Girth Gears — More than Just Metal and Teeth

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Introduction

The clear majority of published knowledge about gear manufacturing relates to two main subjects; material quality and tooth accuracy. In most cases, the mechanical accuracy of the gear blank is taken for granted and, after all, preparing a gear blank normally consists of applying basic machine shop skills taught in high school level vocational technical courses. However, large multi-segmented girth gears do not behave like the relatively compact, rigid, monolithic structures we typically envision when discussing gear manufacturing. Girth gears are very large non-rigid structures that require special care during the machining of individual mating segments as well as the assembled gear blank itself.

It is well known that a gear blank's mounting surfaces must possess certain measures of geometric accuracy, and that the gear's pitch cylinder must bear certain geometric relationships to those mounting surfaces. Moreover, the finest construction materials and the most precise tooth geometry have limited bearing on realized life when these geometric cardinal rules are not upheld. Indeed, the American girth gear rating standard — ANSI/AGMA 6014-B15 — disclaims validity when the required geometric relationships are not achieved. However, what is required to achieve those assumed geometric quality levels in a girth gear may not be so intuitive to the manufacturer or to the purchaser. The following sections will describe common girth gear design features, the normal sequential steps in the manufacturing process, some typical challenges encountered along the way, and the downstream effects of failing to manage those challenges.

Girth Gear Applications

Girth gears fall into two basic categories; flange mounted and tangential spring mounted.

Flange-mounted girth gears, the more common of the two, are most frequently utilized in "cold" processing equipment such as SAG (semi autogenous grinding) mills and ball mills for use in the mining and cement industries. By current standards, girth gears can be as large as 14 meters (46 feet) in diameter, 1.1 meters (44 inches) face width, and 50 module (.5 DP) tooth size, and weighing upwards of 120 tons. Flange mounted gears rely, in large part, on the mill structure to provide the stiffness and geometric stability required for successful operation.

Spring-mounted girth gears, on the other hand, are typically utilized to drive (hot) rotary pyro equipment such as kilns and dryers. For these applications, a securely bolted flange mount is not a viable option when the temperature of the driven machine is typically hundreds of degrees hotter than the surrounding gear that drives it.

The following discussion will focus on flange mounted girth gears since these applications represent, by far, the larger population.

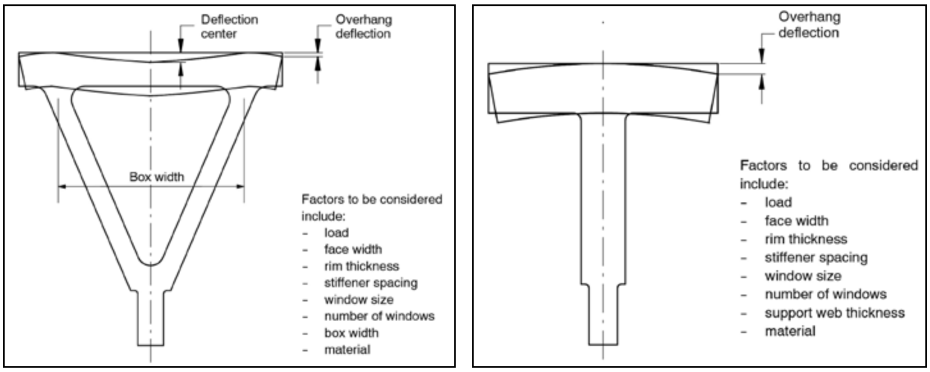


Figure 1 The two basic structural designs for girth gears, consisting of Y-Section (left) and T-Section (right) structures (AGMA). (Drawing from Annex C of ANSI/AGMA 6014-B15; printed with permission of the American Gear Manufacturers Association.

Structural Designs

There are two basic structural designs for girth gears, consisting of Y-Section and T-Section structures (Fig. 1). The Y-Section design is reserved, almost exclusively, for cast steel and, to a lesser extent, for ductile iron. The T-Section is widely utilized in steel and ductile iron castings due to its simplicity and reduced weight. The T-Section is utilized almost exclusively for fabricated girth gears of welded construction. The Y-Section design, when viewed as an independent structure, possesses greater torsional stiffness than the T-Section. However, both designs have many decades of proven reliability and this discussion does not state or imply any preference for either structural design.

Girth gears up to 7.5 meters (24 feet) diameter are typically manufactured in two segments. Beyond this size (Fig. 2), most designs will utilize from four to six segments — depending on the foundry's liquid metal pouring capacity or the largest forging that's available for a weldment. Smaller individual segments also make it easier to adjust for the inherent geometric inaccuracies of raw castings and weldments alike. Splits at the joints are located in the tooth roots and unequal length segments will occur when the number of teeth is not wholly divisible by the number of segments.

