Large Bevel Gears for Crushing Applications

Steve Lovell

Introduction

Large bevel gears drive the crushing machines used to process ores and minerals in the hard-rock mining and aggregates industries. Among the most common machines of this type are gyratory (Fig. 1) crushers and cone crushers (Fig. 2). The gyratory crusher is typically the first process step after initial blasting at the mine, or quarry, with the largest such machines capable of swallowing rocks as large as 72" (1.8 meters) and reducing them to fist-size product. Cone crushers normally see service in secondary and tertiary crushing applications where further size reduction is required. In each case, the gears for the large machines are now approaching 100" (2.5 meters) diameter. Both families of machines are considered quite mature, with only modest design evolution occurring in recent decades. However, during this same period, driven by the need for increased throughput, both speed and power ratings have increased significantly for the same basic machine designs. The challenge for the gear design and manufacturing people is to produce a gearset that performs reliably within the evolving operating conditions of the machines they drive. The following sections are intended to help the reader understand the unique aspects of these machines, and why crushing applications fall outside the traditional automotive paradigm for bevel gears.

Crusher Operating Principal

Both types of crushers consist of a tapered, conical crushing chamber that's created by a fixed conical housing that surrounds a gyrating conical mantle. With the mantle placed inside, and in close proximity to the housing, these two main components form a tapered crushing chamber having a maximum opening at the top — where the raw feed stock enters the machine — and with the tapered chamber opening gradually necking down as the feed stock is crushed and reduced in size. The crushed material progresses its way down thru the tapered crushing chamber by gravity feed, and is finally discharged out the bottom after the desired size reduction has been achieved.

Machine Motion

Crushing action results from the unique motion of the mantle as it gyrates about the machine's vertical centerline. It is perhaps simpler to envision the motion of the mantle as a rotating pendulum, i.e. fixed at the top and tracking a circular sweeping path at the bottom. The heart of the machine is the eccentric, which creates and transmits the gyrating motion to the mantle. The bore of the rotating eccentric is radially offset and inclined on the necessary angle to produce the desired pendulous motion during operation. The machine's main shaft fits into the bore of the rotating eccentric and, working together, these two components form the axis for the path of the gyrating mantle. Finally, drive power is transmitted by the bevel gear, which is firmly mounted to the eccentric wherein plain rotary motion is transformed into the gyrating motion.

Bearing Design

The vast body of knowledge about bevel gears has been built around experience with automotive-type applications including cars, trucks, agricultural equipment, and heavy off-road vehicles. These applications all utilize rolling element bearings to produce hard/fixed mounting points for the gearset. And in these more typical applications, the engineer must consider the anticipated deflection and elastic deformation of the various fixed and moving components of the drive system under load.

The unique part about crushing applications is that the gearset, in nearly all cases, is held in alignment with plain bronze bushings. And with most of these applications falling within boundary lubrication parameters, the resulting bearing clearances tend to be quite large. For example, a large gyratory crusher may have an eccentric bearing clearance exceeding .100" (2.5 mm), with the resulting floating centerline determining the operating centerline for the bevel gear. Now, imagine an automotive-type application, with an 8" (200 mm) ring gear that's mounted in sleeve bearings with .009" (0.23 mm) radial clearance, and consider where the contact pattern might want to go under intermittent load conditions. Making things more interesting, imagine a radial load on the ring gear carrier that, with each revolution, moves in an orbital path about the housing's fixed centerline by an amount equal to the total bearing clearance.

Therefore, in addition to the inherent separating forces and elastic deflections that always occur, crushing applications must also anticipate the effects of generous bearing clearances and a bevel gear that follows an orbital path relative to the fixed centerline of the pinion. Some machine designs serve to mitigate the extent of the gear's orbital path by offsetting the gear radially — off the eccentric's centerline — by an amount equal to the design bearing clearance. However, this compensating feature does not account for the inevitable bearing and shaft wear that naturally occurs, where the total bearing clearance can reach 150% of the design clearance between service intervals.

Material Combinations

For many years, both gears and pinions were made from thru-hardened materials. As throughput and power ratings increased, thru-hardened gears got harder and the pinions became carburized and hardened. Hard cutting of pinions came shortly thereafter, once the necessary tooling and skiving techniques could be developed. But carburizing and hard cutting of the gear component, having many more teeth, was deemed impractical due to period cutting tool technology and machine tool rigidity.

