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Technical Resources

AGMA Technical Paper

Reverse Engineering

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

As Americas manufacturing base has contracted the need for reverse engineering has grown. Well established suppliers have disappeared, often leaving customers with no source of spare parts or technical support. Over time certain pieces of equipment require changes to output speeds or power levels and new parts have to be designed, built, and installed. And unfortunately, some pieces of equipment don't measure up to the demands they are subjected to and need redesign or improvement. In many ways, reverse engineering is just as demanding a discipline as original product development with many of the same challenges but plus the additional restrictions of fitting inside of an existing envelope.

The typical reverse engineering project begins with very limited information on the existing piece of equipment. This paper will describe a methodology for the reliable measurement, evaluation, re-design, and manufacture of replacement parts for gearboxes and industrial machinery. A step-by-step example will be provided.

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Reverse Engineering

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Reverse engineering is a necessary activity in the modern industrial world. Rather than mount a defense against those who label it "copying", the author would prefer to point out the long and honored history of the practice of studying a competitor's product and using the knowledge gained to improve your own products. The largest, most well funded industrial organizations in the world spend millions of dollars each year on "competitive analysis", despite what their intellectual property attorneys might want you to think. The entire automotive aftermarket sector exists because of reverse engineering. Where would car restorers be without reverse engineering?

As America's manufacturing base has contracted, the need for reverse engineering has grown. Well established suppliers have disappeared, often leaving customers with no source of spare parts or technical support. Over time, certain pieces of equipment require changes to output speeds or power levels and new parts have to be designed, built, and installed. Unfortunately, some pieces of equipment don't measure up to the demands they are subjected to and need redesign or improvement. In many ways, reverse engineering is just as demanding a discipline as original product development with many of the same challenges, plus the additional restrictions of fitting inside of an existing envelope.

As engineers, we have an obligation to behave in an ethical manner and to respect the intellectual property rights of others. It is recommended that any questions on possible infringement or conflict be discussed with your legal advisors before proceeding.

Reverse engineering process

The typical reverse engineering project begins with very limited information on the existing piece of equipment. Whether the need is a critical component for your own "down machine", or a customer with a broken gizmo in the back of his truck, people expect an engineer to develop a solution in a very short time. See Figure 1.

What is the part from?

If you know what the part is from, you can simplify your decision making later. Knowing what it is from helps you determine if replacement parts might be available from someone, somewhere. If parts are available you can often scrub the entire reverse engineering activity or get by with a temporary spare while the "good parts" are in transit. If parts aren't available you can concentrate your efforts on making the best parts possible with a clear conscience.

Another benefit of knowing where the parts are from, is the insight it provides on the machine designer's original intent and limitations. For example, a European or Asian machine will most certainly be "metric." An older American machine will almost certainly be "customary units". As you'll see from our example, machines from the United Kingdom may be either system. The vintage of the machine will also tell you much about the materials and technology involved in its design; this is a big help in deciding the level of reverse engineering needed.

Why did it break?

There is little sense in making spare parts in a hurry if you are just going to break something else in the machine as soon as it starts up. Think "shear pins" – one can easily make stronger shear pins for an outboard motor propeller. The problem is you get stuck far from shore with an impossible to repair lower unit failure.

If the part "just wore out" you may want to ask why before making spares. Was preventive maintenance or lubrication lacking? Are related parts also in need of adjustment or replacement? Once a machine is down you might as well fix it right; the next failure might not be so easy to access.