Tooth Alignment

The most common girth gears are helical designs due to cost advantage. Spur gears are second in popularity, with double helical designs running a distant third due to their inherent complexity and higher cost of manufacturing. Double helical and spur gear designs may be necessary if the mill bearings cannot absorb the thrust force from single helical designs.

Joint Designs

The most highly stressed region of any girth gear structure is located nearest the joints, where the mating segments are connected. The joint design must pro-

Figure 2 Girth gears exceeding 24 feet typically require up to six segments.

vide accurate and repeatable alignment of mating segments, sound tangential buttressing of adjacent teeth across the splits, as well as fixed, creep-free connections during operation.

Some helical girth gear designs utilize joint contact surfaces that run transverse to the gear rim face, and not aligned with the helix angle. This design has generally fallen out of favor because it results in an overhanging "tongue," where the teeth falling directly over the splits lack sound radial and tangential support.

Joint Hardware

Joint designs are thru-bolt connections with threaded fasteners consisting of studs with nuts on both ends. Depending on the designer's preference, the same joint can be designed with more fasteners of smaller diameter, or fewer fasteners of larger diameter. Joint closure is typically accomplished by one of two methods; 1) thru controlled tightening of "superbolt"-type hardware, or 2) with slugging wrenches and sledge hammers. Although the latter method is still employed, it has been largely abandoned due to the importance of reliable and repeatable joint closing forces.

Joint Alignment Function

The alignment of mating segments is typically accomplished by one of three methods. The more popular designs employ either fitted studs or tapered studs with split tapered sleeves. Third in popularity is the transverse "dog bone" that is centered on, and runs parallel to, the split surface. Each of the three designs has its own peculiar strengths and weaknesses, but each design can effectively accomplish its intended purpose when accurately produced.

Geometric Tolerances

The ultimate goal is to provide an installed accuracy that effectively supports the design service factors. In order for this to be realized, the gear's mounting surfaces must be manufactured to more strict tolerances than those applied during installation. Installed runouts can be adjusted, to a limited degree, thru the use of radial jack bolts and axial shims. These adjustment features are utilized to compensate for normal stack-up of conforming geometric errors on the multi-component grinding mill assembly; they are not intended to make up for a gear blank that was either improperly toleranced or incorrectly machined.

There are three basic sets of geometric tolerances with which to be concerned. The first set is those tolerances that apply to the various manufacturing processes; the ones that define the accuracy and geometric relationships between the datum surfaces, the mounting surfaces, and the finished pitch cylinder. The second set, equally important, are those that specify the gear's installed accuracy in terms of radial and axial runouts intended to place the pitch cylinder in proper relationship with the driven machine's rotational axis.

The above two sets of geometric tolerances are normally specified by the gear design engineer since both have direct effect on design service factors and life expectancy. The third set of tolerances, much less known or understood, is intended to make the first two sets entirely possible. They are the internal manufacturing tolerances applied to secondary features such as machining datums, machine tool setups, process control checks, intermediate verifications, etc. These tolerances, when they are formally defined, would typically appear on the shop routing or on the machine tool setup sheet. Unfortunately, even with the current state of standardization and centralized process control, these internal tolerances frequently reside only in the machinist's "Black Book." We will soon see that the importance of these tolerances cannot be overlooked.

Layout of Raw Segments

Whether working with castings or weldments, the individual raw gear segments must receive a full layout prior to machining. This operation is intended to balance the built-in machining allowance on all machined surfaces, to establish primary machining datums for radial and axial features, to determine whether sufficient machining allowance exists on all surfaces, and to ensure that minimum design wall thicknesses are maintained throughout. In the raw state at layout, it is usually possible to compensate for the more normal and minor geometric deviations that occur without compromising the strength and/or stiffness of the structure. On the other hand, minimum design values for gear rim thickness and joint flange thickness should never be compromised, and these features are difficult to fix when they do not conform to design requirements.

Machine Tool Setups

Girth gears operate in the horizontal axis of rotation, firmly affixed to the rotating cylinder on which they are mounted. However, due to their mass and dimension, they are machined with the rotational axis set vertically. As a result, machine tool setups for individual segments, as well as for the assembled gear, must minimize the effects of externally applied forces, including gravity. For a typical one-piece gear, this would simply mean making sure that the rough component is supported properly and is not distorted by clamping forces. In our case, the girth gear and its individual segments are categorized as non-rigid components. By virtue of their size, weight, and proportions, this inherent structural flexibility is profoundly affected by gravitational force. Following this further, it is not difficult to imagine a girth gear that was not in a relaxed state during manufacturing, and then takes on a different geometric shape when its rotational axis is turned 90 degrees at installation.

