Failure Analysis Investigation:

Drill Failure in the Body Section of Gundrills

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ABSTRACT

The following failure analysis investigation (FAI) was conducted to determine the cause of failure, from a metallurgical and mechanics standpoint, in a series of gundrills. It was found that they all failed in a similar manner and that the failure was directly related to fatigue crack propagation, which started in the base of the swaged flute. Once the crack propagated, the loading under excessive drilling procedures caused the drill to fail in a catastrophic and brittle nature. The report also includes some insight into the possibility of replacing the 4130 steel used currently, with 4140 steel.

BACKGROUND

The particular failed pieces of interest are high-speed gundrills. In general, gundrills are the most cost-effective means of producing a high quality and precision hole over many cycles in a relatively short length of time. This is achieved through the use of a cemented carbide tip, machined to tight tolerances, which is then attached to a steel body and shank. Furthermore, there is a hole running along the entire length of the drill to allow for a flow of coolant/lubrication to aid in the cutting process and extend tool life, as well as force the chips out of the hole being drilled. The range of materials that can be drilled with a product of this type is broad. Companies have purchased them to drill plastic with compressed air being injected through the inner diameter, but the most common use is in the automotive industry where they are used to drill holes in steel or Aluminum with oil or a water-soluble based coolant being the injected fluid of choice.

Manufacturing Steps

In order to understand how these drills are made, and to have a better idea of where possible failure could occur, the general steps in manufacturing them will be covered under the following format:

Step #) machining step (*shape altering material used in machining step*)

Steel Shank

1) Cut off solid cylinder to length (*abrasive disc*)
2) Contour turn the inner recess with lathe (*carbide cutter*)
3) Chamfer front and back side with lathe (*carbide cutter*)
   Note: Steps 1-3 can be done in one step with a CNC lathe (*carbide cutters*)
4) Gundrill inner diameter (ID) with single flute gun drill (*carbide-tipped gundrill*)
5) Mill flat on inner recess (*carbide cutter*)
6) Centerless grind the outside diameter (OD) (*stone wheel*)
7) Lap (center) the back side ID (*carbide cutter*)

Typical tolerances for the above steps (where applicable): 0.001 to 0.005 inches

Steel Body

1) Cut off round tubing to length (*abrasive disc*)
2) Centerless grind the OD on one end to match the shank ID (*stone wheel*)
3) Swaging process to form inner flute (*tool steel inserts*)
4) Buff to remove residual marks from step 3 (*porous rubber wheel*)
5) Drill hole in end opposite of centerlessed end (*standard tool steel twist drill*)
6) Heat treated in batches (12 min. when T = 1600°F) and oil quenched (2-3 min. at 130°F ± 10°F)
   NOTE: From a dewpoint scale, carbon potential is 1.00 in the furnace
7) Flame tempered (1040°F) under tension forces by pulling a flame source along body at a rate of approximately 5” per second
8) Female V-grinded on end opposite of centerlessed end (*stone wheel*)

Typical tolerances for the above steps (where applicable): No steel imperfections, Proper hardness, design specifications, etc.

Cemented Carbide Tip

1) Cut off to length (*diamond disc*)
2) Male V-grinded on proper end with relation to cutting face (*diamond cup wheel*)
3) Chamfered (centered) on end opposite of V-grind (*diamond cup wheel*)
4) Cylindrically grind the OD (*diamond cylindrical wheel*)
5) Surface grind the cutting face (*diamond cup wheel*)
6) Cylindrically grind a wear land using a cam (*diamond cylindrical wheel*)
7) Various surface grinding steps to form the sharpened point (*various diamond wheels*)

Typical tolerances for the above steps (where applicable): 0.0001 to 0.001 inches

Now that the individual steps to each component of the gundrill have been discussed, the points at which they are joined will be covered. The shank and body are joined after step 5 of the shank and step 7 of the body. They are heated by an induction coil and joined with braze. The body and tip are joined after step 8 of the body and step 3 of the tip. They are heated with an oxyacetylene torch and joined with braze also.