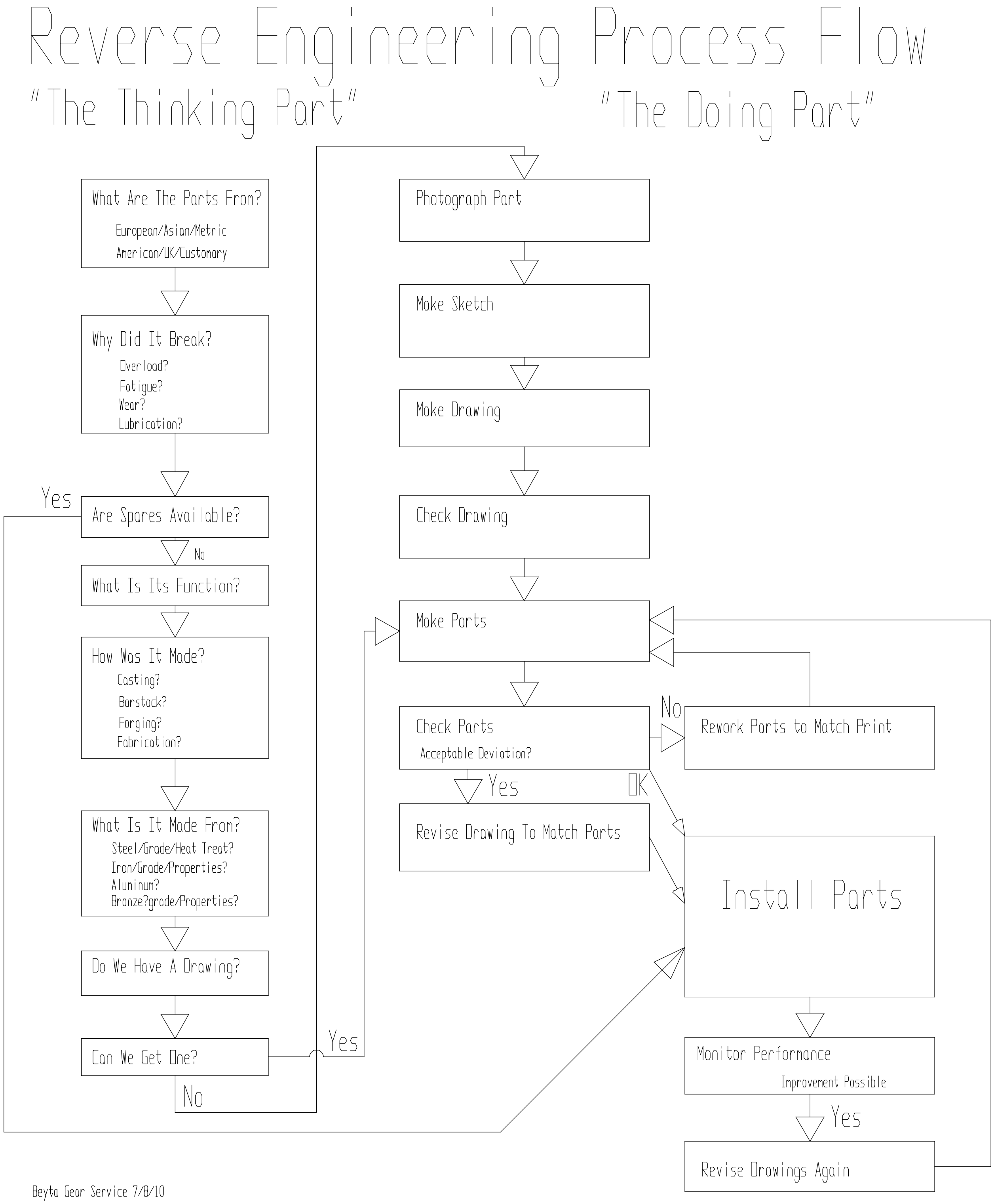

Figure 1. Reverse engineering flow chart

What does it do?

The function of a part may affect how you make the replacement – or if you even want to try. Use extreme caution in reverse engineering parts that could injure people if they break or malfunction. Unless you know the function of a part, you can't properly understand the loads imposed on it. If you don't know the loads you can't intelligently select materials, processes, or tolerances for the replacement part.

How was it made?

Complex castings are not easy to replace or repair. There is a temptation to ignore this step of the reverse engineering process and simply make fabricated or billet replacements. Careful examination of the "how" of the old part can provide valuable information. More than one "casting" has turned out to be an assembly upon close examination. Complex timing relationships between part features can also be missed if the original manufacturing method is not determined.

What is it made of?

