Machining Cobalt-Based Dental Alloys with Tungsten Carbide Millis

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Abstract: Milling characteristics of dental alloys have been investigated and compared. The four differently configured tools used were made of cemented tungsten carbide. Most were uncoated but one was coated with a diamond-like carbon layer. The dental alloys studied were cobalt-chrome (Co-Cr) and cobalt-chrome-titanium (Co-Cr-Ti) alloys, fairly strong alloys. There is a requirement for a reliable test to evaluate the properties of dental tools by measuring the cutting forces during milling. A full characterization of dental mills is a difficult task, because the geometry of the mills is complex, with conical multi-cutting surfaces. In this study a more comprehensive understanding of the effects of cutting rate on cutting forces was achieved by varying the cutting tool rotation speed and measuring the force on the workpiece as it was driven into the rotating tool at a fixed feed velocity. It was observed that the cutting forces were changed by varying cutting speeds. Side milling required lower forces than central slot milling. After milling the surfaces of the dental tools and dental alloy specimen were analyzed by scanning electron microscopy.

Key words: Dental mill, Dental alloy, Milling characteristics, Cutting forces

1 INTRODUCTION

Owing to its excellent properties, namely, high hardness and high wear resistance, tungsten carbide (WC) is used in dental machining applications, such as in prosthesis fabrication. The tungsten carbide mills are very hard and brittle and are prone to wear and fracture during milling of dental alloys. Worn and failed tools have to be discarded, with resource and environmental penalties.

Therefore, investigation of the characteristics of dental tools and dental alloys is important, for example by measuring the cutting forces during milling. A correct dental mill characterization is a difficult task, because of the complex conical multi-cutting surfaces of the milling tools. Some authors have studied dental milling applications, and diamond films have been considered a coating material for dental cutting tools [1-5]. Micro/nanocrystalline diamond films have also been coated on dental cutting tools [6]. A dental cutting test for a leucite-reinforced glass-ceramic has also been performed [7]. However, the results were affected by using a hand milling system, and the work-piece geometries and materials were not constant. A reliable test is required in order to exactly evaluate tool performance.

In this study, we have investigated and compared dental milling characteristics of very hard dental alloys. We have measured cutting forces to examine the cutting behavior of dental mills during milling. Four different WC mill geometries were considered. Three were uncoated and the fourth was coated with a diamond-like carbon (DLC) layer. The two high strength dental alloys studied were composed of cobalt-chromium (Co-Cr) and cobalt-chromium-titanium (Co-Cr-Ti). Two milling operations were performed: the first involved central slot milling to cut a groove through the sample and the second used a lateral side milling operation to plane the sample. For an improved understanding of the effects of cutting rate on cutting forces, the cutting tool rotation speed was carefully varied in the range of 10000~35000 rpm but the tool feed rate was kept constant for all tests. It was observed that the cutting forces were changed by varying cutting speeds. The surfaces of the dental tools and dental alloys were analyzed by scanning electron microscopy (SEM) after milling. The results of the cutting force tests and SEM analysis are discussed below.

2 EXPERIMENTAL

2.1 Experimental equipment

The experimental equipment is shown in Fig. 1. A bench milling machine was modified by the addition of a vertical spindle milling device. The standard spindle of the milling machine was replaced with a high speed spindle (hand piece) fitted by dental technician and held in a securely fixed position. The high speed spindle (Push-BL50) was supplied by Shofu Inc., Japan. The cutting tool rotation speed of the spindle was able to be varied in the range of 1000~50000 rpm. The dental alloy samples were set on a holder above the center of a 200N load cell to measure cutting forces during milling, and the load cell was placed on a table. The samples were moved at a constant slow feed rate into the rotating cutting tool and the resulting load cell signals were amplified and recorded. The machining tests were carried out in still air with no additional cooling or lubrication.

2.2 Dental alloys

Cobalt-chrome (Co-Cr) and cobalt-chrome-titanium (Co-Cr-Ti) alloys were used as work-piece material for measuring cutting forces, because they have high strength and are available in blocks of regular shape. The samples used in the current tests were supplied by Shofu Inc., Japan. The Co-Cr alloy was provided in the form of octagonal base parallel face blocks of 8 mm height and 8 mm octagon edge length. The Co-Cr-Ti alloy was supplied in the form of octagonal base parallel face blocks of 9 mm height and 7.3 mm octagonal edge length. The composition and properties of the dental alloys were provided by supplier and are shown in Table 1.