On a side note, it should be noted that after the three pieces have been joined to form the unfinished assembled product, there is a cleaning step. The cleaning step, which was omitted from the overall steps for relevance, consists of using a wire wheel and sandblaster to remove brazing residue and to enhance the overall visual appearance of the tool. There is also a couple of straightening steps, which are done by hand, that have been omitted for relevance, but are important nonetheless and deserve at least a mention.

Metallurgical Tubing Data

The next area of background development includes data obtained from the tubing mill that supplied the steel tubing to be used for the body of the gundrills.

Size, Shape of Tubing:	#5F,6F	OD: 0.373”	Wall: 0.046”
	#7,8,9,10	OD: 0.436”	Wall: 0.054”

Drills 5F,6F

4130 Seamless Mechanical (ASTM A-519-94)
Eddy current tested to conform with ASTM A-450
Cold drawn seamless
Soft Annealed (Final HT was at 1380°F)
Gundrill quality

Physical Tests:
Yield = 35050 psi (0.2% offset)
Tensile = 62880 psi
Elongation in 2” = 41%
R/B = 66

Chemical Analysis

C	Mn	P	S	Si	Al	Cr	Mo	Ni	Cu	V	Ti	Sn
.300	.490	.014	.004	.230	.039	.990	.230	.050	.080	.004	.003	.003

Drills 7,8,9,10

4130 Seamless Mechanical (ASTM A-519)
Eddy current tested to conform to ASTM A-450
Soft Annealed (Final HT was at 1380°F)

Physical Tests: Yield = 40465 psi (0.2% offset)
Tensile = 75039 psi
Elongation in 2" = 37%
R/B = 84

Chemical Analysis

C	Mn	P	S	Si	Al	Cr	Mo	Ni	Pb	Cu	V	Ti	Sn
.28	.58	.01	.003	.24	.031	.86	.17	.12	.005	.18	.001	.01	.011

Dates the tubing was received from the tubing mill:

#5F,6F – 4/1/98

#7,8,9,10 – 2/28/95

Failure Environment During Operation

Although specific data such as spindle speed, the length of the tools lifespan, etc. are not known, some general data can be stated about the failure environment during operation. The drills were being used to drill 319 Aluminum at an approximate rate of 40+ inches per minute with a 40% water-soluble coolant.

Summation of Important Background Points

From the above background data, the following points should be restated, as they are important points to consider while reading the following failure analysis. All of the drill bodies examined were fabricated from 4130 steel and heat treated and tempered in the manner discussed in steps 6 and 7 of the steel body section of the manufacturing steps. Furthermore, the joining steps of tip to body to shank should also be taken into account. And lastly, the rate of drilling should be considered from the failure environment section.

INVETSIGATION PROCEDURES

Preliminary Examination

Macroscopic Examination (Visual Inspection)

The lot of gundrills was visually inspected. Precautions were taken as to not disturb the fractures and/or fracture surfaces. Photographs were taken via a digital camera to show the failed gundrills in their “as received” states. In the photographs, scaling was accomplished by the use of a ruler or a quarter. The photographs of each gundrill fracture were titled for identification purposes. The fractures were inspected for visual signs of microcracking, corrosion, etc.

Nondestructive Testing (NDT)

Dye Penetrant Testing:

Dye penetrant testing is performed to identify surface defects in nonporous materials. Our samples are made of 4130 steel; hence they are not porous materials. Therefore, dye penetrant testing provided valid information regarding the surface of our material. The surfaces of the gundrills were coated with a penetrant that had fluorescent dye in suspension, which was drawn into the surface by way of capillary action. The excess penetrant was cleaned from the surface, and the gundrills were dusted with developer. Using an ultraviolet light, the samples were examined. The cracks were far more defined when examined in this manner.

The dye penetrant testing was performed with the hypothesis that there might be an excessive amount of microcracking surrounding the failures. This proved not to be the case. Overall, the dye penetrant testing did not give rise to new information; however, it did aid in ruling out some mechanisms for fracture.

Hardness Testing:

The hardness of a material is defined as its resistance to permanent penetration by a harder material. Hardness values have a direct correlation to many material properties such as tensile strength, heat treatment, machining, etc. Therefore, the hardness values of a specimen are important in a failure analysis investigation.

Vickers microhardness tests were performed on a few samples to determine if there was a hardness gradient between the inner and outer wall of the flutes. These microhardness tests were then converted to a Rockwell scale for broader clarity.

