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Galling Tendencies and Particles Produced by Ultra Clean Screw Threads

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1. ABSTRACT

A test was conducted to evaluate the tendency to gall and to collect the particles generated by screw threads that were thoroughly cleaned for ultra high vacuum service. Bars of stainless steel and aluminum were tapped to size ¼-20 using a wide variety of tap configurations, with 20 holes per bar. Screws of various materials and treatments were inserted, torqued and removed 10 times per hole, on 10 of those holes, to check for the effects of material and tap choices on galling tendencies. Particles from these were collected by means of a strip of transparent tape placed before insertions under the row of holes in each bar. After testing, each strip of tape was transferred to a report sheet, which was then scanned at 1600 dpi. The data were evaluated and recommendations are made to minimize particle generation and galling in future designs.

2. INTRODUCTION

The LIGO Project has experienced difficulties from galling of screw threads that have been thoroughly cleaned for ultra high vacuum application. Most of these problems have been overcome by means of material selection and having the holes tapped at 0.005" oversize. High Precision Devices, a contractor on a value engineering task, presented a report which showed that a significant amount of particles are generated by some ultra cleaned screw threads. Since some of the LIGO optics are located below threaded joints utilized for optics installation, we wanted to better understand this effect and how to minimize it.

This task was performed to better understand the potential for galling and particle generation within the resources available to the LIGO Project. Sensitivity of LIGO's optics to condensed hydrocarbons demands that no lubricants are to be used in our vacuum chambers, and all parts must be thoroughly cleaned and baked to minimize outgassing risks.

3. HARDWARE PREPARATION

Test blocks were cut from 0.5" x 1.0" rectangular bar stock: 12 from Type 304 Stainless Steel, and 12 from 6061-T6511 Aluminum. Taps were purchased of various materials and designs, to evaluate the effects that the tap would have on the tendency for galling and generating particles during use. Specific ¼-20 taps purchased were as follows:

1. TiN coated , spiral point tap, H3 pitch dia., 3-flute, 2 ½" overall length.
2. TiCN coated, spiral point tap, H3 pitch dia., 3-flute, 2 ½" overall length.
3. Oxide-over-Nitride treated, spiral point tap, H3 pitch dia., 3-flute, 2 ½" overall length.

4. Nitride treated, spiral point tap for aluminum, H3 pitch dia., 3-flute, 3.15" overall length.
5. Bright finish, High Strength Steel, spiral point tap, H3 pitch dia., 2-flute, 2 ½" overall length.
6. TiN coated, High Strength Steel, spiral point tap, H3 pitch dia., 2-flute, 2 ½" overall length.
7. TiCN coated, High Strength Steel, spiral point tap, H3 pitch dia., 2-flute, 2 ½" overall length.
8. Cobalt steel, spiral point tap, H3 pitch dia., 2-flute, 2 ½" overall length.
9. High performance, TiN coated, spiral flute tap, H3 pitch dia., 3-flute
10. High performance, TiCN coated, spiral flute tap, H3 pitch dia., 3-flute
11. Bright finish, High Strength Steel, spiral flute tap, plug, H3 pitch dia., 3-flute
12. TiN coated, High Strength Steel, spiral flute tap, plug, H3 pitch dia., 3-flute
13. Bright finish, High Strength Steel, thread-forming tap, plug, H4 pitch dia., 2 ½" overall length.
14. Chrome plated, High Strength Steel, hand tap, plug, H3 pitch dia., 4-flute
15. 0.005" oversize, spiral point tap, H11 pitch dia., 2-flute, 2 ½" overall length.
16. 0.005" oversize, High Strength Steel, hand tap, plug, H11 pitch dia., 4-flute

Not all of the taps were used, due to similarities between them. The "H" number designates the oversize dimension in pitch diameter; H3, considered as standard, is +0.0010" to +0.0015"; H11 is +0.0050" to +0.0055". Some of the taps are better for tapping aluminum and some better for stainless steel; others are more universal.

