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ACHIEVING A UNIFORM FACE KNURL ON THE XM1113 ROCKET MOTOR BODY

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Face knurling is a process that can be sensitive to several factors in a manufacturing environment. Knurling, specifically, is a forming process where metal is sheared and pushed to create a geometric pattern. Factors such as material hardness, tool wear, coolant, and cleanliness of the part can make significant differences in the quality of the knurl, including depth, double tracking, and uniformity of geometry. This paper documents an effort to consistently and efficiently produce a uniform face knurl on the XM1113 rocket motor body (RMB) using a 20-teeth-per-inch (TPI) knurling wheel.

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INTRODUCTION

Face knurling is a process that can be sensitive to several factors in a manufacturing environment. Knurling, specifically, is a forming process where metal is sheared and pushed to create the geometry. Factors such as material hardness, tool wear, coolant, and cleanliness of the part can make significant differences in the quality of the knurl, including depth, double tracking, and uniformity of geometry. This paper documents an effort to produce a uniform face knurl on the XM1113 rocket motor body (RMB) using a 20-teeth-per-inch (TPI) knurling wheel. The purpose is to achieve maximum surface friction by scoring the mating surface without wearing down the knurl. The objective is to consistently and efficiently produce a uniform knurl in the shape of a truncated square pyramid with a depth of 0.013 in.

DESIGNING A KNURLING WHEEL

The design of a knurling wheel is very similar to that of a straight bevel gear. As explained in reference 1, “Bevel gears being conical gears, that is, gears in the shape of cones, are used to connect shafts having intersecting axes. The teeth of this most commonly used type of bevel gear are straight but their sides are tapered so that they would intersect the axis at a common point called the pitch cone apex if extended inward” (ref. 1).

The design intent should be a cone geometry that can roll on its own around the flat face of the projectile body and return to its starting point. In this case, if the large diameter of the cone is 1.25 in., then a cone angle of 11.86 deg would generate that cone. The apex of the cone should be at the axis of the part being face knurled.

If the knurling wheel were pressed into a flat piece of clay, the overall effect would look something like figure 1 (ref. 2). Note that the axis of a bevel-geared knurling wheel is focused on the axis of the pattern it makes.

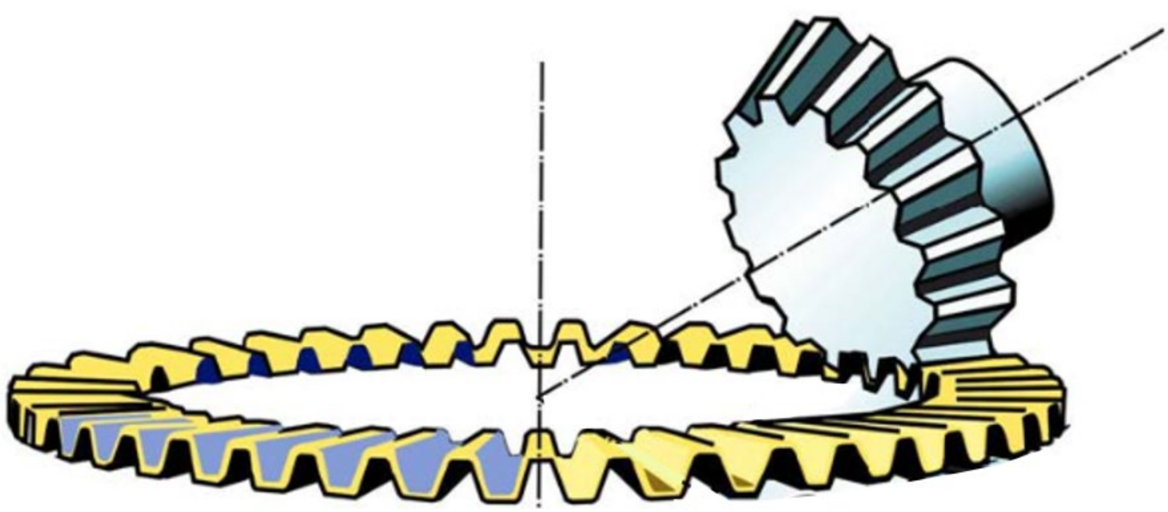

Figure 1
The pattern a bevel-gear-like knurling wheel would make on a flat piece of clay