"Cast iron", "aluminum", "bronze", and "steel" are not sufficient descriptions from which to make replacement parts. Informed decisions require more than these generic material classifications. It is particularly important to understand the original designer's reasoning in selecting the material if a change in material type is planned. Was aluminum used because it was inexpensive at the time, or because the rotating inertia had to be minimized? Was cast iron specified for cost savings, or to achieve a beneficial difference in material in a rotary joint? Was the part surface hardened, through hardened, or not hardened at all? (If you do not have access to hardness testing equipment, check an edge of the part with a file. Soft materials will file easily, through hardened less easily, and surface hardened ones with great difficulty or not at all. In a pinch sandpaper will substitute for a file.) Was a sacrificial coating applied, and if so, for what reason? Failure to investigate the material selection may result in a very expensive problem in the future.

Do we have a part drawing or a sketch in the service manual?

The more broken the part, the more difficult it is to reverse engineer from the artifact. A machine builder may be willing to share a drawing if they are unable to furnish a part. It seldom hurts to ask. In the absence of a detailed part drawing, it is very helpful to have an exploded parts drawing or assembly cross section view. If you know what bearings, seals, snap rings, fasteners, or mating parts interface with the failed item it is much easier to make a new drawing. Each interface you "know" provides a wealth of information about the sizes, tolerances, fit, and finish needed.

Make the drawing

Cleanliness is critical

If you have to make a new detail drawing, start by getting the part as clean as you can. Dirty parts make for grimy sketches, inaccurate measurements, missed features, and undiscovered defects.

Safety first

Don't rush yourself into a first aid situation. Take extra precautions if the part has sharp edges, weighs more than a few pounds, or cannot be set into a secure, stable position. Make certain the work area is well lit, free of slip or trip hazards, and away from lift truck traffic before attempting to measure it.

Photograph everything

There is no substitute for clear digital photos of the part from every angle. What you think you saw may not be so a few days later when everyone has had a good night's sleep and the part is no longer in the same condition. Photos make an excellent substitute for hand drawn sketches if you neatly mark the measurements directly on the printouts.

Measure everything several times and write it down

Poor penmanship, typographical errors, and transportation have derailed many rush repair projects. The best defense is writing things down promptly and having several people make their own measurements. Thoroughly cleaning the part (as advocated earlier) really helps here.

For parts with gears or splines, count the teeth carefully (several times), and write the results on the part with a marker or paint stick. Measure the outside diameter carefully; if the number of teeth is odd or the part is missing some teeth, even a partial measurement is better than none. Whenever possible try to measure the center distance and get a count of the mating teeth. Take a span measurement over different numbers of teeth or measure the size over pins or wires. It is great if you have the "right" measuring pins or the "correct" number of teeth to span but any data is better than none. Measurements over different size wires or pins can help determine the pressure angle needed. Tooth gages are handy tools to have if you anticipate doing a lot of reverse engineering.

Bevel and worm gears should be replaced as sets. If you replace just one member don't expect a long service life.

Most gears and splines are made with standard tools to standard or slightly modified dimensions. If your measurements say otherwise, you would be well served to have someone else confirm the dimensions. Even "custom" gear sets can be replaced with more standard geometry if you carefully think things through.

Always remember that you are measuring a worn or failed part. Particularly when standard components like bearings, seals, snap rings, keys, and locknuts are used, it is more likely that "standard" dimensions will apply.

Make a proper drawing or sketch; then check the artifact to it

If there is one crucial step most commonly skipped, it is this one. Here is one final chance to catch that 0.025" error in reading a micrometer or that 1" error on the overall length. If at all possible have someone not involved in the original measuring and sketching check the parts. If discrepancies are discovered at this stage, cheerfully repeat the steps above and be thankful you didn't waste time and material making a piece of scrap.

Carefully consider "upgrades"

Just because you can "upgrade" the replacement part doesn't mean you should. Keep that shear pin analogy in mind. If it lasted 50 years without heat treatment it probably will again. If, however, it failed because of lack of strength or surface hardness go ahead and make it "better",

Making the spare part

Stay involved with the project while the spare part is being made. Double check any purchased components. Be available to answer questions or to supervise assembly and installation.