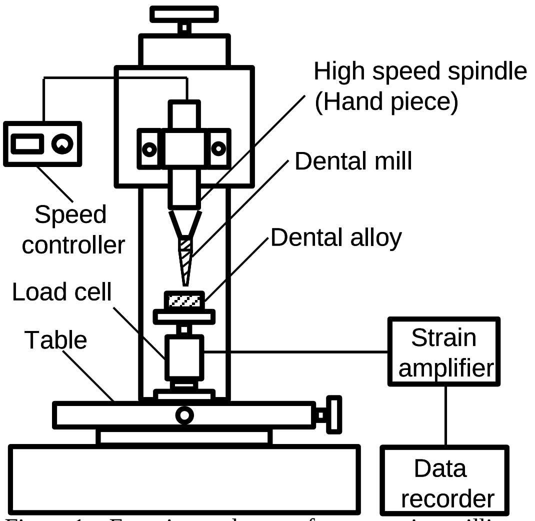

Figure 1 Experimental set up for measuring milling operations.

Table 1 Dental alloy composition and properties.

Co-Cr alloy			
Composition [W/W%]			
Co	Cr	Mo	Si, Mn, N, C
More than 65	29	6	Less than 2
Physical and mechanical properties			
Melting temperature	1395° C		
Yielding strength	938 MPa		
Elastic limit (0.2%)	681 MPa		
Elongation	8.3%		
Vickers hardness	365 HV0.5		

Co-Cr-Ti alloy				
Composition [W/W%]				
Co	Ni	Cr	Ti	Fe, Mo
40	28	23	5	4
Physical and mechanical properties				
Melting temperature	1350° C			
Yielding strength	859 MPa			
Elastic limit (0.2%)	743 MPa			
Elongation	3.5%			
Vickers hardness	315 HV0.5			

2.3 Dental mills

In this study, to investigate and compare dental milling characteristics of very hard dental alloys, four different mill

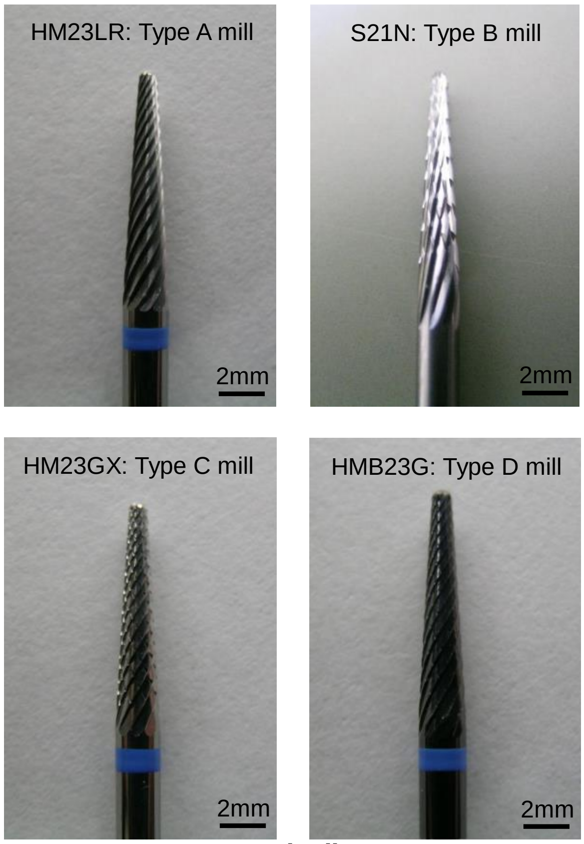

Figure 2 Dental mill geometries.

Table 2 Dental mill details.

