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BRAKE TORQUE VARIATION DUE TO CALIPER MACHINING QUALITY

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ABSTRACT: One of the major concerns of brake NVH is Brake judder coming from Brake Torque Variation (BTV). This is a vibration that occurs during braking and can be felt by the driver through the steering, brake pedal or vehicle body. This can create a feeling of discomfort for the vehicle occupants.

One of the main contributors to BTV is Disc Thickness Variation (DTV), and this relationship is well known in the industry. Current literature focus has mainly been on the sensitivity due to caliper design and pad characteristics. However, this paper introduces a new sensitivity factor, attributed to piston bore machining quality. Specifically, this paper shows BTV sensitivity due to built-up edge; an accumulation of material onto the tool tip which is separated from the chip, and creates surface anomalies which cannot always be captured by normal surface roughness measurements. This paper highlights the importance to ensure good machining quality as well as inspection methods to confirm the presence of built-up edge in the piston bore.

KEY WORDS: Disc brake, Judder, Machining, Built-up edge

1. Introduction

1.1. Background

Brake Judder is one of the main concerns of brake performance in passenger vehicles and has been the focus of many studies. It is a forced vibration occurring during braking which can be felt by the driver through the steering wheel, brake pedal, seat or vehicle body. The frequency is typically lower than 100Hz, but can be up to 500Hz, and is directly proportional to the wheel speed [1].

The cause of judder is a variation of the brake torque (Brake Torque Variation, or BTV), which is also linked with a variation of brake pressure. BTV is the difference of max and min torque values during a brake application. This is demonstrated in Figure 1 where the braking torque is seen to oscillate around the nominal brake torque value.

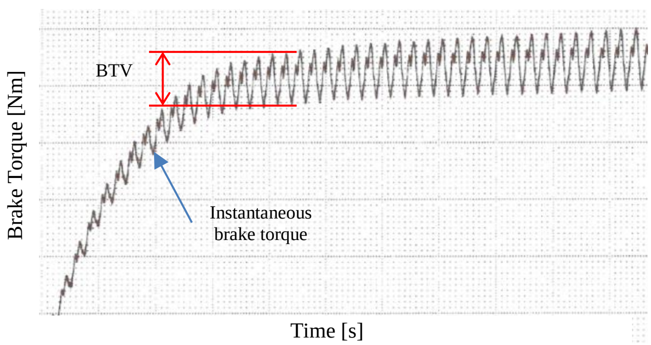

Figure 1: Brake torque during a brake application

The most important influences on torque and pressure variations while braking are disc thickness variation (DTV), friction coefficient variation between the pad and the disc surface, and caliper stiffness [2]. Many studies have focused on the factors that can cause a variation in these parameters, as well as the thermal effects and geometrical irregularities [2] [3] [4] [5] [6],

This investigation intends to identify if any other parameters can influence BTV sensitivity.

1.2. Phenomenon Description

During the development of a newly designed front disc brake caliper, an excessive BTV value was recorded. As the caliper design is a relatively common type, a floating caliper in cast-iron, there is a lot of experience and published information to consult. Unfortunately, the current knowledge could not explain the sensitivity seen in the affected brake caliper. Therefore, this paper focused on identifying the critical parameter of the design and manufacturing process that led to this excessive result.

2. BTV performance results

The BTV value of a prototype part, Part Ⓐ, was double the first prototype result, as well as being double the theoretical calculation, illustrated in Figure 2. To calculate the theoretical BTV; caliper, pad and disc characteristics are considered. The design of the caliper and disc was not modified between the first prototype and Part Ⓐ, therefore the calculation and expectation remained the same as at the first prototype phase.