The blocks were drilled and tapped with 20 holes per block in a uniform sequence, as shown in Figure 1. Tapping on each block was started with a new tap, which then proceeded through the 20 tapped holes (except as noted below). The bars were sectioned through the odd-numbered holes to permit close examination of the helical surfaces and thread edges. These steps were taken in order to:

a. check the effects of tap wear for tapping 20 holes, on the helical surfaces and edges of the threads, and
b. check the effects of that wear on the tendency to gall and generate particles during use.

We had expected that wear effects might be noticeable, especially with tapping the stainless steel blocks.

LIGO requirements forbid the use of cutting fluids that contain sulfur, chlorine or silicone, and require that fluids be water soluble. Tapping was started using Hangsterfers S-500 CF (water soluble coolant concentrate, chlorine free) with machine tapping, and no problems were experienced in aluminum. However, tap seizing caused great difficulties in stainless, and some broken taps. The procedure was changed to hand tapping, with little improvement. Finally, the cutting fluid requirement was relieved in order to make progress. Rapid Tap cutting oil was used, with good results in machine tapping. The LIGO Project should reconsider their current requirement on cutting fluids. Although this experience was by no means exhaustive, it's believed very likely that LIGO shops producing tapped holes in stainless are using forbidden cutting fluids at this time.

One of the blocks for each material (#15, Re-Tap) was processed twice with the #15 tap, to investigate the effects of re-tapping.

Heli-Coil thread inserts (without lube or color) were purchased for two of the aluminum blocks, and these blocks were appropriately tapped for the inserts. Inserts were purchased both in Type 304 stainless steel and in Armco Nitronic-60 (N60) material, an Austenitic Cr-Ni-Mn stainless designed to resist galling.

Socket head cap screws were purchased in size ¼-20 x ½", of various materials: standard 18-8 stainless steel (SS) and electropolished 18-8 stainless steel (EP) for the tapped aluminum holes, and N60 and silver plated 18-8 stainless steel (SP) for the tapped stainless steel holes and for the Heli-Coil insert holes.

Stainless steel flat washers were purchased for the test sequences.

All parts were cleaned with the standard LIGO procedures for in-vacuum parts:

- ultrasonic clean in Liquinox for 10 minutes
- rinse in deionized water at least 3 times, changing the rinse water every time
- ultrasonic clean in methanol for 10 minutes
- vacuum bake for 48 hours: stainless steel @ 200C, aluminum @ 120C

The inserts were then installed in the 2 aluminum blocks, and these assemblies were cleaned by using a CO_2 gun. The post-cleaning step of evaluating the cleaning with an RGA scan was not performed on these parts.

A strip of transparent film tape was applied the the row of tapped holes on the bottom of each block to capture the generated particles.

4. TESTING AND RESULTS

Note: Figures 2, 4 & 5 are converted from the collection tapes scanned at 1200 dpi; zooming in on the electronic .pdf file will yield significant detail.

All testing was performed within a laminar flow bench to maintain cleanliness and to avoid polluting the collected particle data.

10 Aluminum blocks with tapped holes (see Figure 2):

Five SS screws and five EP screws were used in testing each of the 10 aluminum blocks with tapped holes. Each screw was inserted, torqued to 91 in lb and removed (using the same hole for a given screw) a total of 10 cycles, and generated dust was captured on the tape strips. Holes assigned to the two screw materials were alternated in sequence to distribute them over the effects of the tap wear.

The largest particle was generated by an EP screw (hole #4 of Tap #5 block), but in nearly all cases the SS screws generated many more particles than the EP screws (see Figure 2). The exception to this was for the holes in the Tap #13 block, which appears to have nearly equal particle generation between SS and EP screws (both severe). Tap #13 was the only thread forming tap type that was tested. Close examination of the sectioned threads (see Figure 3) that it formed reveals a “W” shaped profile at the thread crest, with very ragged edges. The tapped aluminum was worse than the stainless, which is described below.

The EP screws were generally easier to insert than the SS screws, and their dusting generation was lighter; this could be because of the more polished surface, and/or because of the fact (as later discovered) that the EP screw pitch diameter (.2155”) was 0.001" smaller than that of the SS screws (0.2166”).