The larger the structure, the more sensitive it is to external forces applied by both gravity and the workholding devices. The machine tool setup for each operation must take into account the real potential for geometric deformation from all external forces. Unfortunately, the effects of improper setups and inadequate process controls frequently manifest themselves in the late stages of manufacturing or, even worse, during installation and operation.

Correcting a modest out-of-round condition during installation is generally a simple task, but axial errors are an entirely different matter. During installation it is entirely possible to find a gear rim edge that looks like a lock washer, or a potato chip, or a wave washer, or a combination of these conditions. All of these conditions create installed wobble which translates into drunken lead and wandering contact. It is normally a straightforward task to correct a simple single sine wave condition by shimming axially under the mounting flange. However, attempting to correct one of the more complex, errant geometric shapes will generally produce high levels of frustration and limited improvement at best. This is due to the combined effects of a gear structure that possesses inherently low torsional stiffness and a gear rim whose axial stiffness far surpasses that of the mounting flange.

Let us say we are trying to correct a potato chip (double sine wave) condition during installation on the mill. The mounting flange can be shimmed to make it go almost anywhere you want it to go, but the response at the gear rim edge will be only small a fraction of the shim thickness inserted at the mounting flange. More radical shimming typically does little to improve the installed runout or the wandering contact pattern that it produces. Continue adding shims and the runout signature will change into something entirely different but also unacceptable. It's like a mechanical whack-a-mole game, you can push the bubbles around but you cannot meet the installed tolerance.

These types of built-in mechanical errors cannot be repaired in the field, and the cost of portable cranes, labor, transportation, rework, penalties, and lost revenue can add up to a spoiled annual report. Getting machine tool setups right in the first place requires sound planning and adequate time for execution, and the value of proper process controls and in-process checks cannot be overstated.

Machining of Datum Surfaces

The first machining operation for the raw gear segment is to cut the gear rim edge datum surface, making it a flat and reliable reference surface for subsequent operations. The rough gear segment must be landed on a sufficient number of carefully located support points to minimize the structure's natural tendency to elastically deform under its own weight, and to ensure equal weight distribution across all support points. Furthermore, the locations of, and the forces applied by, workholding devices must be planned and monitored to avoid unwanted elastic deformation. These goals can be achieved in various ways, some more scientific than others, but the results of any such process are measureable and must be verified by reliable means before proceeding to the next machining operation. In-process verification must be carried out with the gear segment properly supported, in the unclamped condition, and in a totally relaxed state.

Machining of Joint Flange Faces

For the majority of today's girth gears, and for the purposes of this discussion, the machined joint face angle is the same as the designed helix angle. This discussion therefore applies equally to spur and helical gears. And it is at this point that the expected gear rim thickness and final joint flange thickness are established. As noted earlier, joint regions and the joints themselves are the most frequent areas of structural failure. Assuming the structural design is adequate to begin with, conformance of the machined joint details cannot be over emphasized. Two factors are in play when joint surfaces are established, listed in order of priority as follows; 1) location relative to the gear rim inside diameter at mid-segment, and 2) final joint flange thickness. Said another way, joint flange thickness may finish up oversize, in order to preserve rim thickness, but it may never be allowed to go undersize. Oversize joint thickness only means that fastener hole spotfaces must go extra deep to maintain proper thread engagement.

Joint face machining will require the same precautions for setup accuracy, uniform weight distribution, and unstressed workholding techniques as previously described. Following the setup, the aim is to produce individual segments with joint faces that are flat, and with helix angles and subtended angles made complementary to their mating segments; all with a high degree of precision. Ideally, when the mating faces of joining segments are brought together, they should be capable of making intimate contact over their entire mating surface area without the need for external closing forces. As a practical matter, this "ideal" state of intimate contact is very difficult to achieve, but rest assured that the degree of angular complementarity of the mating faces will directly affect stresses in the assembly and the geometric accuracy of the gear during installation and in operation.

