Laser Alignment of United States Steel Corporation’s Gary Works No. 2 Caster

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ABSTRACT

This investigation of caster alignment using laser technology was conducted at United States Steel Corporation (U.S. Steel) Gary Works No. 2 Caster. The cast line was reviewed with respect to the alignment of the caster components, and significant misalignment was measured with the Sarclad gap sled between the Bender and Segment 1. There were also other minor misalignments throughout the cast line. Even though the cast line was recently aligned in 2009 from the mold to Segment 12 using a laser tracker, another thorough alignment was conducted. The present alignment removed all segment components from the caster to expose the frame from the mold to the exit of containment and corrected a twist in the cast line. However, the misalignment between segments was only slightly reduced. A review of the alignment data revealed that segment trunnion pin wear and saddle design were the likely root causes of the misalignments measured by the gap sled. A new saddle design was created and will be tested. Finally, the alignment activity did significantly improve caster performance. Recommendations for alignment are also given based on this experience.

INTRODUCTION

The Gary Works No. 2C Caster (C-Line) was constructed by Siemens-Voest Alpine Industries as a single-strand vertical-bending caster capable of producing a 12.0 or 9.1 inch thick slab. The caster was later converted into a flex caster to increase productivity. The conversion enabled the caster to cast twin 9.1 inch thick slabs in addition to the single strand 12.0 or 9.1 inch thick wide slabs. Today, the caster runs predominantly in twin mode.

The Gary Works No. 2C Caster design includes 18 segments in the bow and horizontal sections. It also employs a discharge rack and bender in the upper part of the machine. The casting machine has a radius of 11,684 millimeters (mm) with continuous bending and straightening. The segment rolls are split in three sections along the strand width to reduce bulging and to provide increased support.
The caster has no taper from the mold to Segment 7, and it has a minimal taper from Segment 7 through the end of containment to compensate for thermal shrinkage. The taper in C-Line has not been changed since it was installed by the original equipment manufacturer (OEM).

It is widely accepted that slab quality and caster throughput are heavily dependent on effective strand alignment practices, as well as on secondary cooling water, mold narrow face taper, and mold flux composition. The strand alignment of Gary Works C-Line operating in twin mode was reviewed to assess the status of the caster segments and rolls. The review found several potential problems with strand alignment that could result in slab quality concerns. Examination of the gap sled run revealed a significant step between the exit roll of the bender and the entry roll of Segment 1. The previous sled runs were then reviewed, and the misalignment between the Bender and Segment 1 was plotted as a function of time for each side of the strand. The misalignment between these two cast line components was found to vary significantly with time, as shown in Figure 1. In some instances, the misalignment decreased after the bender was in the line for a period of time, leading to the idea that there is settling of the segment.

![Graph showing misalignment of Bender from gap sled runs](image)

**Figure 1.** Angular misalignment measured at exit of Bender from gap sled runs (up and down) as a function of time for the North and South sides of Gary Works No. 2C Caster. Segment 1 and Bender exchanges are indicated by vertical lines.

The alignment was adjusted over time using the gap sled or a radius gauge, but the most recent alignment of No. 2C Caster cast line was conducted in 2009 using a laser tracker. Prior to that alignment, C-Line had never been aligned with all of the segments removed. A limited alignment was conducted in 2009, and not all problems found during the laser tracker alignment were addressed during that outage. As a result, the machine was aligned only from the Mold to Segment 12. The gap sled was run, and a radius gauge was used to measure the line prior to removing the segments to assist in the interpretation of the new laser survey method. However, the segment alignment was not adjusted properly due to conflicting interpretations of measurement data from the three methods. Since the 2009 alignment, the understanding of the laser survey method has improved, and it has been used successfully to align other casters.

A new laser alignment of the entire strand was therefore undertaken. Alignment with laser measurement technology was preferred to a spot change using the gap sled or radius gauge because the historical alignment was not being consistently maintained with those methods. The spot change would also only smooth the transition between the Bender and Segment 1, while a laser alignment was expected to correct other alignment issues throughout the cast line. The laser alignment of the entire line required removal of all segments to expose the caster frame. After the alignment data were obtained, the segments would be placed back in the line to match the radius.

The gap sled run was run prior to removing the segments. However, a conscious decision was made to not use the radius gauge to measure the line before or after the alignment activity for several reasons:

1. Additional data from alternate sources of measurement may add confusion in interpreting the laser tracker data;
2. The radius gauge data would not relate the north and south sides of the segments to each other and could lead to a toeing/twist of the line;
3. In aligning the segments in a caster using any technique, it is assumed that all segment and caster frame mating surfaces are consistently maintained and rebuilt;
4. Reading the radius gauge data is an art and requires proper placement of the gauge. While it correctly measures the transitions between segments, it can ignore the placement of one segment with respect to the rest of the line.