	WC dental mills	Shape	Chip-breaker	DLC coating
Type A	HM23LR (Hager & Meisinger)	Spiral	-	-
Type B	S21N (Shoufu)	Cross (Large)	○	-
Type C	HM23GX (Hager & Meisinger)	Cross (Small)	○	-
Type D	HMB23G (Hager & Meisinger)	Spiral	○	○

geometries and specifications were considered and they were made of cemented tungsten carbide (WC) by different manufacturers. One of these was in DLC coated conditions. The dental mills were supplied by Shofu Inc., Japan and by Hager & Meisinger Inc., Germany. A significant difference in geometry was observed between the HM23LR mills (Hager & Meisinger: spiral shape) and the S21N mills (Shofu: cross shape with chip-breaker) and the HM23GX mills (Hager & Meisinger: cross shape with chip-breaker), as shown in Fig. 2. One mill (HMB23G, Hager & Meisinger: spiral shape with chip-breaker) was coated in a diamond like carbon (DLC) layer. The HM23GX, S21N and HMB23G mills were all configured with chip-breakers. Table 2 summarises the design details, of the mills identifying them as Type A, B, C and D respectively. All the mills had a 44mm total length with a 32 mm long cylindrical shank and 12 mm long conical cutting surface.

2.4 **Milling tests**

The milling tests with all the different cutting conditions are summarised in Table 3. For a more comprehensive understanding of cutting forces, the rotational speed was carefully varied in the range 10000 ~ 35000 rpm, a typical range during a dental milling application. The feed rate was fixed at 0.15 mm/second. Fig. 3 shows the difference between the central slot and lateral milling configuration. In the central milling tests, the depth of cut was adjusted to 0.5mm. In the lateral milling, the depth of cut was 3.0mm, and the width of cut 0.5mm. All the lateral milling operations were peripheral type.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 **Central milling**

Fig. 4 shows the comparison between average cutting forces of Case A condition (the central milling configuration of the Co-Cr alloy) for four mills. In the figure, the ordinate shows the cutting force and the abscissa shows the cutting speed. The cutting forces varied as a function of cutting speed: cutting forces with rotational speeds of 12000 ~ 20000 rpm for Type B, C and D mills were larger than those with 24000 ~ 30000 rpm. Some instability of cutting force was noted at lower rotational speeds but the cutting forces were relatively stable in the speed range between 25000 ~ 30000rpm. The average cutting force for the Type B mill was highest, and the cutting force for the Type A mill was lower than the other as low cutting speeds. The differences are likely to be due to the different geometries of these mills. The expected lower cutting forces of the coated

Table 3 Milling conditions.

	Milling configuration	Dental alloys
Case A	Central	Co-Cr alloy
Case B	Central	Co-Cr-Ti alloy
Case C	Lateral	Co-Cr alloy
Case D	Lateral	Co-Cr-Ti alloy

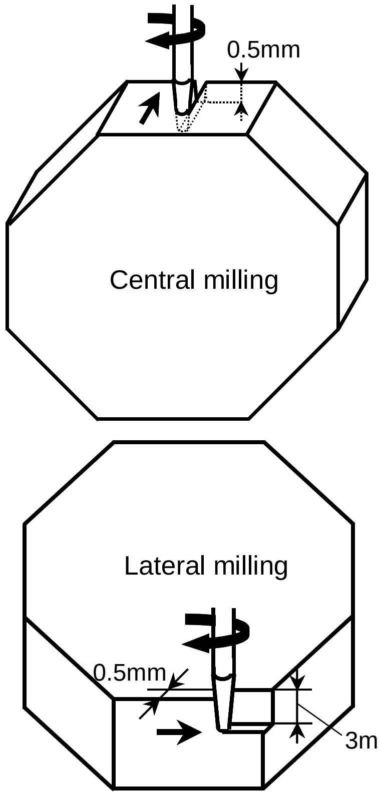

Figure 3 Central and lateral milling configurations. Note that the mill is fixed.