Figure 2 explains the kinematics of a truncated-cone knurling wheel and how a knurling wheel comes very close to generating a uniform face knurl. The intent is to match the tangential velocities of the surface of the cone wheel at the surface of the face of the tube. Deviations in tangential velocity will cause slipping and lead to smearing of the knurl geometry or double tracking. Double tracking is when there is a noticeable indent on the face or side of the knurl structure.

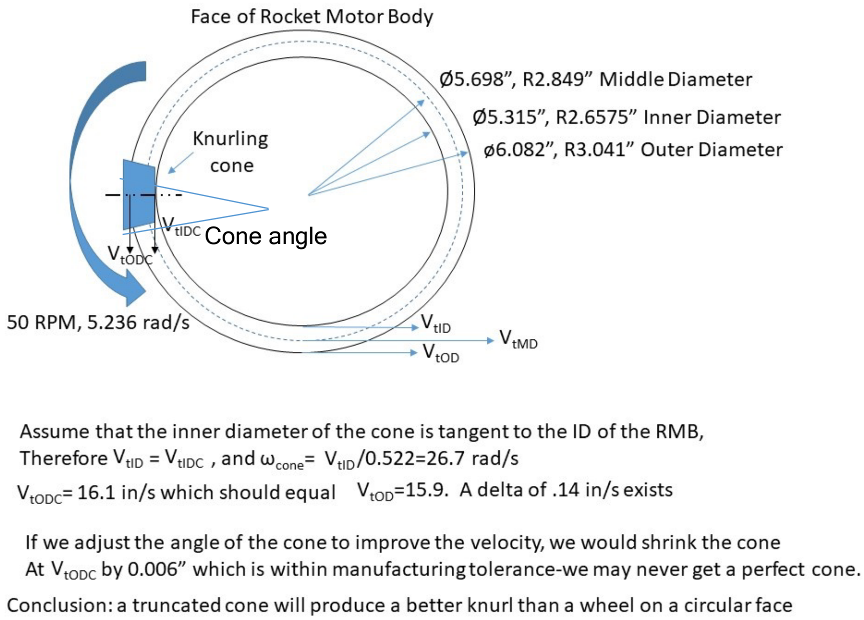

Figure 2
Kinematics of a truncated-cone knurling wheel

If the truncated cone has a different angle than seen in figure 2 or is a right, circular knurling wheel as seen in figure 3, the result of the velocity distribution will be uneven across the face of the tube. Tangential velocity at the inner diameter will be too fast compared to the outer diameter, causing an uneven distribution of the knurl.