In more recent years, carburized and hard cut versions of the larger gears have become a viable option with the advent of larger cutting machines reaching the market, and particularly with the introduction of five-axis milling technology to the gear industry. However, distortion control during heat treatment continues to be a limiting factor due to the lack of quench presses capable of handling the very large pieces. For this reason, many of the larger crushers continue to utilize thru-hardened gears in conjunction with carburized and skived pinions.

Induction hardening of the large gear component has also been utilized to achieve surface hardening, with significantly less distortion than would be seen in a free-quenched, carburized gear. However, this requires specialized equipment for the inductor to perfectly track the spiral angle and radius of curvature in spiral tooth designs.

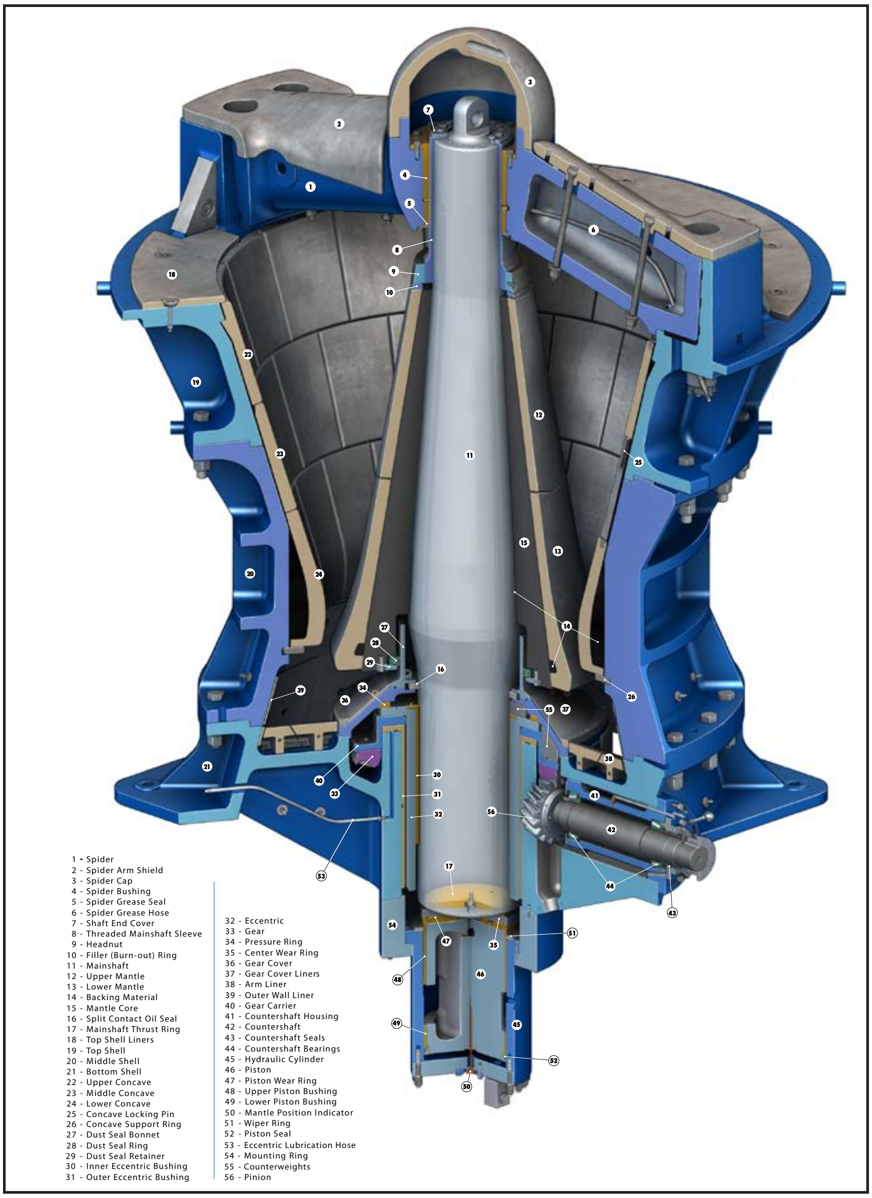

Figure 1 TS Gyratory Crusher. (Illustrations property of FLSmidth A/S, used with permission.)