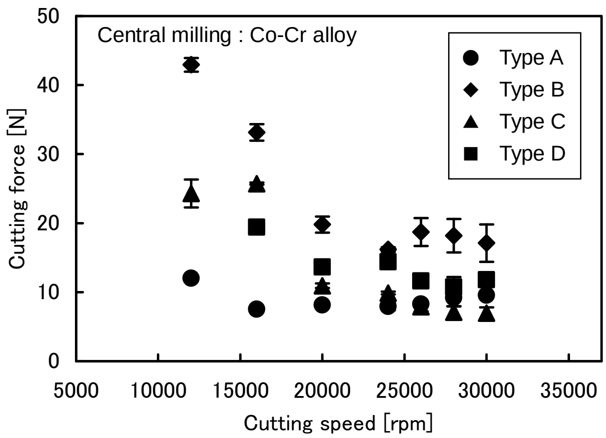

Figure 4 Cutting forces of Case A (central milling of the Co-Cr alloy) for four mills.

Type D mill were not evident. The surface of the DLC coated mill was investigated by scanning electron microscopy and as shown in Fig.5, the coating was found to have detached from the tool tip explaining to some extent why the cutting forces were not appreciably lower than for the other mills. An SEM image of surface of the milling path on the Co-Cr alloy after central milling is shown in Fig. 6. The left side surface is rougher than the right side surface. Fig. 7 is an enlarged image of the left side surface of the milling path and there are indications of chip welding on this surface. This factor may also have contributed to drag on the mill, increasing the linear cutting force.

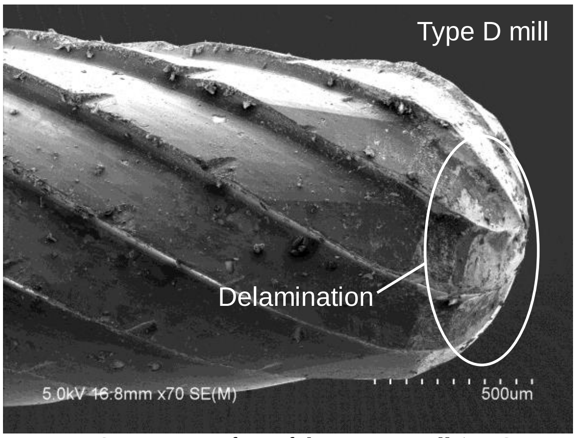

Figure 5 SEM image of tip of the Type D mill (DLC coated condition) after milling showing delamination of the coating.

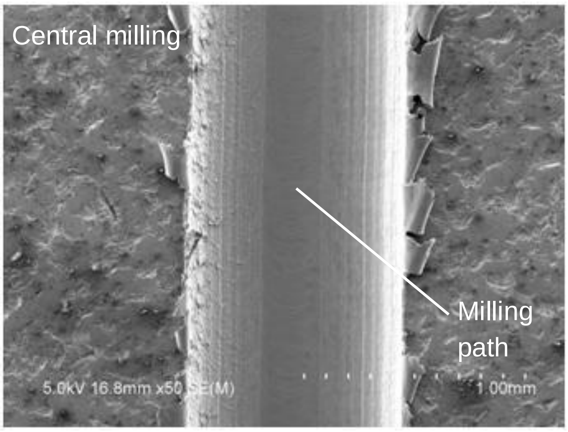

Figure 6 SEM image of the Co-Cr alloy after central milling by the Type A mill.

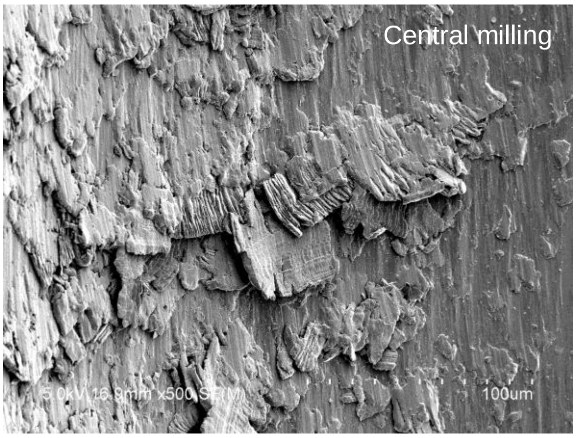

Figure 7 SEM image of machined surface of the Co-Cr alloy after central milling by the Type A mill. Re-welded alloy chips are evident on the surface.