The screw insertions in the two blocks tapped oversize (Tap #15) were fairly smooth, with little difference between the SS and EP screws. Particle generating magnitudes for these blocks were relatively light. The 8 blocks tapped with standard size taps all offered noticeably more torque resistance in screw insertions. One of the eight (Tap #7) was somewhat lighter in resistance than the other seven.

A SS screw with thread damage was inadvertently started in hole #18 of the Tap #8 block. When the higher torque resistance was noticed, it was replaced with a new screw; this screw subsequently galled and was not removable after the 7^{th} insertion cycle. Particles generated for this hole appear lighter on the tape because the 10 insertion cycles were not completed.

The #15 Re-tap block appeared to produce slightly more particles than the Tap #15 block, surprisingly.

The effects of tap wear in the first 20 holes tapped do not appear to cause a significant difference in size or quantity of particles generated.

2 Aluminum blocks with Heli-Coil inserts (see Figure 4):

Five N60 screws and five SP screws were used in testing each of the 2 aluminum blocks with Heli-Coil inserts. Testing methods were as described above. One plate had Heli-Coils of N60 material, and the other used standard SS Heli-Coils. All N60 screws were extremely smooth with every insertion and removal, as if they were well-oiled. The SP screws felt similar to the screws in the oversize tapped holes in the 2 blocks reported above--some roughness, but fairly smooth.

The N60 screw threads were the only screw threads made by cutting, rather than forming, and their pitch diameter (0.2157") was 0.0024" smaller than that of the SP screws (.2181"). Particle generation was extremely light in both cases, with possibly more particles seen from the SP screws; this, as well as the SP screws' slightly higher roughness, could be due to their larger size, which is likely caused by plating. N60 screws are expensive (58 X SS!), and we could find no one that stocked the 1/4-20 size. N60 Heli-Coils' cost is 2 X SS.

The N60 Heli-Coil block was retested with SS screws in the place of the SP screws, which is a more likely configuration for LIGO. See Figure 3 for the particles generated. The SS screws appear to generate slightly more particles than the SP screws.

10 Stainless Steel blocks with tapped holes (see Figure 5):

Five N60 screws and five SP screws were used in testing each of the 12 stainless steel blocks, except as noted below. Testing methods were as described above. Problems with tape removal from Tap #10 block destroyed the particle generation data for holes 2 – 8, but the results for holes 10 – 20 are representative for this block.

Tap #2 and #3 blocks generated large particles with both screw materials. Tap #6 and #13 blocks generated large particles with N60 screws, surprisingly. For the rest of the Tap blocks, SP screws appeared to do as well or better than N60 screws in minimizing generated particles. The current LIGO standard of using SP screws in 0.005" oversize tapped holes in stainless steel appeared best of all (Tap #15 and #16 blocks).

As with the aluminum formed threads from Tap #13, a "W" shape appears at each thread crest (see Figure 6), except that the crest edges appear rolled over. This tends to trap some of the generated particles.

As with the aluminum blocks, the #15 Re-tap stainless block appeared to produce slightly more particles than the Tap #15 block, surprisingly.

The effects of tap wear in the first 20 holes tapped do not appear to cause a significant difference in size or quantity of particles generated.

5. RECOMMENDATIONS

Aluminum in-vacuum parts:

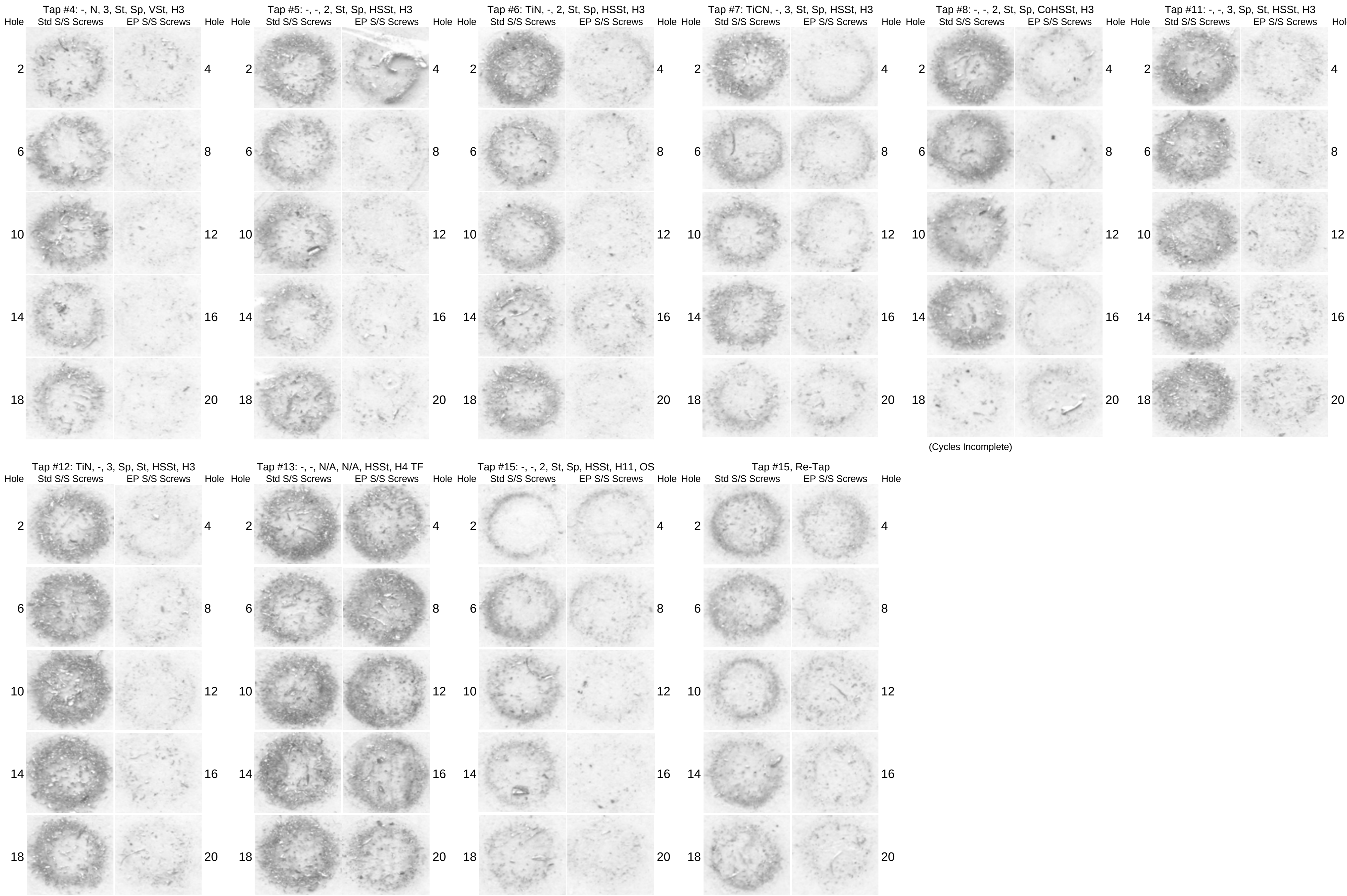
LIGO aluminum in-vacuum parts that are expected to be disassembled (such as clamps for securing optical table components) should use SS screws in N60 thread inserts for the tapped holes, to reduce the amount of generated particles and to reduce the risk of galling. Note that this will minimize, but not eliminate, generated particles and that protection of the optical surfaces is still necessary. The current LIGO practice of using SS screws in 0.005” oversize tapped aluminum should give satisfactory, efficient performance for the rest of the tapped aluminum parts.

Stainless Steel in-vacuum parts:

The current LIGO practice of using SP screws in 0.005” oversize tapped stainless should give satisfactory, efficient performance for tapped stainless steel parts.

Figure 1: Typical tap block; odd-numbered tap sequence holes (sectioned, for examination) are across the bottom, from left to right, 1 through 19. Even-numbered tapped holes are across the top, 2 through 20. Only the even-numbered holes were tested.