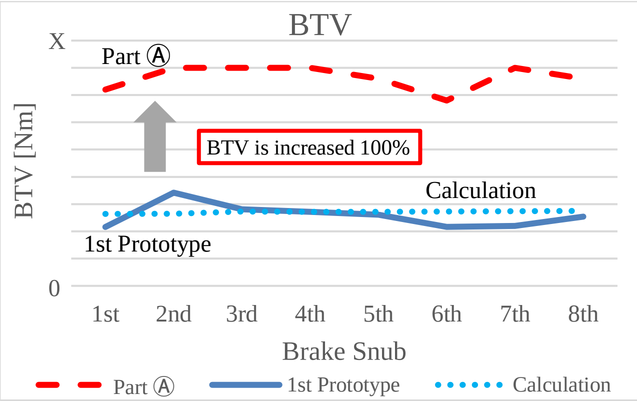

Figure 2: Brake torque variation results

The method used to measure the above BTV consists of eight consecutive brake snubs with limited cooling between each snub. This does not allow the brake to return to the initial brake temperature, hence the variation of BTV at each brake snub.

3. BTV sensitivity investigation

3.1. Component investigation

Taking Part Ⓐ, the fundamental items that influence BTV were investigated to confirm if it was within drawing specifications, as well as to confirm correlation with the theoretical calculation. The caliper stiffness was checked by scanning the components and measuring its deformation under pressure; no difference was found when comparing to the first prototype parts and expected design values. The disc thickness variation (DTV) had the same value as the first prototype parts. Examination of the μ level, Figure 3, showed the same values for Part Ⓐ and the first prototype parts.

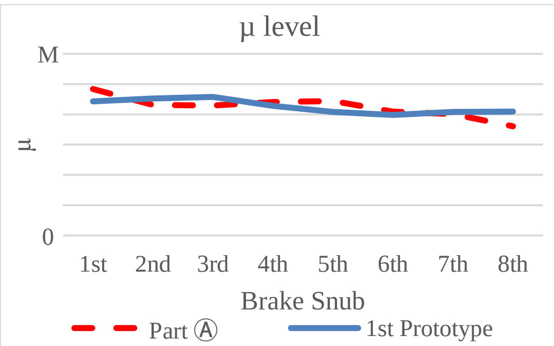

Figure 3: μ level – First prototype vs Part Ⓐ comparison

Analysis of the sub-components showed that the piston had been in contact with the caliper housing piston bore. The marking on the piston is visible in Figure 4 , and enlarged in Figure 5. Equivalent markings were also found on the bore of the caliper housing. This phenomenon can be found in floating type brake calipers and until now has not been highlighted as a concern. However, for this investigation it is worth noting.

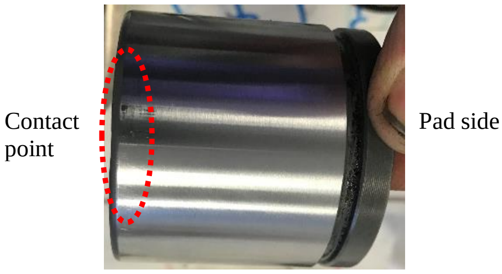

Figure 4: Piston with marking (Part Ⓐ)

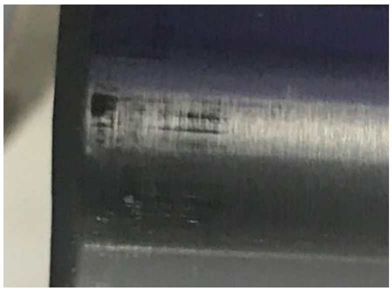

Figure 5: Marking on piston (enlarged)

Further analysis of the caliper housing piston bore shows machining lines in the bore which can be seen in Figure 6. These machining lines were visible on the actual tested parts, as well as on new, unused parts. However, they were not visible on the first prototype part tested in Figure 2. This gave a good hint that the surface machining condition could play a role in influencing the BTV. Hence this became the next investigation point.

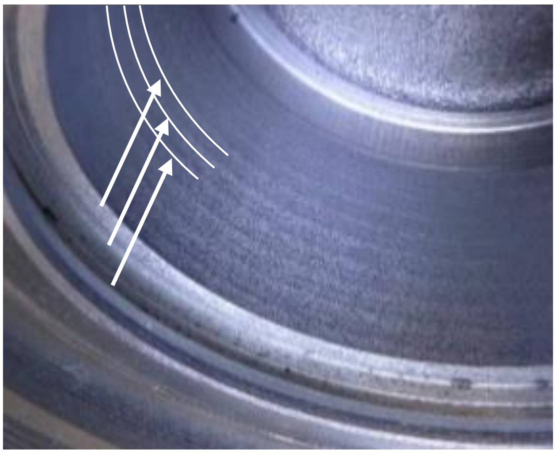

Figure 6: Caliper housing piston bore machining lines (Part Ⓐ)

3.2. Caliper housing piston bore surface

3.2.1. Quality control parameters

The typical parameters used for controlling surface roughness, such as Ra, Rz, and Rp, were checked. The process was confirmed to be within its roughness limits for all criteria. A study of the influence these parameters had on BTV was performed. In general, lower roughness values had a slightly lower BTV value.