Fig. 8 shows the comparison between average cutting forces of Case B condition (the central milling configuration of the Co-Cr-Ti alloy) for two mills. The cutting forces for the Type A and B mills were not obtained in cutting speed 20000 ~ 35000 rpm. The Type A mills were worn during milling at lower speeds. The Type B mills failed during milling. The cutting forces for the Type C and D mills were not obtained in cutting speed 10000 ~ 35000 rpm. The two mills were worn intensely and tips of mills became red hot. In order to confirm the cause, the worn Type A and failed Type B mills were investigated by SEM. The intensely worn tip of the Type A mill is shown in Fig. 9 and the fractured tip of the Type B mill is shown in Fig. 10. A possible reason for the fractures is that the Co-Cr-Ti alloy included Ti and Ni, reducing the machinability of the material in comparison with the Co-Cr material. Also the cobalt content in the Co-Cr-Ti alloys was smaller than that of the Co-Cr alloys. Enlarged images of the fracture surfaces on the Type A and B mills are shown in Fig. 11 and 12, respectively. The grain size

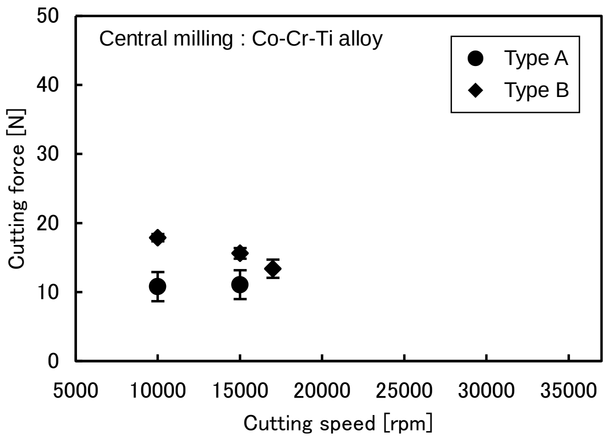

Figure 8 Cutting forces of Case B (central milling of the Co-Cr-Ti alloy) for four mills.

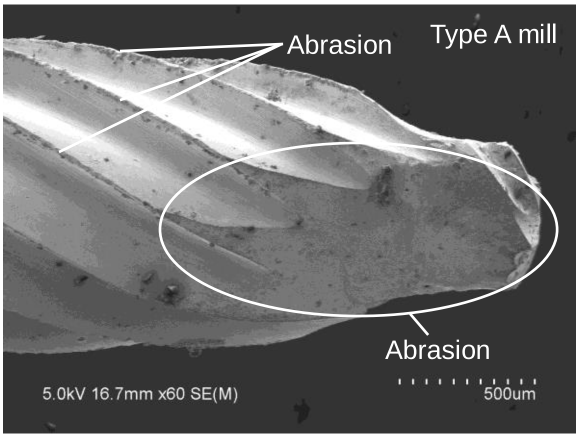

Figure 9 SEM image of worn tip of the Type A mill after milling.

of the cemented tungsten carbide mills was similar but there appear to be differences in fracture deformation of the cobalt binder, possibly explaining the different wear characteristics of the two mills.

3.2 Lateral milling

Fig. 13 shows the comparison between average cutting forces of Case C (the lateral milling configuration of the Co-Cr alloy) for four mills. The cutting forces were smaller than those of the central milling. The cutting forces for the three mills other than Type B mill were relatively high at 10,000 rpm cutting speed but decreased at higher speeds. The cutting forces for the Type B mill were stable in 10000 ~ 35000 rpm. The Type A, B and C mills sometimes fell out of the high speed spindle during milling because the geometry of the mill was such that the spindle grip loosened during the machining operation. Type D mills did not have this problem possibly because the low friction coefficient of the DLC coated mills reduced torsional vibration levels. The SEM image of the machined surface after the lateral milling on the Co-Cr alloy is shown in Fig.14. The right part of the SEM image is the milled area. The smooth surface morphology and comparative absence of chip re-welding showed that the cutting chips had been released rather than retained and welded, reducing frictional effects and associated cutting forces.