Metallographic Sectioning and Preparation

The first step in metallography is the preparation of specimens that will be examined using microscopic techniques. Two drills were chosen to perform our metallographic and microscopic examinations. These two drills were sample 5F and sample 8. The drills were then sectioned at numerous regions of the drill. They both contained sections near the drill tip, near the failure, and remote from the failure. In each section, both a longitudinal and transverse cross-section was taken. The sectioned pieces from drills 5F and 8 were mounted using a Bakelite mounting medium so the microstructures could be revealed. The samples were mounted using a compressive mount that was molded with heat and pressure. The mounting of the specimens allowed for easier handling, while still allowing grinding, polishing, etching, and microscopic examination via an optical microscope or a SEM.

Optical Microscopy

The transverse and longitudinal samples that were mounted were prepared for examination with an optical microscope. The samples were first ground down using a belt sander to eliminate any uneven surfaces or macroscopic scratches. Next, the samples were ground using sandpaper from 100 to 600 grit. They were finally polished with an alumina suspension, where the last polishing used 0.05 micron particles. The samples were chemically etched using a 3% nital solution. They were then viewed under optical microscopes to examine the microstructure.

Scanning Electron Microscopy

Observations that were made with the SEM proved to be some of the most valuable in our failure investigation. The personal SEM that we used was very simple to operate and required very little sample preparation. The SEM yielded fairly good resolution, yet a far greater depth of field than the optical microscope. A SEM utilizes back-scattered electrons, secondary electrons, and x-rays to produce a video image of the specimen topography at a very high magnification. These electrons and x-rays are produced from an incident electron beam that is shot directly at the specimen. The SEM was helpful in confirming the chemical makeup of the samples as well. This is capable due to the distinct energy released by different elements within the material.

Macroscopic pictures were taken of the fracture with the SEM. The crack tip from one end of each of the two failures was also taken. To get a better look at the fracture surfaces, the drill bodies were clamped in a vise and twisted with a pair of vise grips to reveal the inner crack surface. These samples were viewed with the SEM as well.

RESULTS

Macroscopic

Figure 1 is a macroscopic picture of drills 7,8,9 and 10. It was noted by preliminary examination that all of the failures occurred approximately 18-20 cm from the shank end of the drills. Some of the features that were noted macroscopically were as follows:

#5F - Torsional crack propagation is near deformation from straightening step(s).
#6F – Some longitudinal crack propagation after torsional crack propagation.
#7 - Crack in flute is very prevalent with brittle type failure around one body loop.
#8 - Crack appeared to propagate along flute.
#9 - Crack appeared to propagate along flute.
#10 - Crack appeared to propagate along flute.

In addition, all of the samples appeared to exemplify macroscopic brittle failure. Figure 2 is a macroscopic picture of drill 7, and more specifically, the fracture site.

SEM Images

Two samples were chosen for examination to exemplify the lot of failures. The two samples chosen for evaluation were samples 5F and 8. Figures 3A and 3B are the crack profiles taken at 10X, at the bottom of the flute, of samples 5F and 8 respectively. The bottom of the flute is the presumed location of crack initiation. The sites are missing some portions of the base material presumably due to in-service post-initiation chatter. After the crack initiates, the drill is still in service and hence under increasing vibration as the crack propagates to total failure. Figures 4A and 4B are the 10/11X SEM images of the fracture surface after separation. Of special interest in these pictures are the rib-like repeated pattern on the fracture surface. Figures 5A and 5B are the 30/50X images of the rib-like structures found on the fracture surfaces of Figures 4A and 4B. As can be seen here, the fractures were brittle in nature as evidenced by the clean shiny breaks. The rib-like structure also indicates a longitudinal cyclic loading which is probably due to post initiation mass fatigue in the longitudinal direction. The mass fatigue is caused by the in-service post-initiation chatter discussed before, as the crack propagates longitudinally and along the flute bottom. Also important to note on these figures are the small beach marks on both samples. These indicate fatigue failure initiated at the inner radius of the drill wall propagating to the outer radius. Figures 6A and 6B are the 100/76X SEM images of the crack tip profile.