On further analysis, the visible machining lines in the caliper housing piston bore, from Figure 6, could be identified as peaks on the surface roughness profile, and are highlighted in Figure 7. The surface roughness profile of a caliper housing without visible machining lines is shown in Figure 8, Part Ⓑ, and does not have the corresponding peaks. These peaks seemed to correspond with the roughness parameter Rpk; which is the mean height of the peaks protruding from the roughness profile.

At this point it is important to note that both caliper housings were produced by the same process: machined from the same material, on the same machining equipment, using the same tooling.

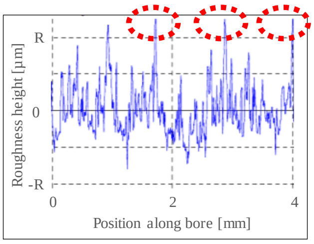

Figure 7: Surface profile of Part Ⓐ (visible machining lines)

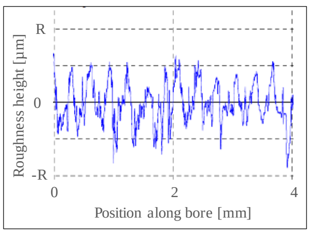

Figure 8: Surface profile of Part Ⓑ (without visible machining lines)

Using Part Ⓑ, with a lower a Rpk value, a BTV reduction of almost 20% was achieved. However, this does not recover to the calculated BTV value. The cause of the remaining 80% was still not identified

3.2.2. Cross Sectional Analysis

In parallel to the above investigation, the surface condition of the piston bore of Part Ⓐ was analysed in more detail. The piston bore was cut open and the investigation areas are illustrated in Figure 9.

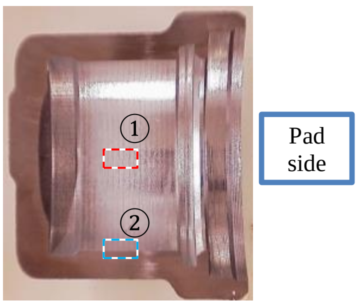

Figure 9: Caliper housing piston bore cross section

The results are shown in the following figures. Figure 10 shows a 2D scan of the surface condition when viewed perpendicularly to the surface. The light-coloured area is indicative of shear occurring during machining. The dark area indicates that the material was torn off which results in a poor surface finish. Ideally, the entire surface should have the light colour, as shear is the preferred mechanism for this type of machining.

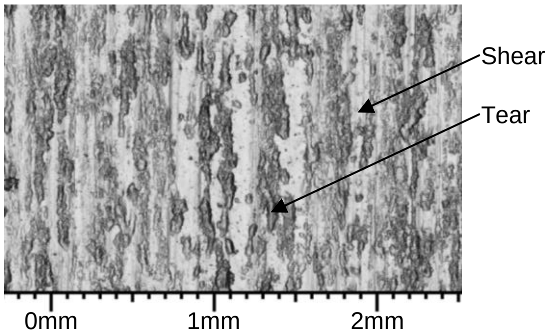

Figure 10: Area ①: 2D analysis of Part Ⓐ surface

The irregularities of the surface can also be seen in the 3D scan presented in Figure 11 and Figure 12. This gives a more detailed understanding of the surface condition than the one-dimensional roughness profile in Figure 7.

