Investigating the machining performance of damped and undamped boring bars

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Abstract

In order to improve both the geometric and dimensional errors resulting from the drilling process, boring is often utilised by which a hole's inaccuracies are in the main, corrected. The boring bar due to its extensive and necessary overhang, often induces vibration on the hole being bored this means that the machined surface texture and roundness harmonic behaviour is compromised. Complex boring bars are available to minimise these errors in the bored hole; being of either an "active" or "dynamic" type, coupled to appropriate tool point control systems although such "damped" boring bars are expensive to purchase.

This paper discusses an alternative machining strategy being based upon the so called "anti-vibration" and "compound" boring bars for smaller length-to-diameter bored hole ratios. A series of machining trials developed from a "Taguchi designed Experimental Array" were undertaken on a limited range of metallurgical compositions of newly developed "free machining steels" in order to determine if low cost boring bars of differing designs would offer satisfactory machining performance. These new steel grades are said to offer; superior cutting performance, a reduction in cutting forces and improved hole dimensional roundness characteristics, these claims would seem to be substantiated in this work.

The machining performance observations are duly reported, with the suggestion that the low technology cost solution is a viable way of achieving high quality hole accuracies.
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Introduction

Unlike a drilling, or reaming operation, where the hole's quality its roundness and straightness characteristics are influenced by the cutting geometry of respective lip angles and lengths when drilling, or the subsequent operation where a reamer follows the previous drilled path, boring generates "almost" a true hole in a similar fashion to a turned diameter [1, et al]. The usual practice of "sizing the hole" whilst simultaneously improving the surface finish and correcting any minor hole deviations is undertaken by boring.

A conventional boring bar can be thought of as a "cantilevered beam" one end held in the machine tool's pocket, or toolpost of distributed mass, with the mass acting upon the "free end" [2], as depicted in FIG 1 showing how length-to-diameter ratios influence rigidity [3 et al]. The natural frequency of transverse vibration in these cantilever bars in the fundamental mode is known [3] to be given by the following equation:

\[ f_0 = \frac{1}{2} \pi \sqrt{\frac{3EI}{L^3}} \left( M_t + 0.23M_b \right) \]

Where \( f_0 \) is the normal force acting on the "free end" of the cantilever (N), \( M_b \) is the Modulus of Elasticity of the bar material, \( I \) equates to the cross sectional moment of inertia, i.e. \( EI \), this being the flexural stiffness (Nm²), \( M_t \) is the mass (kg), and \( L \) the length of cantilever (mm).

Such cantilever boring tools are widely used and it is well known [3, 4 et al] that when machining with a "standard" boring bar whose length-to-diameter ratio does not exceed 5, then relatively stable cutting conditions with controllable vibrational influences can be tolerated. However if larger L/D ratios are utilised, then a potentially disastrous vibrational tendency will occur, leading to poor surface finish and roundness characteristics coupled with limited tool life [5-7]. With any solid/ conventional boring bar instability and chatter-free cutting action there has been attributed a number of factors [8, et al], including:

- boring bar and insert design,
- bar material specification,
- insert orientation,
- natural frequency of the bar,
- mass effect of the bar,
- boring bar overhang,
- vibrational influence along cantilevered bar,
- cutting data selected,
- coolant effects if utilised.
When boring bars have longer than a 5 L/D ratio, it has been observed [9] that the tool tip's vibrationary motion follows an elliptical path in the plane normal to the longitudinal axis of the bar as illustrated in FIG 2. The ratio of the amplitude of vibration along the major to minor axes varies with cutting conditions, moreover, the inclination of these axes to the "radial line" of the tool also varies. Of significance, is the fact that the build-up of chatter will begin almost immediately, even before one revolution has occurred. This build up continues almost evenly until some limiting amplitude occurs, which suggests that the well known "Orthogonal mode coupling" is present [10, et al], further, with the phase difference between the vibrations causing an elliptical tool tip path, the vibrational energy is fed into the tool/ workpiece system promoting self-excitation [9].
Boring bar stability

The dynamic stability of the boring bar is of prime importance [11, et al] with the onset of self-excited chatter, this being governed by the "multiple regenerative effect" which is a function of the so called "space phase" [8]. This "space phase condition, ...is the phase of vibration around the respective turns of work, it fluctuates between 90 and 180 degrees" [8] and is equal to the phase between the inner and outer modulation. Some success has been reported by Takemura, et al [12] and Inamura and Sata [13]. These researchers indicated that by modifying the rotational speed of the workpiece, this disturbs
the "space phase" and consequently the "time phase", leading to a reduction in self-excited chatter.

