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# Substructure of deformation zones in austempered ductile iron finish-turning chips

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ABSTRACT

A series of dry finish-turning tests of a structural austempered ductile iron with PcBN cutting-inserts were run with a depth of cut of 200 μm, a feed-rate of 50 μm rev$^{-1}$ and a cutting length of ~100 m, and using machining speeds stretching from 50 to 800 m min$^{-1}$. Substructure developed within chips' deformation zones was studied by transmission electron microscopy. At machining speeds equal or beyond 150 m min$^{-1}$, shear-induced unlocking of incomplete austempering transformation and continuous-cooling austempering of residual and retained austenite would plausibly stand as phase transformations behind the overwhelming volume fraction of ferrite within the chips' deformation zones and related regions. Formation (and coalescence) of ferrite sub-grains within these zones, possibly concurrently with their parent shear-platelets, would be the result of rotational dynamic recrystallization. Substructure refinement in the deformation zones of chips formed under machining speeds equal or beyond 150 m min$^{-1}$ could heighten the diffusion rates of cutting-insert components therein.

## 1. Introduction

Chips embed most of the tribological, mechanical, thermal, and phase transformation history that prevailed during a machining operation. Such fact could justify why in recent years, chips' microstructural features were revisited by Ingle (1993), Subramanian et al. (1993) and Trent and Wright (2000) in an attempt to advance among other things, the understanding of the responses and interactions of cutting-tool and work-material upon machining.

Machining of most metallic materials usually involves high strain and excessive strain-rate plastic deformation within chips' primary deformation zones. On this matter, Ramalingam and Black (1973) suggested shear strain values in the range of 2–5 while von Turkovich (1967) and later Black (1979) reported shear strain-rate values in the span of $10^3$ to $10^7$.

The work-material response within chips' primary deformation zones is controlled among other things by the strain, strain-rate and microstructure therein. On this matter, standing on the work by Campbell and Ferguson (1970), Trent and Wright (2000) anticipated that the amounts of strain and strain-rate earlier mentioned would be appropriate to back drag controlled dislocation motion within these zones, in preference to thermally activated dislocation motion.

It emerges from the work by Meyers (1994) that twinning could be an extra-mechanism of plastic deformation in chips' primary deformation zones, even for higher stacking-fault energy (SFE) BCC and HCP metallic alloys, insofar as the latter materials twin copiously under high strain-rates. Stress, strain or twin-induced phase transformations may account for the work-material response to excessive strain and strain-rate plastic deformation within these zones.

Shear in chips' primary deformation zones was investigated from live observations of machining within a scanning electron microscope (SEM) by Black (1989). On this matter, this author reported that irrespective of metallic work-material and cutting parameters used, shear in chips' primary deformation zones is essentially composed of a discontinuous series of shear fronts formed upon activation, from the cutting-tool edges, of dislocations' waves travelling along these zones. He claimed that individual shear-fronts coalesce into narrow shear-bands, with the latter bands printing lamellar microstructure within continuous chips. He also claimed that shear-bands are usually 20–200 nm thick and chips' primary deformation zones (lamellae) usually 2–4 μm thick.

Likewise, the formation of transfer fragment, upon adhesive contact between two dissimilar materials in mutual relative motion, was investigated from live observations within SEM. On this matter, Kayaba and Kato (1979) reported that the contact asperities of the more ductile material of the pair deform into sequences of shear-bands.

From this token, it is implied that upon tool-chip seizure, chips' contact asperities deform into a series of shear-bands. In this regard, Trent and Wright, (2000) reported that the shear strain resulting from such a seizure is restricted to the flow (secondary deformation) zone, a

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tinny layer lying slightly above the tool-chip interface. They reported that strains of the order of 100 or greater and strain-rates of the order of $10^4\ s^{-1}$ are typical within chips' flow-zones.

However, Trent and Wright (2000) observed that a steady blending-in delineates the flow-zone from the chip bulk. Likewise, they noticed a shade of the gradation between the built-up edge (BUE) and the flow-zone.

Equally, Trent and Wright (2000) suggested that contrarily to the BUE, the chips' flow-zone is not a transient feature. It is a body of work-material trapped on the cutting-tool rake face. Such body maintains, to some extent, its integrity for the duration of a cutting operation. They also reported that the chips' flow-zone thickness depends considerably on the constitutive equation of work-material right at the tool-chip contact, varying from less than 12 μm for high machining speeds to more than 100 μm for low machining speeds. As the bottom of the chips' flow-zone remains anchored to the cutting-tool rake face, they prompted that the work-material therein is continuously subjected to strain to the extent that its initial microstructural features are drawn out so nearly parallel to the tool-chip interface or transform completely.

From the above, Trent and Wright (2000) claimed that the analysis of the chips' flow-zone with a transmission electron microscope (TEM) reveals the presence of 100–1000 nm equiaxed grains containing few dislocations, a result of concomitant recovery or recrystallization.

The response of work-material to the conditions within chips' deformation zones controls the chips' morphology development. In this connection, Subramanian et al. (2002) suggested that continuous chips form through homogeneous plastic deformation therein, under an equilibrium shear-angle controlled by the cutting parameters and the constitutive equation of work-material.