Document the "as built" condition before closing the book on the project

Double check the finished part against your final drawing to make sure the drawing reflects what was actually made. When spares are made in a hurry other people may have decided to skip steps, alter sizes, or modify features without informing you. Your drawing may have been wrong or a tolerance may have been too tight to hold. If you don't check the part you won't know what caused the second "failure" or you may make another set of spares at a later date that won't fit or work as well.

Example problem

Vintage motor racing has become very popular around the world. An unfortunate consequence of actually operating the cars is the failure of components for which spares are not available. Inability to race the vehicle greatly affects the market value. In the case of our example car, a 1991 Bennetton Formula 1 car, a static display car, see Figure 2, is worth $250,000 while a running car could bring over $1,000,000, see Figure 3. High level race cars are very expensive to operate and are very maintenance intensive. In actual competition, over 100 man hours are spent in the shop for every hour on the track. Top level F1 teams spend $100,000,000 per car per season and have hundreds of highly skilled employees.

Figure 2. Static display Bennetton Formula 1 car

Figure 3. Vintage racing Bennetton Formula 1 car

Rapidly changing technology, operational secrecy, and highly stressed parts makes it very difficult to obtain spares once the race cars are retired from competition. This is particularly true in Formula 1 where even the very top teams may only have a handful of cars. Contrast this to NASCAR where a typical team has several dozen cars at the shop for each one brought to the track. Until recently Formula 1 rules discouraged sharing components between teams so many unique parts are involved. Drawings are very difficult to obtain.

The owner of our example car was fortunate to obtain many spare parts but was down to his last set of trans axle oil pump gears, see Figure 4. The trans axle case is cast magnesium and any assembly or disassembly requires heating the entire case to 300° F degrees in an oven. While it would be possible to retrofit the car with a separate electric oil pump, such a change would detract from the authenticity and resale value, see Figure 5. The least damaged set of gears was provided for measurement along with the parts upon which they mounted. Following the procedure outlined above, preliminary part drawings were made by the author.

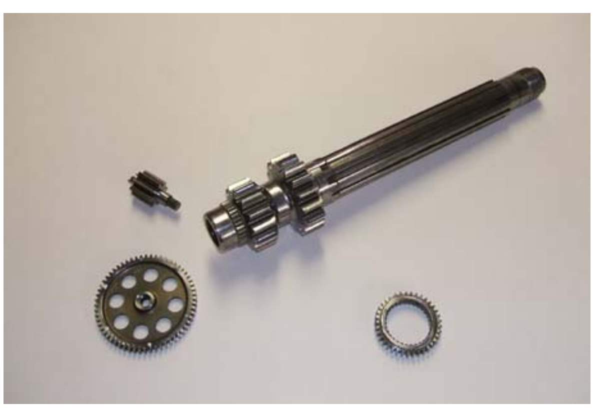

Figure 4. Oil pump drive components

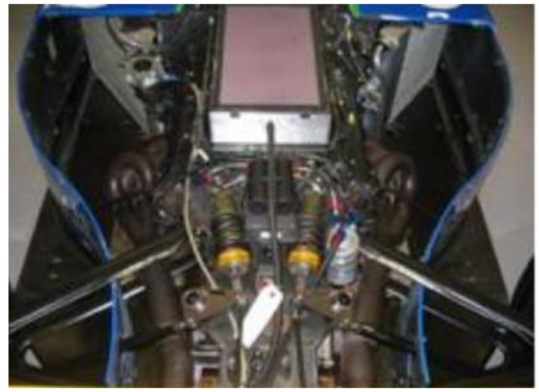

Figure 5. Assembled trans axle

The parts and the drawings were then delivered to the gear supplier for further review. The shop chosen for this project has been reverse engineering rare parts for many years, including a complete transmission set for a Duesenberg and a spiral bevel set for a 1980 Ferrari Formula 1 car. The shop checked the parts against the reverse engineered drawing and found several errors. After revision, an order was placed for (5) sets of oil pump gears. The parts are small and making a larger quantity spread the set-up costs while allowing the car owner to recoup some of his expenses by selling two sets to another Bennetton enthusiast. See Figure 6 and Figure 7.