Kasahara [8] has shown that by modifying the peripheral speed of the workpiece this technique is only partially successful in alleviating chatter and it is necessary to use either "damped" boring bars such as the "Lanchester" type with dynamic vibration absorbers (i.e. DVA's Rivin [3, et al]) to really suppress vibrational influences in the boring process.

Progress on the development of DVA techniques continues, but the real promise in vibrational suppression for boring bars must lie with "active" damper boring bar developments [6], as depicted in FIG 3. These "active" boring bars must lie with "active" damper boring bars invariably involve the supply of energy to the overhung bar; via an external source, this technique was initially developed by Comstock [14] whereby he controlled the cutting edge's position by monitoring the feedback of the relative displacement of tool's edge to the workpiece. In later work [15], chatter suppression was analysed for the boring bar using "feed forward" control of the cutting force, furthermore, the cutting edge was positioned in response to this force, with such "active" control systems being generally termed; "cutting edge positional control systems". Typical of this approach to "active" control is that of Matsuara, et al [6] briefly mentioned earlier, where they damped the forces in response to the vibrational velocity of the cutting edge which they termed as a "vibration velocity control system" as illustrated in FIG 2. In this technique of boring bar suppression a series of piezo-electric elements were used as "active dampers". Such as damper responds to the chatter vibration (i.e. high energy components), moreover, the damping force achieves optimal phase difference since the phases between damping and vibrational forces are controllable. This typical "active" boring bar of the genre (FIG3) achieves directional damping characteristics via its dampers controlling two "degrees of freedom" via the regenerative feedback loop which diminishes oscillatory motion (i.e. harmonics) by careful control of energy losses; as suggested elsewhere [16, et al].

**Experimental conditions**

In order to establish the machining behaviour of a series of damped and undamped boring bars, a machine tool was selected in the Advanced Manufacturing Technology Centre at the Southampton Institute that had a robust one-piece cast iron structure that would be little influenced by any dynamic vibrational content from the boring process. A slant bed turning centre was utilised; Cincinnati Milacron 200/15 model with an Acramatic 850TC CNC controller, having a variable speed range up to 4,000 rpm with a motor power rating of 15.75 kW.

Three boring bars were utilised in this work, all having a ø 15 mm shank with location flat- being 125 mm long with a 93° entering angle and 7°
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clearance for the 8 mm indexable inserts of left-hand orientation to suit the top indexable turret. These boring bars were the type; 15KSDUCL8, being of:

- Solid cemented carbon designated by the code; SC
- Composite carbon (i.e. medium carbon steel shank with a "flash butt welded" tool head of cemented carbon), designated by the code; CC,
- Cemented carbon "damping rod" situated within the medium carbon steel boring bar body designated by the code; CD.

All boring bar cutting inserts were; DCMG080304TL types having a 0.4 mm nose radius. Insert grades of the grade P20 with a TiN coating and T-land edge condition.

Three workpiece materials were utilised in these machining trials and were of a "free-cutting" low carbon steel type, the samples having been "turned slugs" of ø 40 mm, which were faced-off to 25 mm long and prior to the boring operation commencing, were U-drilled to ø 20 mm in situ. The workpiece grades were:

- Commercial steel 0.07% C "leaded" obtained from a stockist and were designated; CS.
- Evako steel (Finland) 0.07%C having a calcium (Ca) treatment and were designated; ES.
- British Steel (XLCUT Pb) having 0.07%, 0.3% Pb, 1% Mn, plus other trace elements and were designated; BS.