Joint face machining is accomplished by one of two basic techniques. The first technique employs a large diameter face milling cutter that is accurately inclined on the helix angle or mounting the split joint at the helix angle perpendicular to the face of the cutter. The cutter is then fed horizontally across the joint face for the number of passes required to machine the entire surface area. For each successive milling pass, the cutter is moved inward the amount needed to produce a flat angular surface with no steps at the lines of overlap with previous cutter pass. Poor mechanical alignment of the machine tool, or a face mill body that is insufficiently rigid, can cause multiple hollow spots, or wavy profiles, across the finish milled surface. A joint face that is not sufficiently flat will not seat tightly with its mate, and the tangential tooth buttress effect across the splits will be diminished. The second technique employs a large diameter ball end mill that is fed horizontally across the joint face. The cutter is repositioned in the Z-Axis, according to the helix angle, for each successive milling pass; the spacing of which is selected based upon the cutter's ability to produce a sufficiently flat surface with the given tool nose radius. Although joint face flatness is usually not a problem with this technique, mechanical error and backlash in the machine tool's individual axes of movement, or poor synchronization of the machine's interpolating axes can create errors in both the helix and subtended angles.

There is an alternate philosophy that says the actual sum of the machined subtended angles should be something less than 360 degrees. When joining segments with joints of this type for assembly, their mating faces will first make contact at the tooth root and exhibit a progressively widening gap moving inward toward the mounting flange. This produces a significant gap at the innermost point of interface. The underlying philosophy being that the interference angles provide enhanced joint tightness in the tooth root. However, the fastener preload expended in forcing the interference angles together reduces the clamp load under each fastener, at the joint interface, and causes the assembly to take on an unnatural geometric shape. It also causes alignment holes to assume a dogleg configuration at the interface, making the insertion of alignment hardware an unpleasant mechanical process.

In all cases, the designer should employ a technique known as "joint relief." This consists of relieving the rudimentary portion of the joint surface that resides inboard of the inner most joint hardware holes. This area serves no practical purpose with respect to joint integrity. It should therefore be milled below the working joint surface in order to prevent any potential problems it could otherwise create if left on the same plane.

Joint Alignment and Hardware

The joint hardware serves two purposes — to provide precision radial and axial alignment of segments during assembly, and to make the multi-piece assembly act as a monolithic structure during operation. There are normally two precision fasteners that provide alignment at each joint, with the balance of fasteners providing closing force only. Deep section gears may require a third alignment hole to reduce twist of the split. Joint hardware holes are machined parallel to the gear rim edge which, for a helical gear, means that they are not machined normal to the helix angle.

Alignment holes are very accurately placed and spaced, both radially and axially, as defined on the manufacturing drawing. They must also be precisely positioned relative to the axial datum surface on the gear rim edge. This latter requirement does not normally appear on the manufacturing drawing, but this absence does not mean that it can or should be ignored. If the positions of the otherwise properly spaced alignment hole patterns are not all machined on the same plane, the assembled gear may try to assume the appearance of a lockwasher or some other stepped configuration. This type of built-in error makes it impossible to assemble the gear in a relaxed state, and challenges the manufacturer's ability to provide a support system for subsequent operations that does not add further stress to an already unhappy structure.

Gear Blank Assembly

With all segments having flat datum surfaces, complementary joint face angles, and alignment hole patterns on the same plane and properly spaced, the gear segments should be ready for assembly. The first step is to prepare a proper assembly surface, the flatness of which should relate to the flatness tolerance specified for the gear rim edge and/or mounting flange face. A large machine tool table frequently serves this purpose, but there can be other options. For example, a very accurate and reliable setup surface can be established on the shop floor with carefully placed independent support blocks that are precisely adjusted onto the same plane throughout. The quantity, locations, and spacing of support points for the assembly operation are no less important than they were during the previously described machining operations. A common support should be utilized at each of the joint locations, straddling the split lines.

The individual segments are landed on the prepared assembly surface, one by one, and brought into initial contact with their mates. For a four segment gear, the first two mating quarter segments are brought together to make one half, with the same process applied to the second two segments, and the two assembled halves are finally brought together to make the full gear. Assuming the preceding machining operations were carried out with the necessary care, and once the hole patterns are brought into close visual alignment, the alignment hardware can be inserted with little resistance. With the mating faces making initial contact, and with no closing force applied, the split line gap is checked with feeler gauges to verify angular compatibility of the interface surfaces. Acceptance criteria of the maximum measured gap opening will depend on the gear diameter, facewidth, depth of section, and the designer's threshold of tolerance for inducement of unplanned stresses. In this case — and in the final analysis — basic mechanical knowhow goes a long way towards determining what is acceptable and what is not.