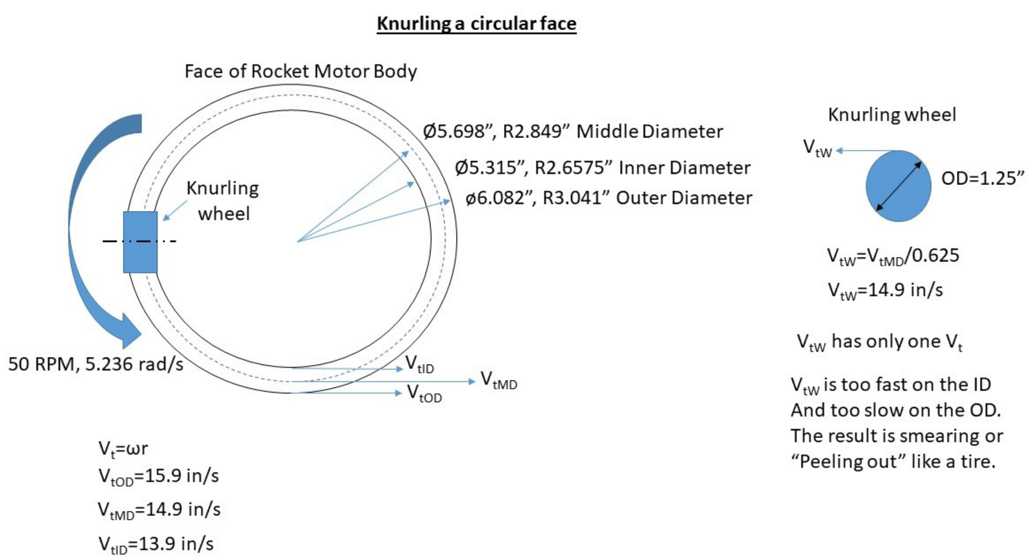

Figure 3
Rotational mechanics of a right, circular knurling wheel

A pitch of 33.3 TPI is required by design; however, a prototype 20-TPI knurling wheel, made by Accu Trak, was introduced to see if a more uniform and deeper knurl could be manufactured. The 20-TPI wheel is pressed onto the face of the trunnion specimen as seen in figure 4.

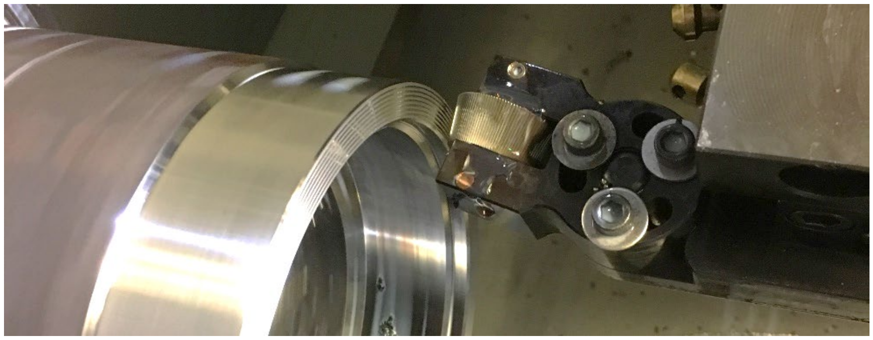

Figure 4
A prototype 20-TPI knurling wheel imprinting on the face of a test item

The desired depth of the knurl chosen was 0.013 in., which was based upon a tribology test design. Based on the design, eight circumferential grooves are first cut into the surface of the face. The spacing is 0.044 in. between grooves, and the depth of the grooves should be between 0.012 and 0.017 in. The groove allows for metal to flow during the forming process. The spacing and depth of the grooves help to control the shape of the knurl. A deep groove will also be wide at the top, minimizing the shape of the knurl. A shallow groove or wider spacing means that more material resists the knurling wheel and more force is required to form the metal.

KNURLING PROCEDURES

The standard knurling depth is 35% of knurl circular pitch (ref. 3). This implies that we can push the 20-TPI wheel into the workpiece by 0.017 in., whereas the 33.3-TPI wheel should only be pushed to 0.011 in. maximum. Additionally, the knurled material should have a Rockwell C hardness of less than half the hardness of the knurling tool. Variations in hardness of material will affect knurl depth. The harder the workpiece, the more stress and wear is put on the tooling and the machine that has to exert force on the tool.

The goal of the experiment was to consistently create a knurl with a depth of 0.013 in. Based on the procedure outlined above, the maximum depth to plunge the tool is 0.017 in. It should be noted that there is a draft that is built into the tool due to its truncated-cone shape, such that the teeth get larger as one goes towards the larger end of the cone, which provides a margin on the tooth depth. In figure 3, the smaller end of the wheel has a depth that is shallower than at the larger end. A 33.3-TPI knurling wheel may only get to 0.009 in. at the inner diameter.