Fig. 15 shows the comparison between average cutting forces of Case D (the lateral milling configuration of the Co-Cr-Ti alloy) for four mills. The cutting forces for four mills were also smaller than those of the central milling on the same alloy. In this case, the cutting forces for all mills were generally stable in 10000 ~ 35000 rpm although Type A, B and C mills were also again affected by problems of tool release from the

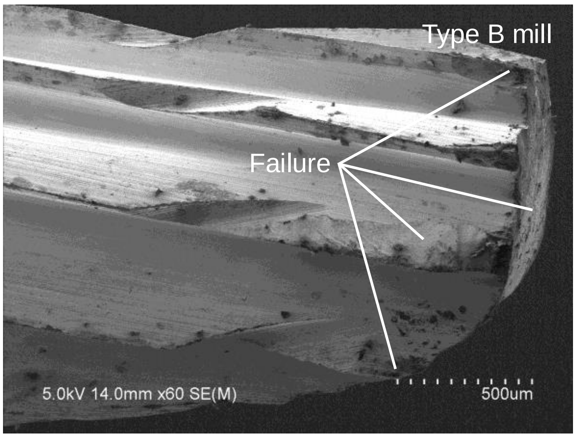

Figure 10 SEM image of failed tip of the Type B mill after milling.

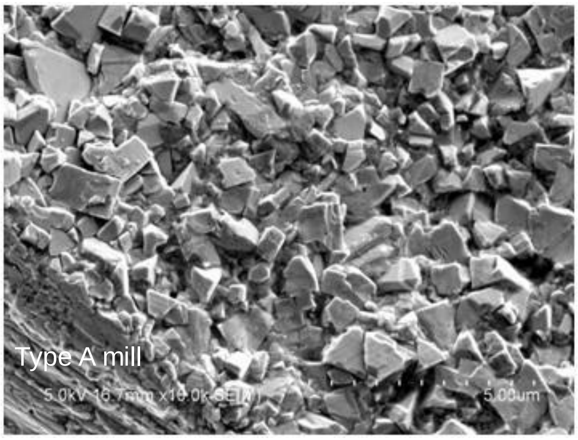

Figure 11 SEM image of a fracture surface near the tip of the Type A mill after milling. (x10,000)

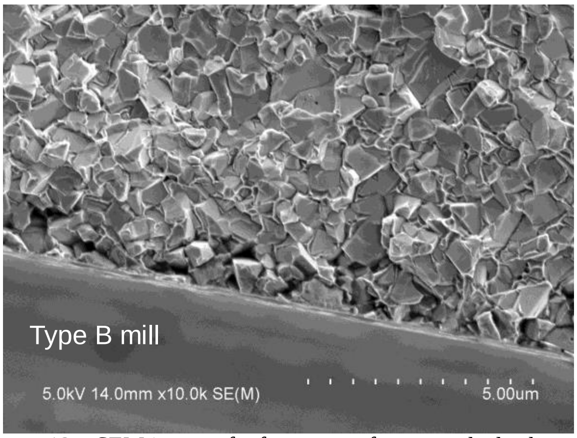

Figure 12 SEM image of a fracture surface near the broken tip of the Type B mill after milling. (x10,000)

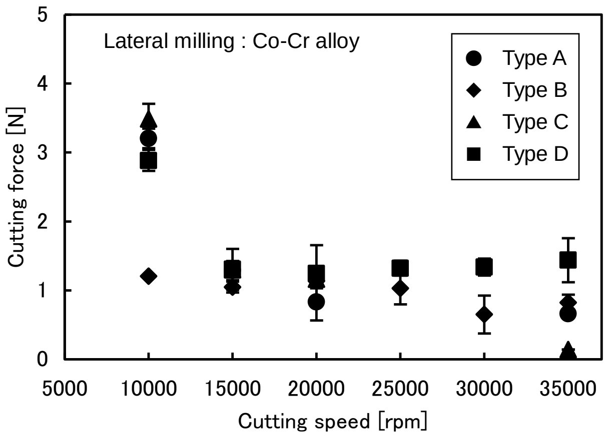

Figure 13 Cutting forces of Case C (lateral milling of the Co-Cr alloy) for four mills.