Joint hardware is tightened in planned sequence and at planned stages until the specified tightness has been reached throughout. Ideally the joint faces will make intimate contact over their entire joint surface area, but this is frequently not the case and is not an absolute necessity. For this reason joint tightness should be verified before proceeding with further processing. This test consists of trying to insert a feeler gauge with a maximum thickness of 0.0015" (0.038mm) around the entire perimeter of each assembled joint surface. The measured gap opening, the depth to which the opening extends, the location of the opening, and the area over which the discernible opening exists are the basic criteria utilized when evaluating an open joint condition. As in the previous case, there are no magical acceptance criteria. Basic mechanical knowhow and a good dose of common sense will assist the engineer in determining what is acceptable and what is not. A word of caution — the engineer should look critically at joint openings occurring in the tooth root. Depending on the length of the opening, the resulting loss of tangential buttress effect across the split can allow the first tooth on the trailing side to heel over under load and cause the pinion to find the second tooth early. This is a dynamic pitch error condition that can cause an audible "bump" during operation and, ultimately, can cause tooth failure — typically within the first two teeth on the trailing side.

Turning the Gear Blank

Most assembled girth gear blanks are finish machined on a vertical boring mill (VBM) and, for this reason, the following section pertains to the setup employed on that particular type of machine tool. Ideally, the gear blank will be setup such that all radial and axial features and dimensions can be finished in one setting. This ensures that all specified geometric relationships are produced to their best possible condition.

The first step is to prepare the work support system, the flatness of which should bear direct relationship to the flatness tolerance specified for the gear rim edge. The quantity, location, and spacing of support points utilized for turning the gear blank are no less important now than they were during the previously described machining and assembly operations. Passive restraint in both axial and radial directions is key during finish machining of girth gear blanks.

Clamps can be used during rough cutting operations, to ensure no movement of the piece during heavy cutting, but all finish cuts should be taken with clamps released and only gravity providing the downward restraining force. Chuck jaws may be used to center the piece radially, ensuring that minimum gear rim thickness is maintained throughout, and that all joint split lines are centered on their respective (yet to be cut) tooth roots. As a practical matter, split lines may reside anywhere below the design form diameter, which allows for ample radial adjustment in deference to gear rim thickness. Radial deformation of the gear blank must be avoided. All preload must be backed off during finish machining, while keeping the gear trapped to prevent any radial movement. Proper backing off of radial clamp force is most easily verified by monitoring structural relaxation via dial indicators placed next to each chuck jaw as they are being released. Finally, the gear blank must be restrained to resist any tendency to move tangentially, or circumferentially, due to the inertial changes in rotary motion during turning.

Lifting and Handling

Up to now, much focus has been placed on proper support and workholding to avoid elastic deformation during machining. Another real concern, frequently overlooked, is what happens to the assembled gear when it is lifted and transported between operations. During machining, we can add as many support points as we would like, but this is not the case with lifting. Girth gears are typically lifted by either two or four pick-up points depending on various factors; the more obvious of which being weight and diameter. Lifting tackle can consist of spreader bars, slings, chains, wire rope, or any combination thereof. Regardless of the number of pick-up points, the elastic deformation that takes place during a lift is breathtaking; it's like watching the piece unwrap itself from the floor. The biggest concern is the load that's placed on the joint hardware during a lift, loads that far exceed anything the gear will ever see in service. Putting this into perspective, it is not uncommon to find significant joint misalignment after lifting the finish machined gear blank off the vertical boring mill, and landing it on the gear cutting machine. This is caused by two factors working in tandem — 1) because the fasteners undergo temporary additional elongation during the higher lift loads, allowing the joints to open up due to lost clamp loads; and 2) because additional elongation of the alignment hardware causes necking of their alignment features and a temporarily sloppy fit. High helix angles, as well as the slippery nature of ductile iron, make these designs more susceptible to joint movement during lifting, while spur gears tend to be more stable. Regardless of the joint configuration and material, joint alignment should always be checked before tooth cutting, with the design engineer making technical disposition for any steps that are found.

Double Processing

Consideration for residual stresses plays a major role in the processing of segmented girth gears, significantly more so than with gears of one piece construction. Reason being, residual stresses in a typical one piece gear are rather homogenous and evenly distributed throughout the entire 360 degrees. On the other hand, it is usual for each girth gear segment to be poured from a different heat, to be heat treated individually, and then stress relieved in separate furnace loads. With no two segments having the same metallurgical properties and characteristics, one can imagine how multiple segments can react very differently, very independently, when large volumes of metal, measured in tons, are removed during machining. And due to sheer size and scale otherwise small deformations that occur during machining become major show stoppers when projected out over arc lengths approaching 70 feet (22 meters). The challenge now becomes one of ensuring that the finished gear segments, however many there are, will reassemble into a geometrically acceptable gear when installed on the machine it is intended to drive.