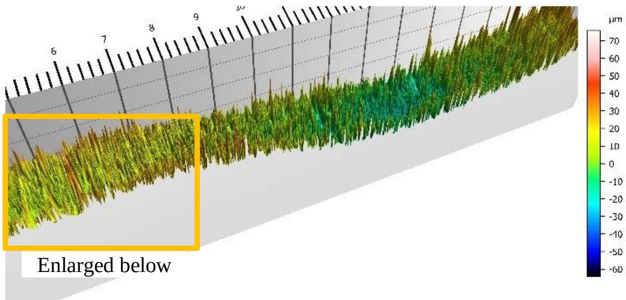

Figure 11: Area ①: 3D surface analysis of Part Ⓐ

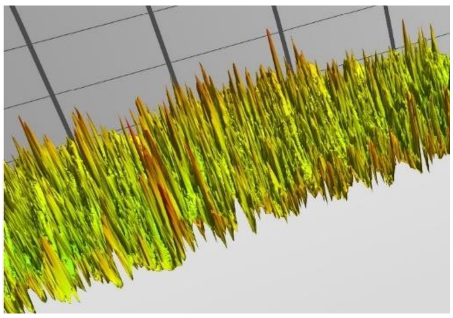

Figure 12: Area ①: 3D surface analysis of Part Ⓐ - Enlarged

The cross-sectional analysis in Figure 13 gives a clearer view of the concern. Here it is possible to see small “spikes” about 20µm long. These are deposits which are the result of a machining phenomenon known as “built-up edge” (BUE). It is worth noting that these spikes have depth as well, but is not visible in the image.

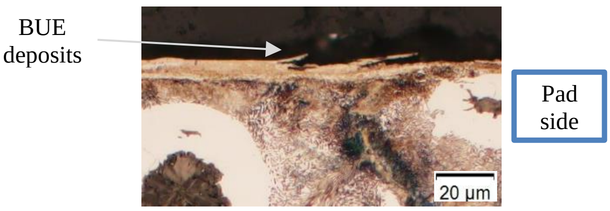

Figure 13: Area ②: Cross-section analysis of Part Ⓐ caliper housing piston bore

BUE is an undesirable feature as it reduces machining accuracy, quality of the machined surface and damage to the cutting edge [7]. Therefore, the focus was to understand this phenomenon and attempt to eliminate it.

3.2.3. Generation of built-up edge (BUE)

At this point, it is useful to know how BUE deposits form on the surface of the caliper housing piston bore. An illustration of BUE formation is shown in Figure 14 [8]. Some material, from the material being cut, accumulates on the cutting edge of the tool. This accumulated material work-hardens and becomes part of the tool itself. This then forms part of the cutting edge and, as it builds up, it cuts deeper into the material creating surface anomalies. At a certain point, the build-up detaches from the tool tip and deposits into the machined surface. This deposit is shown in Figure 14 and is the same phenomenon as found on the piston bore in Figure 13. These BUE deposits, or spikes, were found to play a significant role in the sensitivity of BTV which can be seen in the following section.

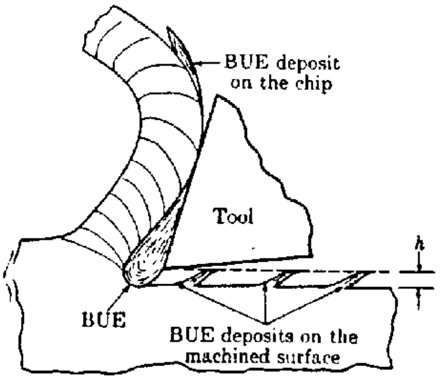

Figure 14: Generation of built-up edge [8]

BUE is well known within the machining industry, as well as the key parameters that influence its creation [8] [7]:

- Rotation Speed
- Feed Rate
- Cutting Temperature
- Tool rake angle
- Tool material

Tuning of these parameters could eliminate the BUE deposits in the caliper housing piston bore of this study.

4. BTV influence due to built-up edge deposits

The machining process for this caliper housing was tuned to eliminate BUE, considering the parameters mentioned in the previous section. This had a positive effect on BTV performance. The following will explain the theoretical mechanism and the final results.

4.1. Theoretical influence / mechanism

To understand the mechanism of how built-up edge (BUE) deposits affect BTV, it is necessary to visualise how the caliper behaves during a brake application:

Referring to Figure 15, when pressure is applied, the housing "opens" slightly. The piston will then push flat against the pad. This combined opening and piston movement, reduces the internal clearance between the piston and the caliper housing piston bore, which allows the piston to contact the caliper housing piston bore. This can be exacerbated by taper wear of the pad.