Tooth Configurations

Following the chronological evolution of tooth configurations, the oldest crushers utilized straight bevel gears, and a considerable number of these machines remain in operation today. As throughput and power ratings increased, and along with increases hardness, the industry further responded with skew tooth designs. Numerous skew tooth cutting machines also remain in operation today — the "senior citizens" of the bevel gear shop — producing good quality components on busy production schedules. Spiral bevel gears appeared later and, until more recent years, only a few cutting machines were capable of producing spiral bevel gears in the larger sizes. This situation has been largely remedied with the introduction of high-precision 5-axis milling machines, along with the sophisticated software that supports them.

Design Considerations

The challenge for the engineer is to produce a design that will accommodate the wandering contact that naturally occurs in these soft bearing applications. This accommodation includes: 1) lowering traditional expectations for contact patch area relative to total available tooth flank area; 2) compensating for the reduced contact patch area thru the augmentation of other design attributes; 3) increasing static backlash and root clearance values to prevent hard mesh conditions as the gear follows its orbital path relative the pinion's fixed centerline and 4) applying a contact test method and acceptance criteria that provide satisfactory operation and life expectancy given the unique operating characteristics of these machines.

Testing

The contact testing technique for crushing applications needs to account for the wandering contact that naturally occurs as the gear's rotational axis, mounted in soft bearings, follows an orbital path with respect to the pinion's fixed centerline.

When utilizing a test machine with

both horizontal (H) and vertical (V) axes adjustment capability, the H and V axes are sequentially adjusted to mimic the orbital motion of the gear, and to simulate the resulting contact patch movement that naturally occurs during operation. This results in contact tests being performed at five different test machine settings as follows: 1) with the gear and pinion both set on basic centers; 2) with the pinion moved out (H-plus); 3) with the pinion moved in (H-minus); 4) with the pinion moved up (V-plus); and 5) with the pinion moved down (V-minus). In each of the five tests, the gear remains set on basic centers, with each pinion offset movement being equal to the uncompensated bearing clearance.

At each of the five test machine settings, the contact patch should be of an acceptable shape and size, and remain within the allowable window of movement; and, observing the prescribed standoff values (no-go zones) with respect to the tooth extremities. In addition, minimum backlash and root clearance values must be observed at each of the four test machine settings to ensure that adequate clearance exists and that hard mesh conditions will not occur during operation. With straight and skew tooth designs, contact patch movement and changes in backlash are greatest when test machine settings are adjusted in the V-plus and V-minus directions. With spiral tooth designs, contact patch movement and changes in backlash are greatest with test machine adjustments in the H-plus and H-minus directions.

When using a test machine with no vertical axis of adjustment (V-plus/minus), the gear is radially offset, relative to the test machine's horizontal axis of rotation, by an amount equal to the uncompensated bearing clearance. This arrangement produces radial runout of the gear, simulating its orbital path relative to the pinion's fixed centerline. Once the proper offset (radial runout) value has been accurately set, the gear tooth that best aligns with the maximum runout value is identified, as are the teeth that best align with the remaining three cardinal coordinates around the gear. Testing is then a straightforward proposition, with contact patch size and location being evaluated, along with backlash and root clearance values, at the four pre-marked tooth positions representing the four cardinal coordinates around the gear. And prior to this offsetting routine, the contact patch should first be evaluated with the gear runout set at zero, thereby producing the five test results described in the foregoing procedure for a test machine with both H and V axis adjustment.

With either of the above testing arrangements, an additional test can be performed with offset values set to represent operating conditions when bearing/shaft wear reach the point at which bearing replacement should occur. As a practical matter, the scope of such testing should be limited to evaluating the extent to which the contact patch intrudes on the tooth extremities, and whether backlash and root clearance values are diminished to dangerous levels at these extreme settings.

Design simulation programs can predict what happens to the contact patch and backlash as the gear moves around its orbital path. They can also aid in predicting what type of crowning and tooth thinning is required to achieve the desired results. However, these simulations provide only an informed starting point for the tooth cutting programs; actual results of software outputs should always be validated thru one of the above-described testing regimens. Fortunately, cutting programs produced directly from simulation software will typically allow adequate opportunity for further development and tweaking, once the initial contact test results are observed.