In essence, the radius gauge is a two-dimensional way of looking at a three-dimensional structure. The radius gauge is good at measuring the curve of the strand, but it falls remarkably short on quantifying the spatial relationship between points not in the same plane. Since Gary Works chose to rely solely on the laser survey data, Research recommended measuring the entry and exit rolls of
each segment as they were installed in the line. These measurements would give a more complete picture of the caster rolls with respect to the rest of the cast line after the alignment.

The first published use of a laser tracker for caster alignment was in American Iron and Steel Engineering in September 2002. In 2008 when Gary Works used this technology, it was relatively new in its application to the steel industry, and the only other reported use of this technology was at Claymont Steel. Since 2008, this method of strand measurement has been used several times at U. S. Steel. A brief history of this technology and its application can be found at the Faro Laser Tracker website. A discussion of laser tracker measurement and the different available commercial systems can also be found in a paper by Burge et al., who used it to measure aspheric mirrors.

In this work, the FARO Laser Tracker (FLT) was selected for the laser alignment. The FLT is a measurement tool used in various industries, and it was previously used for the 2009 laser survey. It has good accuracy over long distances (150 feet is typical in the steel industry environment). The newest FLT can accurately measure objects located 300 feet from the device and can determine the coordinate locations of each defined object in a given space.

The FARO Laser Tracker consists of a laser source and receiver. Reflectors are placed at each location that needs to be measured. The primary component of the FLT is a robotic unit, shown in Figure 2, which sends and receives the laser beam. A Spherically Mounted Retroreflector (SMR) is placed at each location to reflect the laser beam back to the robotic unit. Each SMR consists of three mirrors placed at 90° with respect to each other like the walls at the corner of a room. This corner is at the center of the sphere defined by the SMR. The arrangement of the mirrors reflects the laser beam back to the FLT parallel to the original beam. The arrangement of the mirrors with the corner at the center implies that no matter how the spherical housing is rotated, the center is at the same distance from the component to be measured.

The FLT is able to accurately measure points in space. The FLT uses spherical coordinates to determine the location of points in space, which are then converted to Cartesian or cylindrical coordinates using a simple conversion. The Cartesian coordinates of each caster frame location are evaluated using CAD software to determine deviation from design dimensions. A typical method of reporting the measured deviation is shown in Figure 3. The origin is determined when an SMR is homed on the robotic unit. Radial distances from the tracker are measured by the FLT in two ways. In the absolute distance meter (ADM) type of laser tracker, a proprietary time-of-flight technique is used to measure distances accurately. For this purpose, a second laser with a different wavelength than the tracker can be used. This method of measuring distance is much more user friendly in an industrial setting. The second type of laser tracker is based on incremental distance meter based on interferometry (IFM). In this instrument, once the SMR is homed and the laser acquired, the laser tracker incrementally keeps track of the distance as the SMR is moved. However, if the beam is broken, the SMR has to be re-homed and the tracker moved to the appropriate location. The FLT needs a stable base and a clear line of sight. The FLT can be moved, but it needs common reference points to join the measurements to a common origin. The FLT angles are typically accurate to one arc second or five microradians. This means that the angular error of the FLT is 25 micrometers over a length of five meters (0.001 inch over 16 feet). The distance measurement error of an absolute distance measurement (ADM) based laser tracker is 25 micrometers at a distance of 35 meters. In comparison, the distance measurement error of an interferometer (IFM) laser tracker is about 15 micrometers at a distance of 35 meters. While an ADM laser tracker is not as accurate as an IFM laser tracker, the ADM technology is able to measure points without a requirement to continuously maintain laser contact with the SMR. As a result, more measurements can be obtained in a given amount of time.
As with any optical or laser-based system, the amount of measurement error can be affected by several factors which influence the air refractive index when using the FLT. Air temperature, pressure, and humidity can each contribute to the measurement error. Each environmental variable is measured by the device, but environment measurement error can affect the distance measurement. For example, the air temperature error factor is 1 ppm/°C, the air humidity factor is 0.36 ppm/mmHg, and the humidity variation is 0.01 ppm/%RH. This means that a temperature variation of 0.5°C over 35 m leads to a 17.5 micrometer error. On-board statistical analysis gives immediate analysis of the quality of the readings.

All caster reference points should be stable and have clear line of sight to the FLT robotic unit. The reference points need to be created prior to the outage in locations that can be seen from all required positions of the FLT robotic unit. The reference points should be located on structures which are rigid and not affected by day-to-day vibrations in the shop. Once these reference points are established, they are used to establish the location of the FLT prior to any measurement of the caster machine structure. The calibration establishes the measurement accuracy for the given conditions.

It takes between 18 and 36 hours after all segments have been removed before segments can be reinstalled when using the FLT. All caster components should be removed from the cast line to expose the mounting saddles and pads prior to the measurement. The mold, zone, bender, and all segments need to be removed to allow for full measurement of the backbone of the caster. Measurement of the line typically takes about 8 to 12 hours once the segments are removed. Interpretation of the data obtained from the FLT and development of the reinstallation plan then takes an additional time. The FLT data must be carefully interpreted to determine the amount of deviation of the entry and exit of each segment saddle and pad from the theoretical design of the caster.