Figure 2: Particles From Inserting Fasteners In 1/4-20 Holes Tapped In 6061-T6 Aluminum



Format for tap specifics: Coating, Treatment, No. Flutes, Type Flutes, Type Point, Material, Pitch Oversize, Note

Coating:
TiN = Titanium Nitride
TiCN = Titanium Carbonitride

Treatment:
Cr pl = Chrome Plated
N = Nitride
O/N = Oxide over Nitride

Type Flutes:
Sp = Spiral
St = Straight

Type Point:
Sp = Spiral
St = Straight

Material:
CoHSSt = Cobalt High Strength Steel
Co&VSt = Cobalt & Vanadium Steel
HSSt = High Strength Steel
VSt = Vanadium Steel

Pitch Oversize:
H3 = + 0.0010" to + 0.0015"
H4 = + 0.0015" to + 0.0020"
H11 = + 0.0050" to + 0.0055"

Notes:
OS = Oversize Pitch diameter
TF = Thread Forming

Figure 3: Section through Tap #13 in aluminum, showing “W” form of thread crests caused by thread forming tap.

Figure 4: Particles From Inserting Fasteners In Heli-Coil Inserts In 6061-T6 Aluminum

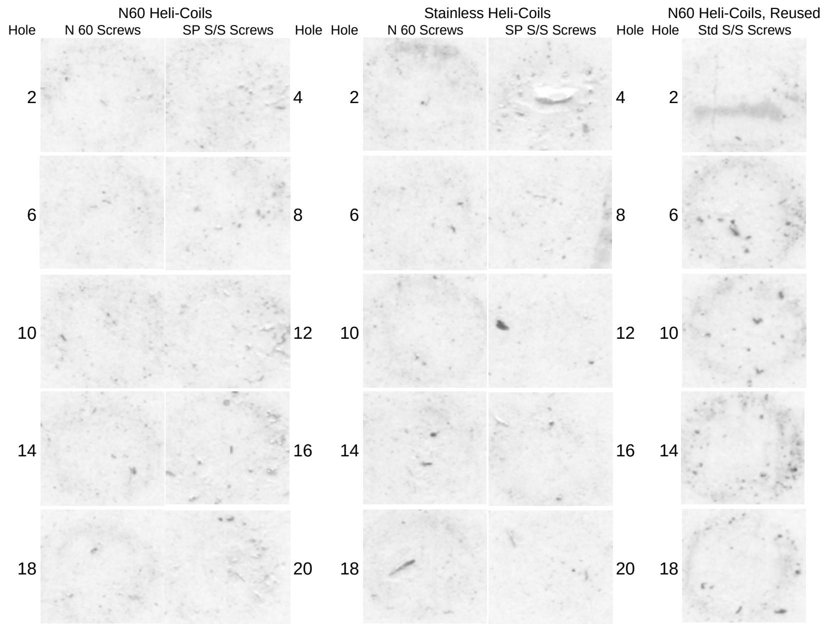
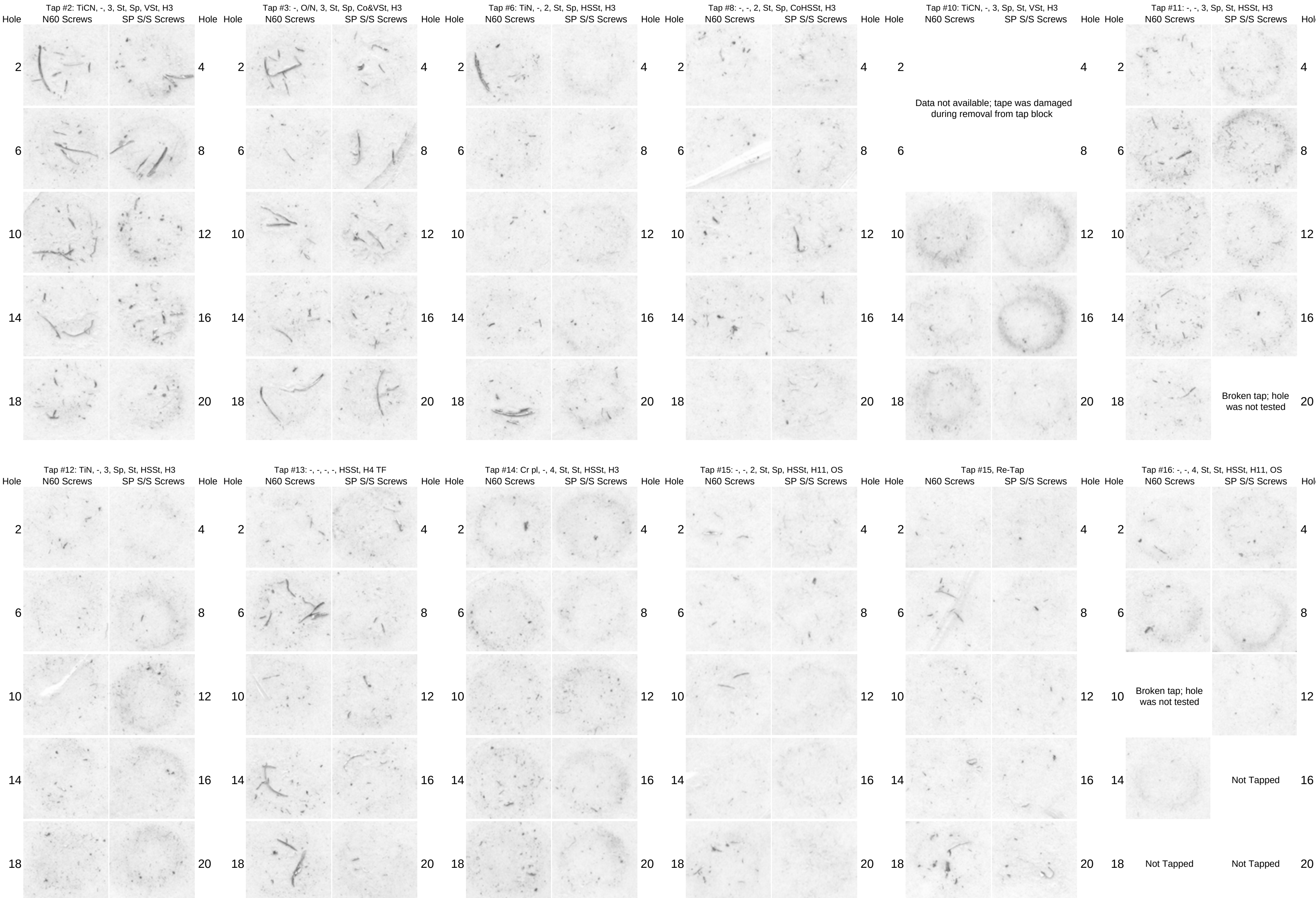


Figure 5: Particles From Inserting Fasteners In 1/4-20 Holes Tapped In Type 304 Stainless Steel



Format for tap specifics: Coating, Treatment, No. Flutes, Type Flutes, Type Point, Material, Pitch Oversize, Note

Coating:	Treatment:	Type Flutes:	Type Point:	Material:	Pitch Oversize:	Notes:
TiN = Titanium Nitride	Cr pl = Chrome Plated	Sp = Spiral	Sp = Spiral	CoHSSt = Cobalt High Strength Steel	H3 = + 0.0010" to + 0.0015"	OS = Oversize Pitch diameter
TiCN = Titanium Carbonitride	N = Nitride	St = Straight	St = Straight	Co&VSt = Cobalt & Vanadium Steel	H4 = + 0.0015" to + 0.0020"	TF = Thread Forming
	O/N = Oxide over Nitride			HSSt = High Strength Steel	H11 = + 0.0050" to + 0.0055"	
				VSt = Vanadium Steel		

Figure 6: Section through Tap #13 in stainless steel, showing rolled-over “W” form of thread crests caused by thread forming tap.