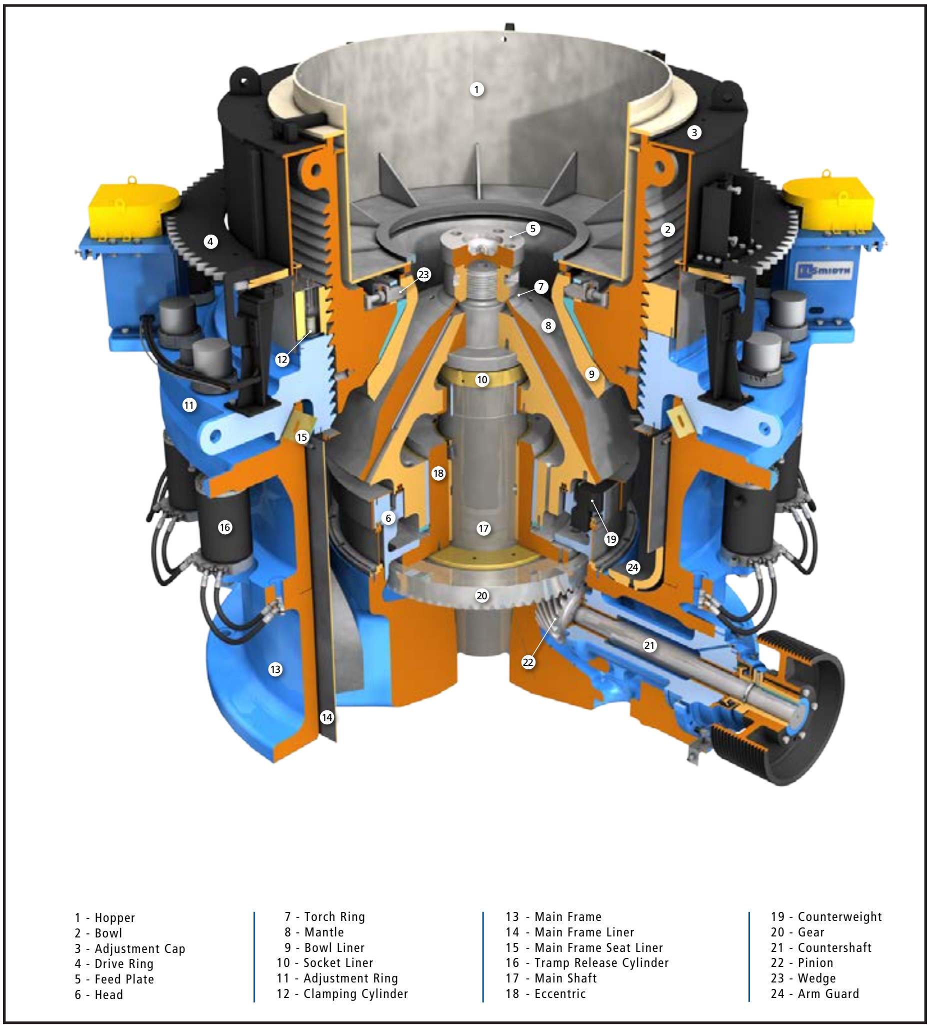

Figure 2 Raptor 2000 Cone Crusher from FLSmidth.

Summary

Although all bevel gears share many commonalities in design and manufacturing, those destined for crushing applications must possess certain key characteristics that fall outside the automotive paradigms routinely observed by the greater bevel gear industry today. These key characteristics are not widely understood within the engineering community, and it goes without saying that far fewer gear manufacturers are adequately informed on the technical requirements for these applications.

For crushing applications, the gear's operating axis depends on plain bronze bushings to maintain alignment, and these require generous oil clearance to survive under boundary lubrication conditions. The wide bearing clearances, working in tandem with gyrating crushing forces, cause the gear's pitch cone to take on an orbital path relative to the pinion's fixed operating centerline.

The resulting wandering contact imparted on mating pitch cones requires special attention to 1) avoid overload conditions at tooth extremities and 2) prevent dangerous hard mesh operating conditions. To avoid these unwanted consequences, mating components are machined with additional crown and backlash, and are finally tested by a method that simulates the gear's orbital path relative to the pinion.

The advent of precision 5-axis milling has extended the effective size range and improved efficiency in manufacturing of large bevel gears. As a positive result, this new technology has introduced many new sources for the buyers of large bevel gears. Conversely, a broader supplier base also serves to further dilute an already-limited understanding of what's required for crushing applications.

The preceding sections of this article are aimed at improving the reader's depth of knowledge with respect to these unique applications and, hopefully, serve as the impetus for more dilligent research when approaching that next crusher gearset order.

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.

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