Shear-localized chips form through heterogeneous plastic shearing under conditions of shear-instability within either chips' deformation zones - following either a thermo-mechanical primary deformation-zone instability model for Hou and Komanduri (1997) or a secondary deformation-zone strain-rate hardening model for Trent and Wright (2000).

Hou and Komanduri (1997) claimed that these conditions of shear-instability are connected to poor thermal properties, high hardness or fewer slip systems of work-material. However, Subramanian et al. (2002) argued that such shear-instability conditions are fostered by the incidence, within either chips' deformation zones, of high strains and strain-rates.

Such strains and strain-rates trigger either a very short rise of high temperature, under adiabatic conditions, or an incompatibility of plastic deformation between the matrix of work-material and any inhomogeneity embedded within.

Thus, Subramanian et al. (2002) reconciled the two models of shear-localised chips earlier referred to, proposing a model based on the incidence of dynamic softening within either chips' deformation zones. These authors argued that shear-localised chips take over from continuous chips from a threshold machining-speed beyond which the shear-angle starts oscillating between a maximum initial value and a critical value situated above the equilibrium value.

Zhu and Subramanian (2003) claimed that such a critical value is reached at a threshold temperature-corrected strain-rate for dynamic recrystallization, an onset temperature for phase transformation, or a sill strain for fracture.

Referring to the findings by Zener and Hollomon (1944) on the strain-rate affected plastic deformation of steel, Subramanian et al. (2002) argued the following. At the threshold machining-speed earlier mentioned and beyond, the dynamic-softening decrements of shear flow-stress, within the adiabatic shear-lamellae of either chips' deformation zones, significantly overpower the coupled strain and strain-rate hardening increments of shear flow-stress.

Standing on the claims by Sullivan et al. (1978); Trent and Wright (2000) alternatively argued that at the threshold machining-speed earlier referred to and beyond, the strain-rate hardening within the chips' secondary flow-zone re-introduces gradually, at the tool-chip contact, the operation of a stick-slip action. Such action backs the oscillation of shear-angle which effects the formation of shear-localised chips.

Substructure within chips' deformation zones is critical in the tool-chip interactions. The same is true for the conditions prevailing to the development of such substructure. In this connection, the works by Ingle (1993) and Subramanian et al. (1993) gathered pieces of evidence that suggest that the substructure refinement in either chips' deformation zones, upon shear-localisation therein, would back a high-rate diffusion-wear of cutting tools.

Katuku et al. (2009) and Bhople et al. (2016) conducted comprehensive reviews of a substantial amount of works published in recent years and devoted to the machining of austempered ductile iron (ADI), using different types of coated and uncoated cutting-tool material under different cutting geometries and parameters. It emerges from these reviews that the substructure characterization of the related chips' deformation zones, as well as the simulation, improvement and optimization aspects related to such machining, are not addressed so far.

The latter aspects of the dry finish turning of structural ADI, as they could be inspired by the works of Subramanian and Zhu (2004) and Bejjani et al. (2016), should rely on various models which development is not addressed so far. The same is true for the design of optimum cutting-tool material and geometry specific for this particular turning.

As it could be instigated from the publication by Campbell et al. (2006), the efficiency and reliability of such models should rely on the coherent integration of the dry finish-turning process and the related chips' microstructure development and workpiece residual-stresses sub-models. The same would hold with the cutting-tool wear and workpiece surface-finish sub-models.

Although Katuku et al. (2009) reported on the effect of machining speed on chips' characteristics upon dry finish turning of ADI with PcBN cutting-inserts, they did not stress enough the substructure development in either chips' deformation zones.

The understanding of such development would be pivotal for the elaboration of the chips' microstructure development sub-model. The same would be true for the cutting-tool wear sub-model development. To the best of the author's awareness, the investigation of the substructure of deformation zones of chips formed upon dry finish turning of structural ADI did not receive much attention to date.

Accordingly, in an attempt to advance the understanding of chips' morphology development to an extent which could ultimately support the development of refined physics-based sub-models of chips' microstructure development and cutting-tool wear, the current work focusses on such investigation. The scope of this investigation is limited to the dry finish turning of a structural ADI using PcBN cutting-inserts and the use of TEM.

## 2. Experimental procedure

A structural ADI work-material of chemical composition reported in Table 1 and conforming to the ASTM Grade 2 specification, was used for a series of dry finish-turning tests. This composition yielded a eutectic saturation of 1.021. This work-material had a microstructure made of a matrix of ausferrite and graphite nodules dispersed within (Fig. 1).

The latter matrix was formed of sheaves of ferrite needles and islands of residual austenite. Stringers of retained-austenite settled in

**Table 1**
Chemical composition of the structural ADI work material, wt%.

| C | Si | Mn | Cu | Ni | Mg | S | P | Fe | $C_{eq}$[a] |
|---|---|---|---|---|---|---|---|---|---|
| 3.51 | 2.61 | 0.19 | 0.62 | 0.002 | 0.044 | 0.009 | 0.016 | Balance | 4.385 |

[a] $C_{eq}$ = carbon equivalent = C + (Si + P)/3.