Knurling with a Small Lathe

The Haas ST-20 lathe (see fig. 5) was used for knurling process development, specifically, small trunnion test specimens. This lathe is rated for 20 hp and can only handle smaller parts. The trunnion test pieces were no larger than 6.25 in. length by 6 in. diameter. With a desired depth of 0.013 in. for a knurl, we chose a 0.014-in. groove depth and used the specified number of circumferential grooves from the RMB drawing. On the Haas ST-20 lathe, the initial knurl depth programmed was 0.038 in. (an actual depth of 0.038 in. is not achieved but is meant as a means of loading the tool into the workpiece) with a feed rate of 0.001 in./sec and a turning rate of 50 rpm. A 60-sec dwell followed the plunge step. During this cycle, the ST-20 pushed the tool and created an axial load that went up as high as 90% with the load dropping to 80% during the 30-sec dwell time. The result was the knurl in figure 6.

Figure 5
Haas ST-20 lathe

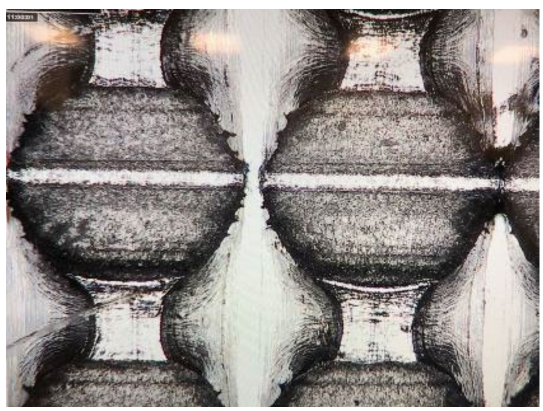

Figure 6
Knurl pattern with 0.013-in. depth produced by the Haas ST-20 lathe

Knurling with a Large Lathe

The Haas ST-40 is a 40-hp lathe (see fig. 7) that is much larger than the ST-20. The purpose of moving to this machine is that it can handle much larger items, such as a complete RMB. To accommodate the size and power differences, multiple adjustments in the set up and programming of the ST-40 were made to get the lathe set up to produce knurls that were 0.013 in. deep with a square base and square top. It took several different adjustments in the programming of the chuck pressures and tooling forces to finally produce what was thought to be an acceptable knurl.

Figure 7
Haas ST-40 large-frame lathe

As the ST-40 is a larger and more powerful machine than the ST-20, it was programmed to plunge to a depth of 0.033 in. at a feed rate of .006 in./sec with a turning rate of 50 rpm and a dwell time of 15 sec. This produced the knurl pattern depicted in figure 8.

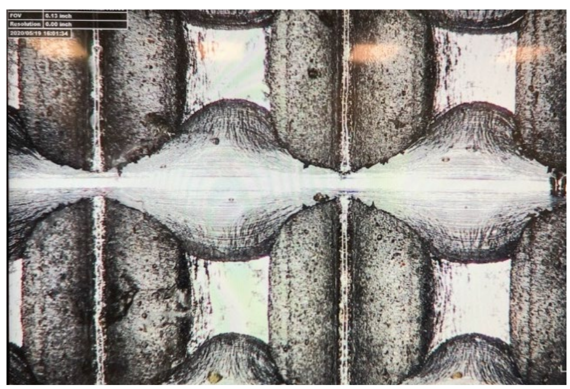

Figure 8
Knurl pattern with 0.013-in. depth produced by the Haas ST-40 lathe

It should be noted that the knurl pattern shown in figure 8 was created on an RMB from a previous manufacturing lot that used the 33.3-TPI tool to create an average knurl depth of 0.009 in. Also note that the average groove depth was increased to 0.016 in., which is still within the tolerance. These specific dimensions may have a tolerance of +/- 0.005 in. or an allowable variation of depth not to exceed +/- 0.005 in.

COMMON KNURLING PROBLEMS

Aberrations in creating the knurl pattern should be noted to recognize parameters that can lead to improper geometry such as improper depth or double tracking. Cleanliness of the workpiece prior to chucking is important.