Optical Micrographs

Figures 7A and 7B are the micrographs of sample 5F at 200X, in the longitudinal/transverse directions, near the drill tip, using a nital etch. This revealed that the microstructure was completely martensitic with small carbides dispersed in it. This indicates that the flame tempering did not have a large impact on the microstructure at the tip of the drill. This is proven by comparing it to the figures 8A and 8B which are micrographs that were taken remote to the fracture near the shank end of the drills. The microstructure was not any different at the crack tip region, as indicated by figures 9A and 9B. Figures 10A and 10B are polished, unetched micrographs at 100X, of the crack tips of samples 6F and 10, respectively. These show that the crack tips on both samples are sharp which is another indication of brittle failure. Figures 11A and 11B are micrographs of the transverse cross-sections of samples 5F and 8 respectively at the bottom of the flute, remote to the fracture location. As can be seen from these images, cracks are present at the bottom of the flute region. These microcracks are all possible macrocrack initiation sites.

Hardness Data

Figures 12 and 14 are the Vickers microhardness values taken transversely through the wall thickness of samples 5F and 8 respectively. Figures 13 and 15 are the corresponding Rockwell C hardness values. The data in raw form is found in tables 1 and 2. As can be seen from the data and figures, there is no correlation between depth and hardness.

Blueprints

Figures 16 and 17 are the schematics and specifications for both drill types examined.

Hardenability

Finally, figures 18 and 19 are the hardenability charts for both 4130 and 4140 steel [2]. These will be used in the discussion section.

DISCUSSION

Cold Working

The high-speed gun drills that are the subject of this investigation went through a cold working or swaging process, which was listed in the background information, to form the flute region of the drill. During this swaging process, small cracks were initiated in the base of the flute. The cold working also produced a stress riser at the base of the flute in the form of a sharp point. This stress riser helped to propagate the original microcracks, during the use of the drill, which could be found along the entire length of the flute region. The microcracking can be seen in figures 11A and 11B, which were taken with the aid of an optical microscope. In order to help alleviate this inherent problem, a possible action to take would be to make the radius of curvature in the flute larger, so the stress concentration at the base of the flute would be lowered. Also, lowering the strain rate at which the flute is made would minimize these initial microcracks and their detrimental effects to fatigue life.

Fatigue

The first factor that might be involved in premature fatigue failure of the gundrill is the mean stress level [1]. If the drill is operated at a speed that is too high for what the design intended, the probability that failure due to fatigue will happen is amplified. In the background information it was noted that the drills failed while drilling 319 Al at a rate of 40+” per minute using a 40% water-soluble coolant. The speed rating that the company that produces the drills recommended for 319 Al is 16.0-16.8” per minute. The drills failed at a cutting speed that was over twice the recommended rate.

The second factor that could influence the fatigue life of the drills could be related to surface effects [1]. The first group of surface effects is related to the design of the drill. As stated earlier, the radius of curvature of the flute along the drill body could be increased to reduce the stress riser. If there were no microcracks present or concentrated stress areas to promote cracking, the fatigue life of the drill would be increased.

The second surface treatment that could increase fatigue life would be a slight case hardening. With carbon introduced into the surface of the drill, compressive stresses could be induced, so that any cracking from the swaging step would be suppressed following the heat treatment. The case hardening would also strengthen the drill at the same time. Due to the process involved in heat treating the tubing, there will be an inherent, but slight case hardening effect. It was decided that increasing this effect could be beneficial. The time that the drills were carburized was investigated to see if any benefit could be gained by leaving them in the furnace for a longer period of time. The following procedure was used:

The constants that were used are:

Diffusing Species: C
Host Metal: γ-Fe
Furnace Temp: 1144 K or 1600°F
D_o = 2.3E10^{-5} m^2/sec.
Q_d = 148 kJ/mol or 1.53 eV/atom
R = 8.31 J/mol*K or 8.62E10^{-5} eV/atom

The following procedure was used to calculate D:

$D = D_o \exp(-Q_d/RT)$

$D = (2.3E10^{-5}\ m^2/sec.) \exp(-(148000\ J/mol)/((8.31\ J/mol*K)*(1144K))$

$D(1600°F) = 4E10^{-12}\ m^2/sec. = 6.2E10^{-9}\ in^2/sec.$

Finally, the average carbon diffusion distance, X, could be found:

$X = (Dt)^{0.5}$

X(12 min.) = 0.0021”

X(15 min.) = 0.0024”

X(20 min.) = 0.0027”

As can be seen by the above calculations, longer time in the furnace would not produce results that would be beneficial to the drill, in the form of residual compressive stresses on the surface. By increasing the time from 12 to 20 minutes, the average diffusing distance increased by only 0.0006”. Increasing the carbon potential is not a feasible solution either, due to the fact that if the carbon potential in the furnace exceeds approximately 1.0, then pro-eutectoid carbides could result. In this case, pro-eutectoid carbides would be detrimental, as they would produce points for cracking to initiate. The only other variable that could possibly be altered is temperature. By ASTM standards the recommended furnace temperature range for 4130 steels is 1500 to1600°F. The temperature that the drills were austenitized at was 1600°F. Since it was postulated that carburizing to a further extent might be a beneficial possibility, all of the variables to increase the carbon content have been explored. Based on these results, carburizing to get further penetration or concentration is no longer recommended due to an inability to yield promising data.

Another factor that could increase the fatigue life of the drill is related to the hardenability of the steel that is used. By increasing the hardenability, the hardness will also increase slightly from a 4130 to a 4140 steel, causing the strength of the steel to increase. As a general statement, which can be applied in this particular scenario, an increase in strength will correspond to a longer fatigue life. Although the SAE/AISI 4130 steel that is currently being used is quite hardenable, a slight increase in carbon could both increase the strength and hardenability, and thus increase the fatigue life. The steel that we investigated was SAE/AISI 4140. As can be seen in figures 18 and 19, the Jominey end quench test data shows that 4140 steel is significantly more hardenable. At 1/16” from the quenched end, the 4130 produced an average hardness of HRC 52.5, while the 4140 reached an average hardness of HRC 56.5. Two inches from the quenched end, the maximum hardness of the 4130 was 29 HRC (the minimum hardness fell off of the HRC scale). The 4140 yielded an average hardness of 37 HRC, two inches from the quenched end. The recommended austenitizing temperature for 4140 steel is 1550°F, which would fit right in with the process that is already being used. SAE/AISI 4140 steel is a promising alternative that can be considered to allow for increasing the fatigue life of the gun drills.

CONCLUSIONS

It has been concluded that the failure of these drills begins at the swaging process used to form the flute, which introduces small cracks at the base of the radius. Once the drills were put into service, the initial cracks were propagated in a cyclic manner due to excessive mean stress levels during operation and the fact that a stress riser exists from the geometric discontinuity in the drill body. The fatigue crack propagated along the flute until it reached a critical level, where the drill body then failed catastrophically and in a brittle manner, since there was an unsupported load at the flute base.

RECOMMENDATIONS

The first series of recommendations deals with the swaging process used to form the flute. By increasing the radius of curvature produced in the flute, the geometric stress raising ability of this shape could be reduced. Also, assuming that the customer using this drill will not slow drilling rates or change the drill design, problematic drills should be swaged at a slower rate. More specifically, by decreasing the strain rate during deformation, the material will be less prone to producing the initial cracks at the flute base, lowering the likelihood of crack initiation points. This is somewhat viable to the present operation, as it simply requires only a little more time with specific drills that are likely failure candidates.

The second recommendation is to consider the possibility of switching from the present 4130 steel to 4140 steel. As stated in the discussion, 4140 steel is more hardneable and would be of higher strength than that of 4130 steel. This increase in strength would increase the fatigue resistance of the steel as well. It should be noted though, that increasing the carbon level will have these desirable properties that were mentioned, but it will also result in less formable steel [2]. Various test runs would have to be conducted to see if 4140 steel is 100% compatible with current operations.

APPENDIX 1: FIGURES

APPENDIX 2: TABLES

APPENDIX 3: REFERENCES

1) Callister, WD, “Materials Science and Engineering: An Introduction”, 4th edition, John Wiley and Sons, New York, 1997, Pg. 216-219

2) “ASM Metals Handbook”, 10th edition, Volume 1, “Properties and Selection: Irons, Steels, and High performance Alloys”, 1990, Pg. 430-432, 510, 513