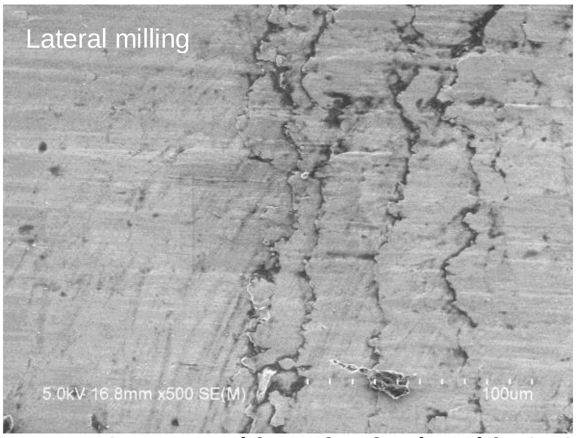

Figure 14 SEM image of the machined surface of the Co-Cr alloy after lateral milling.

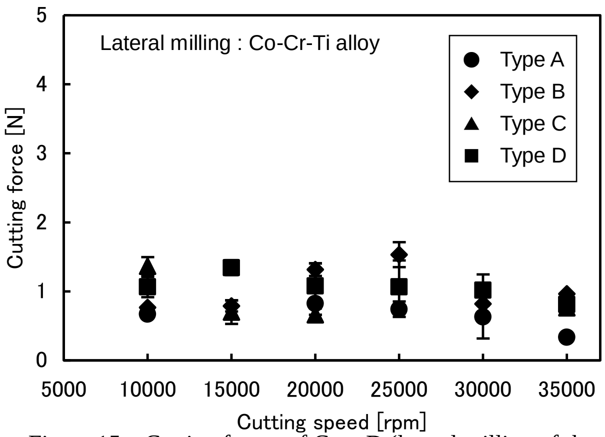

Figure 15 Cutting forces of Case D (lateral milling of the Co-Cr-Ti alloy) for four mills.

spindle.

4 CONCLUSIONS

In this study, we have investigated and compared dental milling characteristics of relatively hard dental alloys. We have measured cutting forces to examine the behavior of dental mills during constant feed rate milling at different mill rotational speeds. The tools used were made of cemented tungsten carbide. Milling tools of four different geometries were considered and one of these had a diamond-like carbon (DLC) coating. The dental alloys studied were cobalt-chrome (Co-Cr) and cobalt-chrome-titanium (Co-Cr-Ti) alloys. The machining operations performed were central slot milling and lateral side milling. For a more comprehensive understanding of the effects of cutting rate on cutting forces, the cutting tool rotation speed was carefully varied in the range of 10000 ~ 35000 rpm. It was observed that the cutting forces changed as a function of cutting speed.

In the central milling configuration of the Co-Cr alloy, a difference in the cutting force for each mill was observed. The cutting forces generally decreased with increasing cutting speed and were relatively low and stable in 25000 ~ 30000 rpm speed range. The cutting force measured from the mill with the low-friction DLC coating was not greatly different from that of the uncoated mills. One reason for this was that the DLC film was delaminated near the tip of tool. Chip re-welding was also noted within the machined slots generated by all of the mills. This effect would have increased the frictional forces in every case. For the Co-Cr-Ti alloy, the cutting forces for the Type A and B mills were not obtained in cutting speed 20000 ~ 35000 rpm and the cutting forces for the Type C and D mills were not obtained in cutting speed 10000 ~ 35000 rpm. There was an indication that the Co-Cr-Ti material has lower machinability than the Co-Cr alloy.

In lateral milling of the Co-Cr alloy, the cutting forces from all four mills were smaller than those of central milling. The Type B mill had low cutting force at low speed and there was little change in force when this mill was run at higher speeds. The other three mills showed a higher cutting force at low speed but the force declined with increasing cutting speed. For the Co-Cr-Ti alloy, the cutting forces for four mills were also smaller than those of the central milling. For all mills used to side-machine this alloy, the cutting forces were relatively constant in the rotational speed range between 10000 ~ 35000 rpm, with a slight force reduction evident at the highest speed.

It can be suggested that the use of a cooling fluid during the machining operation is considered likely to reduce the problem of chip re-welding as well as abrasion related issues. Therefore, this needs further investigation.

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