Each boring bar type and workpiece material grade used the following cutting data:

- 0.2 mm rev⁻¹ @500 rev min⁻¹ termed; high feed/high speed,
- 0.2 mm rev⁻¹ @250 rev min⁻¹ termed; high feed/low speed,
- 0.1 mm rev⁻¹ @500 rev min⁻¹ termed; low feed/high speed,
- 0.1 mm rev⁻¹ @250 rev min⁻¹ termed; low feed/low speed.

During machining, cutting force analysis was undertaken using a Kistler 3-component platform dynamometer (model 9257B) with "matching " charge amplifiers, data logging, via a software program known as DADISP. After machining the bored components were taken to Southampton Institute's Metrology Laboratory (i.e. temperature-controlled) where the bores surface texture and roundness were assessed utilising: Talysurf 6 with Data General computer used in the "Skidless mode" "condition with a 0.8 mm standard cut-
off; Talyrond 200 equipped with straightness column; establishing Ra (surface texture) and least squares circle (roundness), respectively.

![Diagram of boring bar design to suppress vibrational influences](image)

**Nomencature:**
- $C$: equivalent damping coefficient
- $D$: diameter of solid boring bar
- $\Theta$: principal axis of bending
- $H$: width of cross-section of boring bar
- $k$: static cutting stiffness
- $m$: equivalent mass
- $\phi$: angle between resultant cutting force & Y-axis
- $\Theta$: principal mode direction
- $X$: reference axis
- $Y$: reference axis

**FIG 3** "Active" boring bar design to suppress vibrational influences during the boring operation. [After, Matsubara, et al 1987]
The boring cutting forces are depicted in FIG 4, which indicate proportional increases in the force components of, radial, axial and tangential forces in a rising trend for all the machined workpiece materials and boring bar types tested. This is not unexpected, as the insert inclination and its plan approach angles produce an oblique cutting action typically denoted by 3 cutting forces [17, et al]. However if the tangential force being the largest and most indicative force component is used to explain the differences in the effect of machining with boring bar types, workpiece materials and differing feeds and speeds, then a series of trends can be established. Interestingly, the boring bar that introduced the lowest forces was the solid tungsten carbide version, which is to be expected as its density and hence rigidity mitigates any fluctuations from the dynamic force component when cutting. Conversely, the worst boring bar for increased cutting forces was the flash- butt welded composite bar where the "spring effect" of the medium carbon steel body and its associated overhang nullified the addition of the carbide boring bar head. As a compromise, the carbide damping rod situated within the boring bar's medium carbon steel shank, both stiffened and damped the dynamic force component reasonably well. In all cases, the lowest forces regardless of boring bar types were generated by the British Steel products with their free-machining additives proving to be superior to the calcium-treated Ovako steel grade, whilst the "commercially" available free-machining steel from a "stockist" in general, introduced the highest boring forces. The introduction of either increased, or reduced feeds and speeds influenced the mean (tangential) cutting force across all bar types and workpiece materials in the following manner:

- high feed, high speed, gave a mean cutting force of 212N,
- high feed, low speed, produced a mean cutting force of 227N,
- low feed, high speed, gave a mean cutting force of 117N,
- low feed, low speed, produced a mean cutting force of 133N.

This illustrated that the highest mean forces generated were by the high feed, low speed combination and the lowest mean forces were produced by the combined effects of; low feed, high speed which was anticipated [16, et al].