Cleanliness of the Workpiece in Process

As this procedure for the RMB is performed on hardened steel, it is imperative to make sure that chips and strands of steel are removed from the RMB prior to knurling. If the knurling runs over debris that is displaced by coolant, it will jump and start double tracking.

The first aberration was due to a thin piece of masking tape adhered to the side of the RMB. The tape was initially a label to identify the RMB and had not been removed. The Haas ST-40 chuck with hydraulically-actuated jaws, which are depicted in figure 9, had clamped onto the region where the masking tape was located. During the 15-sec knurling cycle dwell, an audible wavering tone was evident. The load meter dithered between 50 and 75% during this time. The knurl depths ranged from 0.011 to 0.013 in. and are indicated in table 1.

Figure 9
Haas ST-40 hydraulic chuck with standard jaws

Table 1
Variation in knurl depth due to piece of making tape on rocket motor body

RMB angle (deg)	Average knurl depth (in.)
0	0.013
90	0.013
180	0.011
270	0.013

Minor double tracking was noticed, but what stood out was the 0.002-in. difference in knurl depth at the 180-deg region. The part was rerun but without the tape. As a result, the tone produced from the knurling dwell cycle was steady and the load meter held at 74%. This resulted in an average knurl depth of 0.013 in. This cycle had a feed rate of 0.006 in./sec with a dwell time of 15 sec and a dwell depth of 0.033 in. It should be noted that the clean knurls had a steady load rate during the dwell cycle.

Variations in Material Hardness

Variations in material hardness will affect knurl depth. Using the exact same knurl parameters from the previous pieces, the first RMB was knurled from a rejected lot of production RMBs. The RMB was rejected due to an improper knurl. However, it is assumed that the RMBs were from a different chemistry and heat lot than the RMBs manufactured at Scranton Army Ammunition Plant (SCAAP), Scranton, PA, and whose pilot face knurling processes were developed at the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ. The resulting average knurl depth was 0.012 in., which is 0.001 in. less than the previous setup piece. At this point, it was decided to push the tool harder and make the dwell depth 0.036 in. This change in the process yielded an average knurl depth of 0.013 in., which is the desired depth. More specifically, the 0.003-in. adjustment produced at least a 0.001-in. difference in knurl depth.

Insufficient Coolant

Ample coolant is required during the knurling process to remove debris and to cool the knurling wheel. The Accu Trak knurling wheel is a cone-shaped knurling wheel with a hardened steel pin for an axle. Running without enough coolant will cause the wheel to overheat and possibly craze or crack.

RESULTS

A uniform knurl was created on the RMB face using the 20-TPI knurling wheel. Figure 10 shows a 60x magnification view of the knurl pattern. The lower portion of the image stops at the inner diameter, whereas the top of the image is the outer diameter. The dotted lines show the slight taper of the knurl tops due to the taper of the cone wheel. For the most part, the tops of the knurls are square. Table 2 lists the average knurl and groove depths for all seven RMBs knurled with the 20-TPI knurling wheel.