Thermal stress relief is an absolute necessity, as one might expect, but the net benefits of this process should not be overestimated. It is well known that residual stresses can be redistributed, even mitigated, but they cannot be eliminated. For example, in the case of a weldment, it is not uncommon for measured residual stress levels, after a satisfactory stress relief cycle, to be found at or near the material yield strength. This is clearly in excess of what it takes to cause significant geometric deformation during subsequent machining operations. Although multiple stress relief cycles are sometimes employed to achieve a more stable final condition, the effects of each thermal cycle are cumulative, which can cause further tempering and reduce hardness below acceptable levels.

One of the trickiest parts about manufacturing a girth gear is that tooth cutting releases and redistributes the inbuilt stresses that were both thermally and mechanically induced during the various preceding manufacturing processes. A simple way to envision the stress lines in a gear rim is to imagine them as existing like tree rings. A well-known axiom states that the last metal to cool following any thermal cycle will always reside in tension. And, with all forces seeking a natural state of equilibrium, it goes without saying that, conversely, the first metal to cool will always reside in compression. Following the tree rings of residual stress inward thru the gear rim, we pass from maximum compressive stress found at the outer and inner rim surfaces (addendum), to neutral stresses at both one-quarter and three-quarter thickness (pitch line), to maximum tensile stress at mid-thickness (dedendum). During tooth cutting, the compressive and neutral stress regions in the tooth volume are interrupted and nullified, while the compressive stress region opposite the tooth volume is still in compression, and there are no opposing forces remaining to balance the newly exposed tensile stress in the tooth root. The result being that each segment will open up (straighten out) to some certain extent when the gear is disassembled. Said a different way, when the gear is disassembled, the base pitch on each tooth space contracts slightly, which translates into an increased chord length for each gear segment. Given the number of teeth in play, the growth in chordal length can be dramatic; as much as ¾" (19 mm) over 180 degrees. The extent of actual dimensional change that takes place depends on numerous variables including gear diameter, depth of structure, number of teeth, gear material, rim thickness, and tooth depth relative to rim thickness.

The technique that is used to overcome these obstacles is called "double processing" which, as one might expect, consists of machining the entire gear twice. The joint features are semi-finished, the gear is assembled with non-precision process hardware, the assembled gear is then semi-finish turned and the teeth are rough cut. After this, the gear is disassembled, joint features are finish machined, the gear is reassembled with service hardware, finish turned, and the teeth are finally machined to design requirements. To validate the final result, an "open joint inspection" is performed with the gear in a properly supported, unrestrained, fully relaxed condition. Multiple dial indicators, placed in close proximity to one joint, are used to measure the relative movement across that joint while the fasteners are being released. As stated in previous sections, there are no magic acceptance criteria for this test either. Generally speaking, if the alignment hardware can be reinserted without the need for undue external forces, and providing that acceptable joint alignment and tightness are achieved after the fasteners are re-tightened to spec, the gear should be good to go. It should be noted that double processing is not necessary in all cases, and different manufacturers have their own formulae for determining whether double processing should be part of the initial manufacturing plan. However, whether or not the gear is double processed, an open joint inspection should be performed on every finished girth gear; the aim being to gain assurance that the gear can be reassembled and installed, in the field, within the published installed tolerances for radial and axial runout.

Tooth Cutting

If we have implemented the recommendations up to now, then we will have a good gear blank worthy of tooth cutting, and the foregoing concerns for proper support and clamping must carry on to the gear cutting machine. From the grinding mill's perspective the mounting flange is the critical datum, but the gear rim edge is no less important because 1) it is assumed to be parallel to the mounting flange, 2) it is assumed to be perpendicular to the pitch cylinder, and 3) because it is the reference surface for measuring axial runouts during installation.

If the axial and radial runouts were acceptable, while in a relaxed state on the vertical boring mill, then it is merely a case of duplicating those runouts, as close as possible, when setting up on the gear cutter. In any event, the installed runouts on the gear cutter should fall within the geometric tolerances specified on the manufacturing drawing, paying particular attention to the mounting flange to rim edge relationship. However, unlike the vertical boring mill operation, cutting forces encountered during tooth cutting will necessitate secure clamping for both rough cutting and finish cutting, and design runouts must be achieved with all supports and clamps fully tightened.