The affect of cutting data on feeds and speeds and other "fixed" processing parameters, such as; tool geometry and workpiece material, influenced machined surface texture as depicted in FIG 5. As expected, the high feed variants (i.e. FIG 5 a and b) produced considerably greater residual machined roughness, than the lower feed varieties, i.e. FIG 5 (c and d).
FIG 4 The boring cutting forces for the three boring bars and steel grades at different feeds and speeds. Where: SC = Solid tungsten carbide, CC = composite carbide CD = carbide damping rod, ES = Evako Steel, BS = British Steel and CS = Commercial Steel.
FIG 5 Surface texture results from the boring of free-cutting steels with different cutting data boring bars.
Where; Rsk = skewness, Rku = kurtosis
The reason for this is because of the retained cusp effect of the higher feedrate leaving behind the partial tool nose geometry effect, after the passage of the tool along the bore [18]. Thus the finer the feedrate, the smoother the bore's surface. The boring bar type for set feedrates also had a marginal influence on the surface texture. Surprisingly, the worst surface was produced by the solid carbide boring and the best using the carbide damping rod bar, whereas the influence of these free-machining steel grades showed no significant improvement in bored surface texture which was anticipated across the feed and speed range assessed in this work. Although at set combinations of feed and speed, a marked improvement via specific free-machining grades, could be established particularly with the Evako steel (i.e. calcium-treated) which proved to offer the better machined surface and the "commercial" steel was significantly worse for bored surface texture values.

The influence of the hybrid surface texture descriptors, namely; skewness and kurtosis can explain the condition of the machined surface [19]. If a highly negative skewness occurs in combination with a value of kurtosis greater than 3, this would denote the surface topography is of a "bearing" type and is akin to a "honned" surface. Conversely, if the surface descriptors indicate a positive skewness and lower kurtosis, this topography can be thought of as a "locking" surface, typical a turned machined condition [17, 20 et al]. Referring to FIG 5, the scatter of results would seem to indicate that no specific surface topography resulted from the boring bar trials, although a general trend seemed to show a "bearing" machined surface condition occurred, namely most of the plotted values were of a negative skewness. Greatest dispersion of these "beta functions" was produced using the "commercial steel" grade, whereas both the Evako and British steel grades were approximately the same in their spread and magnitudes which is to be expected [21].

Roundness of the bored holes is shown in FIG 6 for a range of cutting data and boring tools, across the free-machining steels under investigation. Regardless of the pre-selected cutting data, the British Steel components showed the least "harmonic" out of roundness [22], which was more-or-less the case for specific feed and speed combinations, as indicated by the "Least squares circle (LSC) values [23]. This was not the case for the "commercial" steel material, indicating considerably worse in the main, LSC values under most conditions of cutting data and boring bar combinations. The boring bar offering the best machined roundness characteristics was the composite carbide bar, which proved to be marginally superior to the carbide damping rod type. At specific combinations of feed and speed, the best out-of-roundness conditions occurred regardless of boring bar type employed were found utilising the high feed high speed relationship. This was not anticipated, but may be due to the fact that using a higher feed and speed range, this promoted greater cutting forces and caused the individual boring bar types to be subject to a greater compressive load and hence consistent elastic distortion
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which in turn, minimised the boring bars tool point motion leading to less harmonic out-of-roundness.

**FIG 6** Machined roundness of the bored free-cutting steel components, using different boring bars and feeds and speeds.
Concluding remarks

In order to establish in an unbiased and objective manner the relative machining performance characteristics for the combinations of; material grades together with feed and speed groupings, Value Analysis (VA) was employed [24, et al]. This VA technique resulted in the following relationships:

- boring bar types in general produced the best overall performance using the carbide damping rod (i.e. denoted by CD) for force surface finish and roundness, whereas the worst performance occurred utilising the solid carbide tooling (i.e. SC),

- free-machining steel grades particularly the British Steel product gave the best overall machining performance, with the "commercial" grade the worst,

- feed and speed combinations showed that the cutting data giving the best performance was not surprisingly the; low feed and high speed grouping and the worst; high feed and low speed,

- force analysis indicated that the lowest forces occurred using the solid carbide (i.e. SC) bar, with the highest forces resulting from the composite carbide (i.e. CC "flash-butt" welded) type,

- the best surface finish within the bores was produced using the carbide damping rod bar (CD) and the worst, with the solid carbide type (SC),

- the best roundness occurred with the composite carbide boring bar (CC) and worst, using the solid carbide version (SC),

- the best combination of feeds and speeds for improved surface finish occurred using; low feed, high speed.

Therefore, the boring bar with the carbide damping rod (i.e. CD) having the least quantity of tungsten carbide present, proved to offer overall superior cutting performance and illustrates it as a viable and economic alternative to the more costly boring bar techniques.

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References