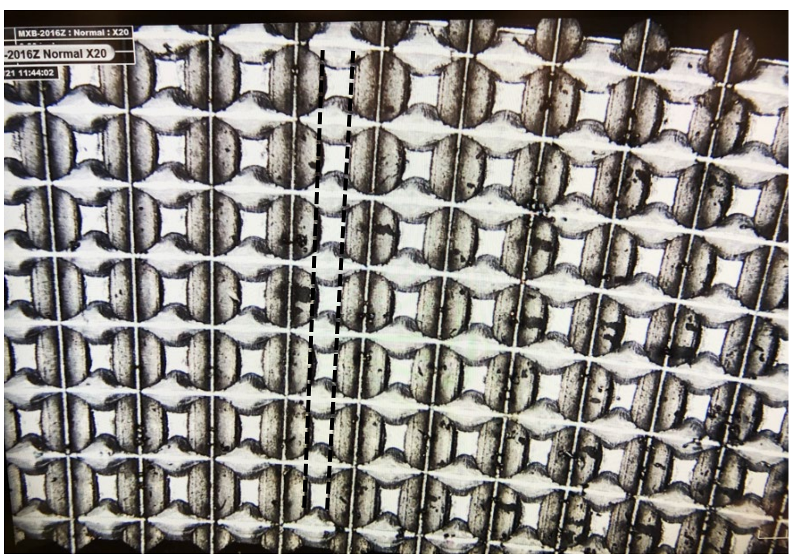

Figure 10
An example of a uniform knurl pattern created with the 20-TPI knurling wheel

Table 2
Average knurl and groove depths for seven XM1113 rocket motor bodies face knurled with 20-TPI knurling wheel

RMB no.	Average knurl depth (in.)	Average groove depth (in.)
1	0.013	0.016
2	0.013	0.015
3	0.014	0.016
4	0.013	n/a
5	0.013	0.015
6	0.014	0.016
7	0.013	0.015

The knurl depths vary by 0.001 in. at the most. The groove depth is more difficult to measure, as the apex of the groove has a parabolic shape that produces reflections that make it difficult to optically measure.

Figure 11 is an isometric view of the knurl pattern at 100x magnification using a Hirox three-dimensional (3D) digital video microscope. The image was created by stitching multiple images. The arrows show how the microscope software is approximating the groove geometry. Using a diffuser on the microscope light and providing more samples improve the images and measurements.

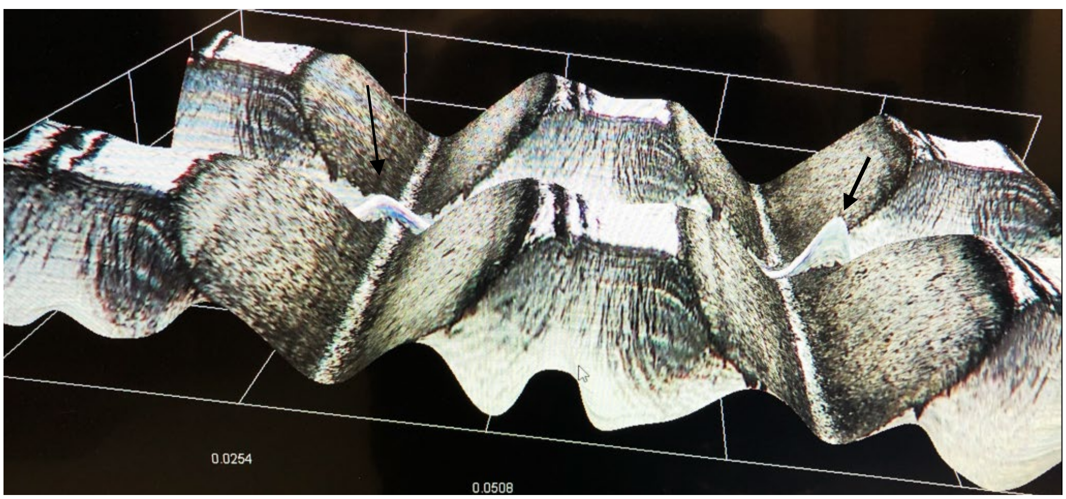

Figure 11
An isometric view of the knurl pattern under 100x magnification

The double tracking could be from a jump of the tool due to debris or bouncing due to backlash of the tool being plunged into the part. In figure 12, an indication of double tracking is seen as a faint line across the face of the knurl top.