Fortunately, these parts used standard inch series hobs and splines. This saved the time and expense of obtaining custom gear cutting tools. Had special tools been required, the owner would have faced a painful decision on just how authentic he could afford to be. These parts are very deep in the trans axle and would never be seen by anyone other than the mechanic rebuilding the assembly. The center distance is adjustable during the assembly process so had a slight change been required to use standard tools it would not have affected the function. The original gears were carburized and hardened as are the replacements. We elected to make them of AISI 9310 steel and vacuum carburize them to reduce distortion.

The car is currently running the new gears and will be participating in vintage racing events around the country throughout the year.

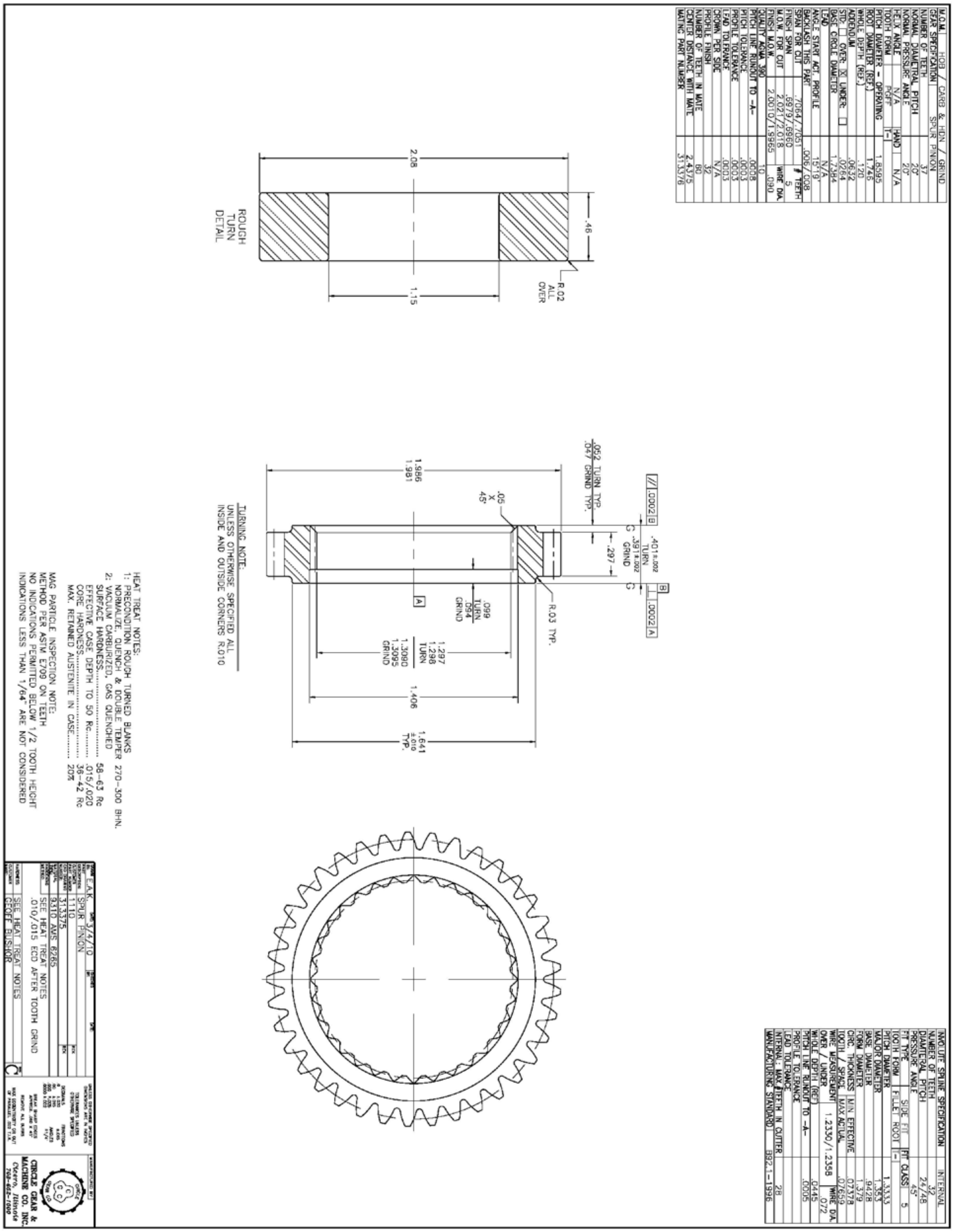

Figure 6. Component drawing

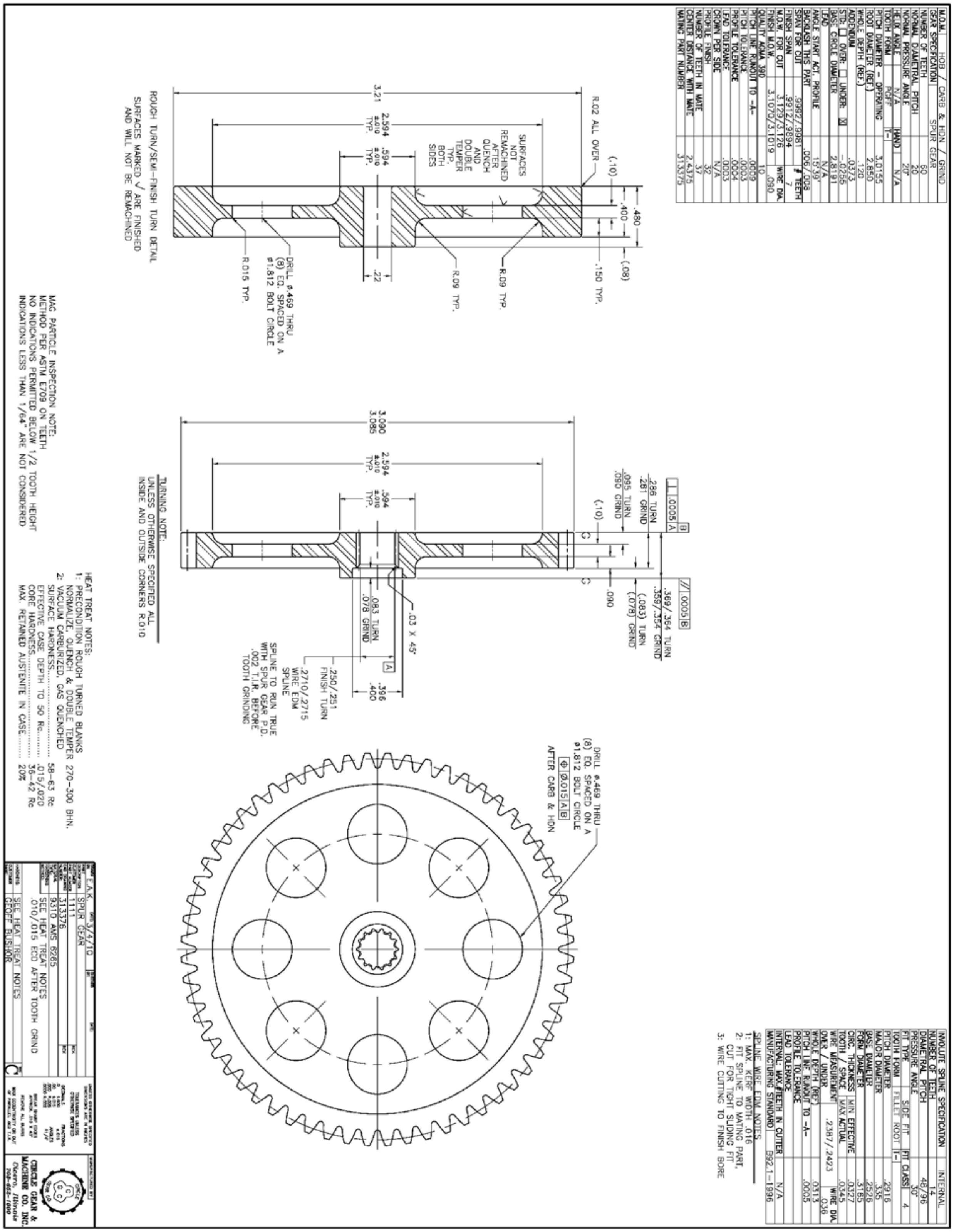

Figure 7. Component drawing