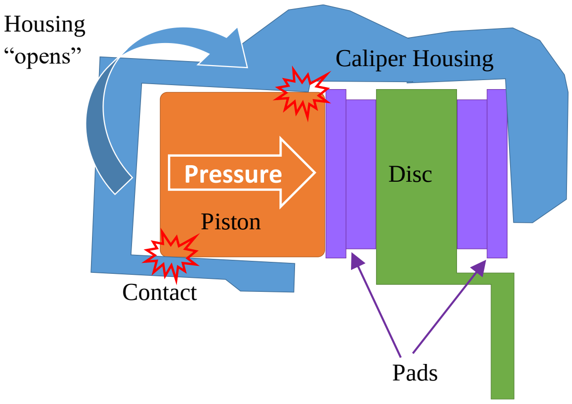

Figure 15: Piston and caliper movement

The contact is most critical at the back of the piston; highlighted in Figure 15. At the contact position, the BUE deposits are orientated such that they prevent the piston from smoothly sliding back into the piston bore, as illustrated in Figure 16. Since the piston cannot slide smoothly, it has the effect of increasing the caliper stiffness which affects BTV.

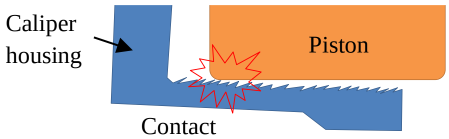

Figure 16: Piston touching BUE deposits on the caliper housing piston bore

4.2. Caliper housing piston bore surface (improved process)

The surface condition of a part, Part Ⓒ, from the improved process was analysed using the same methods as in Figure 9. Figure 17 shows that the caliper housing piston bore has a more consistently machined surface, and is created mostly from the shearing action of the cutting tool. Comparing to Figure 10, this is a significant improvement.

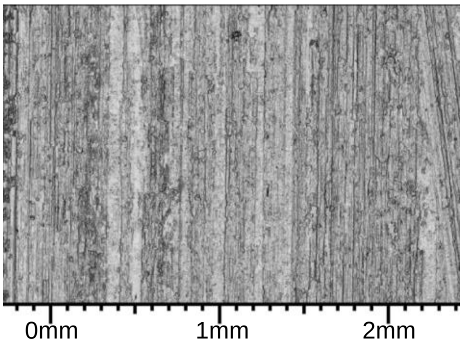

Figure 17: Area ①: 2D surface analysis of Part Ⓒ - without BUE deposits

The improvement is again visible in Figure 18 and Figure 19. When compared to Figure 12, the surface condition is much more even.

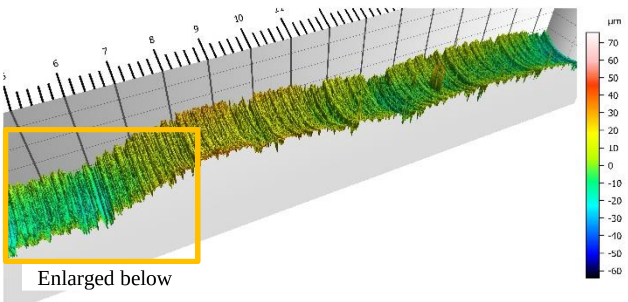

Figure 18: Area ①: 3D surface analysis of Part Ⓒ - without BUE deposits

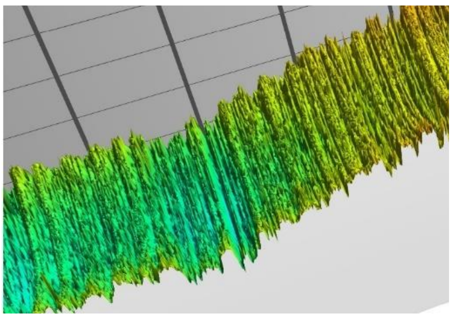

Figure 19: Area ①: 3D surface analysis of Part Ⓒ - without BUE deposits - Enlarged

The final confirmation is on the cross-section in Figure 20. There are no BUE deposits like those seen in Figure 13, thus confirming the process tuning was successful.