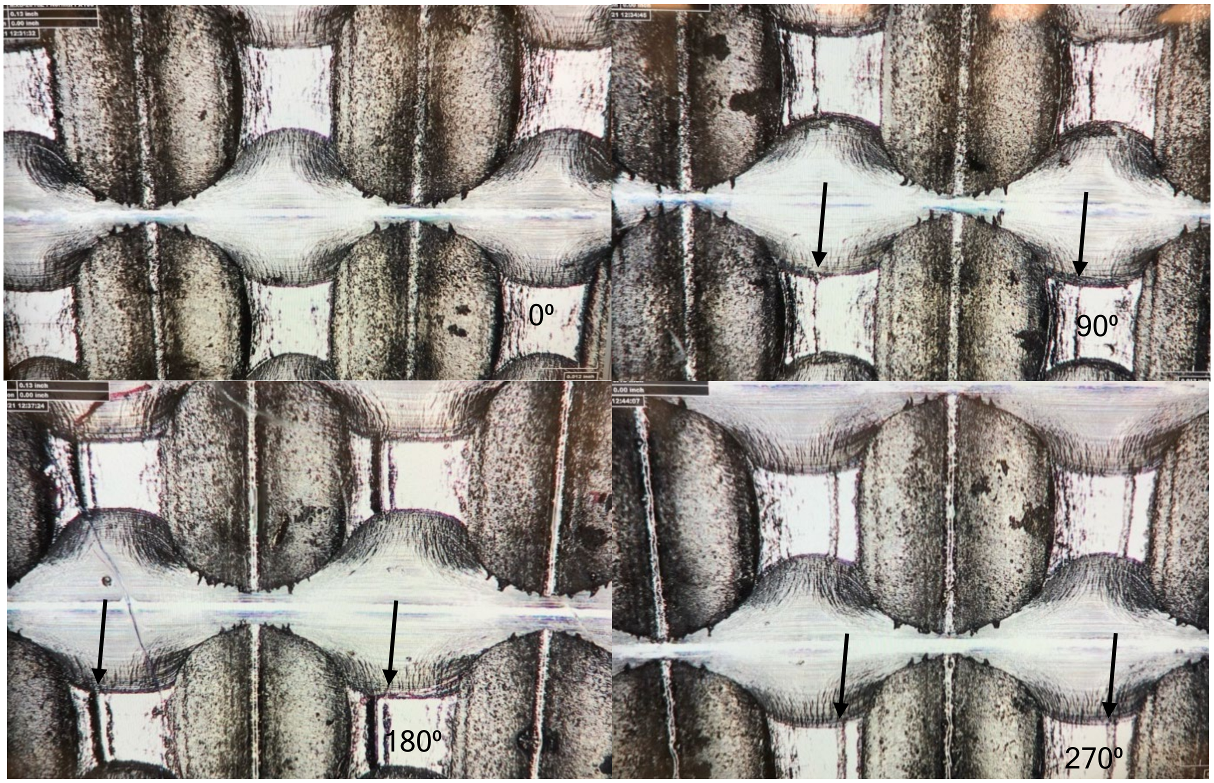

Figure 12
Images of knurl topology at 0, 90, 180, and 270 deg

Several attempts were made to measure the depth of the apparent double tracking using the microscope. The accuracy of the measurements made it too difficult to quantify any indication of double tracking. It is assumed that the double tracking seen in figure 12 is most likely a slight denting of the knurl top just prior to the tool getting actual traction.

CONCLUSIONS

Seven XM1113 rocket motor bodies (RMB) were successfully face knurled with a 20-teeth-per-inch (TPI) knurling wheel. The desired knurl depth of 0.013 in. was achieved using 35% of the pitch depth with knurl depths ranging from 0.013 to 0.014 in. Regarding double tracking, three-dimensional (3D) digital microscope images indicate very minor double tracking in some regions, but the depth of double tracking was not quantifiable. It is assumed that the double tracking is due to minor denting from the knurling wheel trying to get traction on the surface to be knurled.

In order to create uniform knurl geometry and depth and to avoid double tracking, there are several items to consider, including material hardness, tool wear, coolant, and cleanliness. As the face knurling is performed on hardened steel, chips and strands of steel must be removed from the RMB prior to knurling. Ample coolant should be used during the knurling process to remove debris and to cool the knurling wheel. Proper lubrication is important, and cooling parts should be regularly inspected for wear.

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