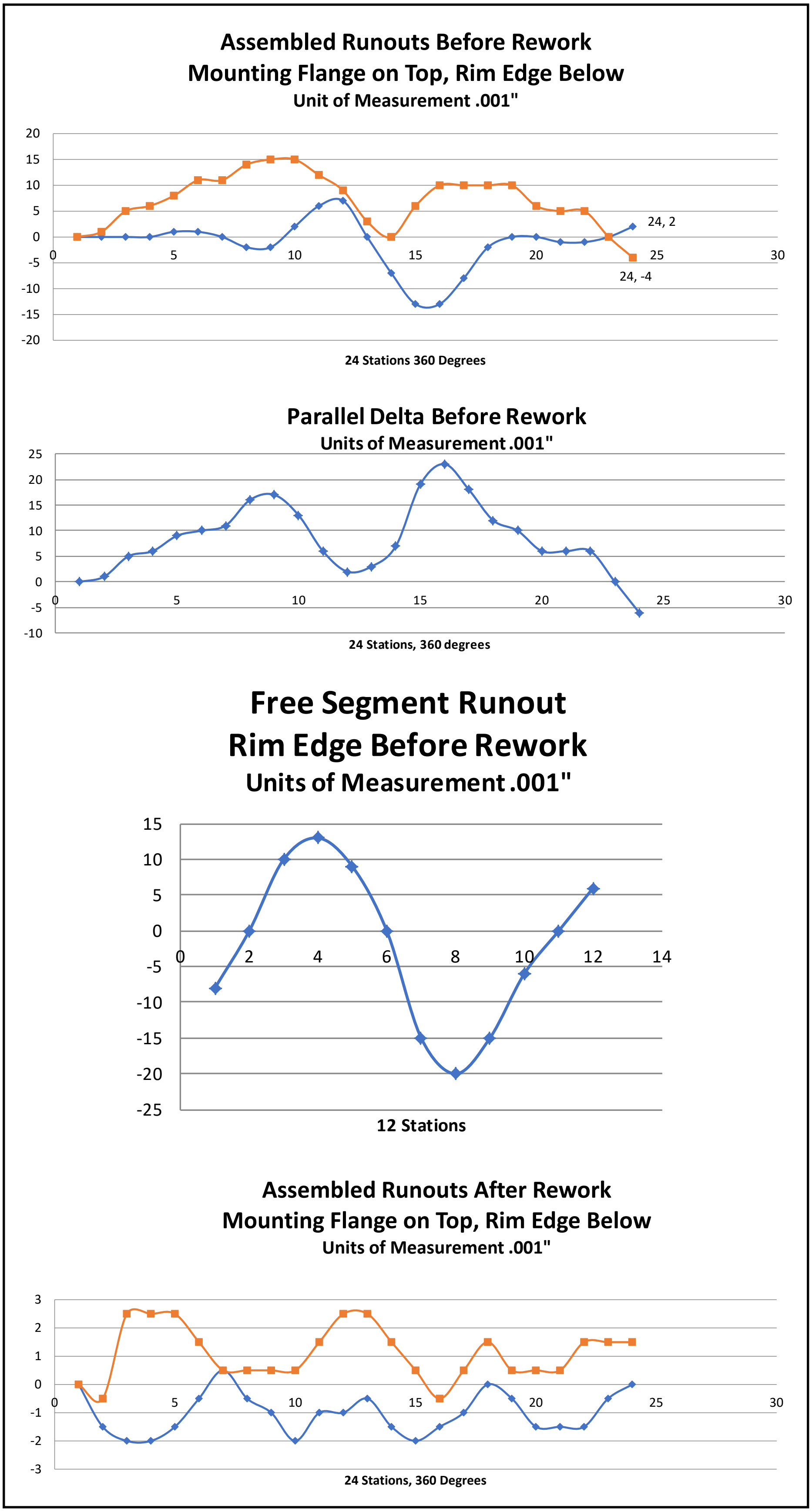
Modern Manufacturing Technology

The girth gear business is very competitive and manufacturers are embracing new technology out of sheer necessity. The machine tool, cutting tool, and supporting software industries are responding to this demand with entirely new designs and concepts, as well as the adaptation of existing non-gear-making technology to suit the gear making industry. Girth gears which, 20 years ago, might have required eight or more machining operations for completion, are being successfully machined today in nearly half as many setups. Although these refinements are intended to improve both efficiency and quality, the need for in-house expertise is no less important today than it has ever been in the past. In short, new technology makes manufacturing easier and quicker, but it does not guarantee good quality. Modern machine tools, cutting tools, and supporting software are no smarter than the people who purchase and utilize them. If the design engineer does not understand the application, or does not properly define the necessary requirements; if the manufacturing engineer lacks the necessary respect for mass, elasticity, and residual stresses; if assembly and setup equipment consists of slugging wrenches and large hammers; if the machine tool operator and the inspector do not respect the drawing callouts; then a good quality outcome is unlikely regardless of the technological state of art.