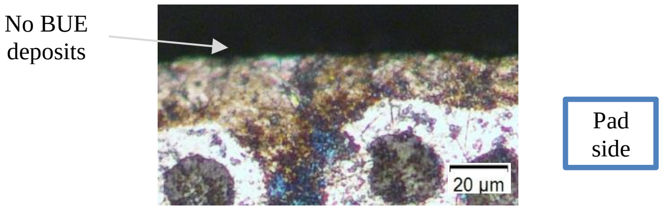

Figure 20: Area ②: Cross-section analysis of Part Ⓒ (without BUE deposits)

4.3. BTV confirmation

The theory was confirmed by measuring the BTV of the above parts, Part Ⓒ. The results in Figure 21 show that the BTV has returned to be in line with the first prototype result and the theoretical calculation.

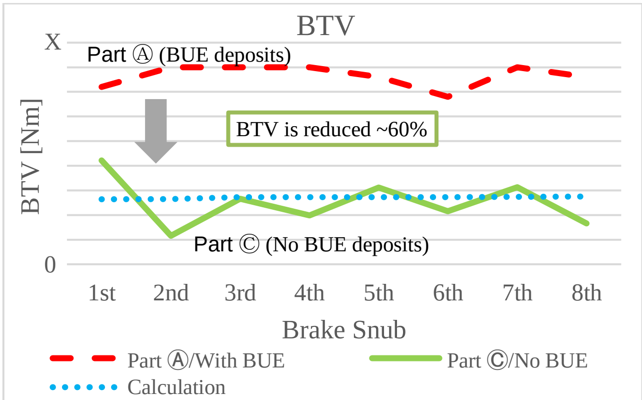

Figure 21: BTV reduction (BUE vs No BUE)

The roughness characteristics of these parts were compared to previous data, Table 1. The roughness values of Part Ⓒ are higher than Part Ⓑ. Therefore, it can be concluded that the roughness is not the main contributor to BTV sensitivity. The 20% improvement seen with Part Ⓑ (over Part Ⓐ) could be due to roughness improvement or a possible reduction of BUE (BUE was not controlled on Part Ⓑ). Controlling roughness by surface profile measurements is not robust enough to confirm BUE presence. Additional surface analysis is necessary.

Table 1: Roughness confirmation

	Part Ⓐ	**Part Ⓑ**	**Part Ⓒ**
BTV	= Calculation + **100%**	= Calculation + **80%**	**= Calculation**
Machining process	Standard	Standard	**Improved**
BUE deposits	Yes	Yes	**No**
Visible lines	Yes	No	No
Ra	3.08µm	2.29µm	2.61µm
Rz	18.72µm	14.14µm	18.38µm
Rp	9.99µm	4.73µm	7.76µm
Rpk	5.35µm	1.70µm	3.42µm

Considering the roughness values, BUE deposits and final BTV values, it can be concluded that the main contributor for the BTV sensitivity was the BUE deposits. By eliminating these, the performance returned to the original expectation.

5. Conclusion

After completing this study, a new and interesting influencing parameter was found for a fundamental brake performance concern. Although this study concentrated on one brake caliper design, the theory should hold true for other designs, with perhaps a different sensitivity.

The main points that can be concluded:

- The presence of built-up edge deposits in the caliper housing piston bore has been shown to double the BTV value for this caliper design. This increased sensitivity is created because the piston gets blocked on the sharp edges created by the built-up edge deposits. When the piston is blocked, it cannot move back into the caliper housing freely, thus increasing the caliper stiffness.
- The identification of built-up edge deposits cannot be done using surface roughness measurements only. Ra, Rz, Rp, and Rpk are not reliable indicators of its existence. It is necessary to analyse the surface under magnification as well as taking a cross section of the piston bore surface. In this way, the surface machining quality can be visually confirmed and the presence of BUE deposits can be seen.
- Methods to prevent BUE deposits on the machining surface are well known in the machining industry. The main parameters to consider are rotation speed, feed rate, cutting temperature, tool rake angle, and tool material. Tuning of these parameters is dependent on the machining equipment and components and is usually the responsibility of the manufacturing plant, but should not be neglected by the designer.

In summary, this study highlights the importance of machining quality on brake performance, which was not previously noticed in other investigations.

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