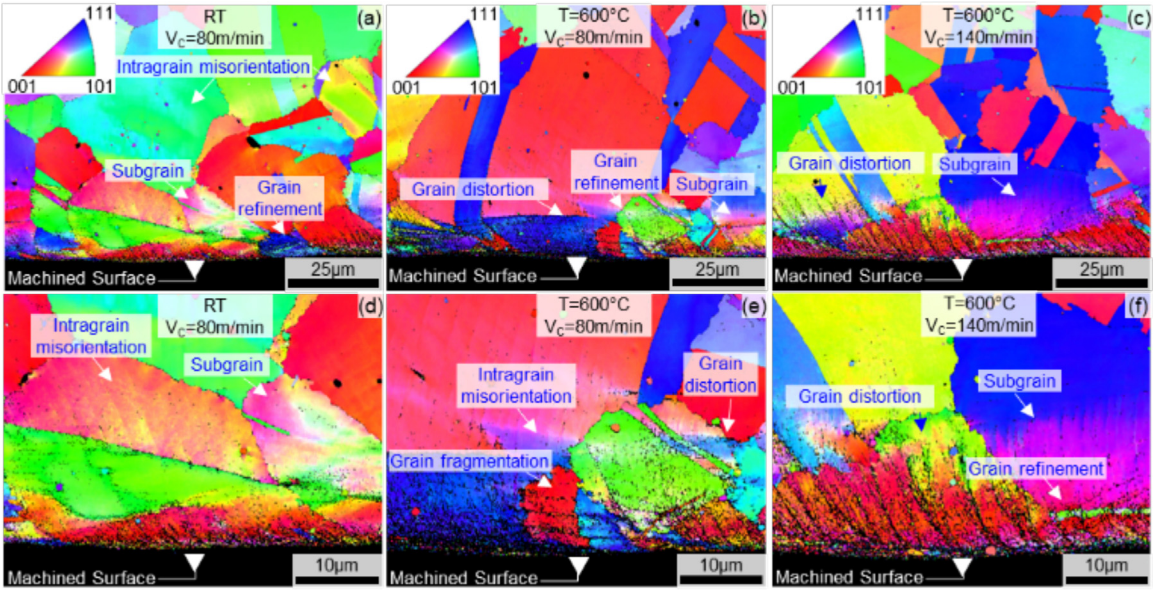

Fig. 8. Microstructural surface deformation observed through Electron Backscatter Diffraction (EBSD) analysis for selected thermo-mechanical conditions. (a) Low-speed & low-temperature (80 m/min, RT) (b) Low-speed high-temperature (80 m/min, 600 °C) (c) High-speed high-temperature (140 m/min, 600 °C), (d) Detail surface view at 80 m/min, RT; (e) Detail surface view at 80 m/min, 600 °C; (f) Detail surface view at 140 m/min, 600 °C;.

elongation, displaying traces of high intra-granular misorientation up to relatively high subsurface depths (> 50 µm in Fig. 8a). Contrary, cutting under the same parameters but at higher temperature (Fig. 8b, e) appears to promote grain fragmentation rather than elongation, which can be associated to the higher resistance to propagation of plastic deformation towards higher subsurface depths as a result of the high-temperature surface strengthening. Finally, a deformation mechanism involving significant grain fragmentation, refinement and intra-granular rotation is also observed under high speeds and high temperatures (Fig. 8c, f), with practically no traces of plasticity away from the main deformation layer. Thus, this further indicates that propagation of subsurface plastic deformation is decreased in the high-speed high-temperature range, which is attributed to the beneficial combination of lower cutting forces due to increased chip shear localisation, together with a favourable material response in TSZ under high-temperature strengthening conditions.

6. Conclusions

Advanced Ni-base superalloys can involve significant machining challenges due to their outstanding high-temperature performance. For the first time, this work conceptualised and investigated how, under controlled conditions, higher cutting speeds and temperatures can improve both machinability and surface integrity of Ni superalloys by promoting softening effects in the chip forming zones together with strengthening behaviour in the machined surface region. Furthermore, it is revealed how better surface integrity is not only a consequence of the material behaviour and thermal fields in TSZ, but it is deeply coupled to the other shear zones at the tool-workpiece interface. In fact, lower surface deformation levels are additionally favoured by the decrease in cutting forces resulting from a more localised chip formation mechanism. Thus, this further highlights how understanding of the interplay between physical processing conditions, shear localisation mechanism and material behaviour can lead to better control of microstructural integrity of advanced materials by exploiting their anomalous yielding behaviour at high temperatures. In a wider sense, these concepts could be further explored for the microstructural control of other manufacturing processes involving high-temperature material deformation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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