Case Study — Due Diligence Failure

The following facts and supporting data relate to a two-segment, ~20-foot (~6 meter) diameter girth gear. These are intended to illustrate the potential downstream effects of previously described failures of due diligence.

The gear in question was produced with incompatible joint angles. This angular incompatibility, caused by inadequate support and excessive workhold-


Assembled Runouts Before Rework
Mounting Flange on Top, Rim Edge Below
Unit of Measurement .001"

Parallel Delta Before Rework
Units of Measurement .001"

Free Segment Runout
Rim Edge Before Rework
Units of Measurement .001"

Assembled Runouts After Rework
Mounting Flange on Top, Rim Edge Below
Units of Measurement .001"

Figure 3 Axial runout measurements pursuant to investigation and rework. (Printed with permission of the American Gear Manufacturers Association).

ing force, exceeded .040" (1 mm) in the helix angles and the subtended angles of both joints.

The gear blank was then assembled into an unhappy, pre-stressed condition in preparation for turning. The workpiece support system and workholding forces applied during turning further complicated the gear blank's already prestressed condition. Runouts after turning were measured with the gear still in its clamped condition, making it impossible to detect the magnitude of the induced errors up to this point.

The finish turned gear blank was then mounted on the gear cutting machine, disregarding the geometric tolerances applied to the datum surfaces. And, finally, an open joint inspection was not performed after tooth cutting.

In addition, the gear did not undergo double processing, but the effects of this omission cannot be reasonably quantified due to the magnitude of the other errors that occurred along the way.

The following axial runout measurements (Fig. 3) were collected during the subsequent investigation and rework operations (Figs. 4–5). All measurements were taken with the gear properly supported and resting in a relaxed state of repose.

In order of presentation, the first chart depicts the mounting flange and rim edge runouts, and their interrelationship, as-manufactured. The second chart depicts the parallel delta between these two key features. The third chart illustrates the relaxed condition of one free segment, properly supported and completely unrestrained during measurement. The last chart depicts the mounting flange and rim edge runouts, and their interrelationship, following rework. In this final condition, the gear was installed well within the required installation tolerances and with minimal effort.

Summary

It is important to understand that excellent material quality and extreme tooth accuracy have limited value when the gear's pitch cylinder sees excessive wobble and cranking with each revolution. Girth gear structural designs are, out of necessity, a compromise in terms of stiffness of the discreet component. As a nonrigid structure, the girth gear relies on the driven machine to provide its structural backbone, and this reality presents unique challenges in manufacturing; a time during which this backbone does not exist.

The effects of gravity and clamping force, when not properly managed, can cause elastic deformation of dramatic proportions. Left unchecked, the described deformations will cause installed wobble of the pitch cylinder, wandering contact, and overloading in areas of short contact. Machine tool setups are of paramount importance in minimizing the effects of external forces on the girth gear's structure.

The presence of residual stresses is an important consideration, particularly since each gear segment possesses its own unique metallurgical characteristics. Although thermal stress relief offers a certain degree of stability, it does not preclude geometric deformation caused during machining, and particularly during tooth cutting. For this reason, special processing techniques are frequently employed to minimize the real effects of redistributed stresses.

Finally, the overall goal is to produce a girth gear that is geometrically correct when it is in a fully relaxed state (Fig. 6). A happy gear is one whose pitch cylinder and datum surfaces possess acceptable geometric features and relationships while resting in a fully relaxed state; it must reassemble and install accurately in the field, closely reproduce contact patterns observed in the workshop, and provide uniform load distribution during operation.

Figure 4 **Prepping girth gear segment for reworking.**

Figure 5 **Unassembled segments for 34' (10.5 meters) 4-piece girth gear.**

Figure 6 **Finished 40' (12 meter) 4-piece girth gear.**

Steve Lovell is a journeyman machinist, having learned his trade in Navy and civilian machine shops, with brief career excursions working as a foundryman and a welder. Following early years as a craftsman, he held various management positions at Ingersoll-Rand (Pump Group) and the Fuller Company (Minerals Processing), and most recently as director of quality for FLSmidth Minerals. Having worked with more than 30 suppliers of large open gearing on all six inhabited continents, he is an innovator, technical writer, mentor, and recipient of awards in technological leadership. Following retirement from full-time employment in 2010, Lovell remains active today as a consultant for organizations in and around the global mining and cement industries. *Stephen.lovell1@gmail.com*