Full alignment of the caster containment section requires an evaluation of actual measurements along with the cast line OEM specifications. The caster strand containment is a defined cavity in space. The cavity is constrained by the tundish location, water connections to the segments, oscillator table, and supporting structure. The water connection locations are important because segment location must also comprehend the alignment of segment cooling joints.

Finally, the presence of segments in the cast line can affect the location of the cast line structure. A radius gauge measures the cast line with segments installed, while the FLT requires the segments to be removed. It is difficult to predict the caster frame deflection (sag) when the segments are installed. Depending on the location of the frame and the construction, the deflection can be from 0.020 to 0.250 inch. While the FLT is essentially an infinite radius gauge, the potential cast line structure deflection under load after alignment without load is a concern. The caster frame can experience additional deflection during casting as the strand threads the line and applies load. In addition, the potential deflection is critical during periods of drastic speed change.

Figure 3. Example of FARO Laser Tracker (FLT) data presented by Falk PLI after the measurement of C-Line.
A full caster alignment that includes a laser survey is expected to take about ten days to perform. The bulk of the time is spent in the removal, adjustment, and installation of the segments. Once the preliminary measurement is obtained, it takes another day to determine the required shim adjustments and evaluate the proposed moves.

In preparation for the strand alignment outage, locations on the structure near the discharge rack and bender were measured several times before the outage. Initially, based on experience with other cast lines, the measurements indicated that the bender pads were worn unevenly. Half-shims were used in response to minimize the misalignment between the Bender exit roll and Segment 1. Without a plan dimension to compare the measurement against, it is difficult to say whether the measured dimensions reflected a cast line issue.

The relevant OEM specifications of the cast line were obtained, and a measurement plan for the laser survey was developed. The measurement plan was developed by a team consisting of U. S. Steel operating and maintenance personnel, CIM-Tech, Falk PLI, and U. S. Steel Research. CIM-Tech was charged with obtaining all relevant diagrams with respect to the caster and its components for Falk PLI. In addition, CIM-Tech developed the outage timeline and determined the tools needed for the outage. They also developed a practice for segment and saddle removal as well as for reinstallation. Falk PLI developed appropriate CAD diagrams needed to adjust segment entry and exit location based on the laser survey measurements. The measurement plan was developed over a period of several months by the team. Meetings were held monthly at first and weekly in the last month before the outage. The Gantt chart developed for the outage is provided in Figure 4.

The upper part of the machine was measured several times prior to the outage in an attempt to understand the alignment. The Bender redirects the strand from a vertical orientation produced in the mold to a curved shape that matches the machine radius. The machine radius is constant from the bender to the straightener. Therefore, as long as the bender is set up correctly with respect to its locating point, the rest of the line should tie in to this component and be aligned properly. Since the location of the Bender is very important, the measurements included the Bender trunnion pins and pads, in addition to the Bender saddle and pads.

The additional measurements revealed an issue with the location of the Bender rolls relative to the OEM specification. Specifically, the first two rolls were supposed to be vertical when installed, but they were being aligned with the bender frame when refurbished. In other words, they were vertical when the bender was sitting plumb. However, the C-Line OEM specification for the Bender indicates that it should sit in the cast line at an angle of 1.6436 degrees from vertical. The Bender orientation angle is formed by the trunnion pins at the top and the resting pads at the bottom. The design aligns the first two rolls of the Bender vertically when the Bender is installed in the caster at 1.6436° from plumb.
The roll alignment issue was discovered when the Bender and Segment 1 were measured by Falk-PLI at Caster Maintenance of America (CMA). An additional 0.05 inch was measured on one of the Bender pads. This difference was intentional and based on an incorrect understanding that the bender should sit plumb in the cast line. The other Bender pad was found missing 0.05 inch from specification, which would encourage a twist due to the 0.10 inch difference when the bender was installed in the caster.

Prior to the main outage, CIM-Tech measured some of the segment trunnion pins to determine the amount of pin wear using a micrometer. A summary of the pin wear measurements is provided in Table 1. A significant amount of wear was observed as flat spots on the bottom of each trunnion pin. This wear originated from segment installations over time due to friction between the trunnion pin and the side walls of the saddle.

<table>
<thead>
<tr>
<th>Caster</th>
<th>Drive Pin</th>
<th>Opposite End</th>
<th>Drive End</th>
<th>Opposite</th>
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</thead>
<tbody>
<tr>
<td>1-3 A</td>
<td>6.642</td>
<td>6.680</td>
<td>0.051</td>
<td>0.013</td>
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<tr>
<td>1-3 D</td>
<td>6.666</td>
<td>6.662</td>
<td>0.027</td>
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<tr>
<td>4-6 A</td>
<td>6.613</td>
<td>6.630</td>
<td>0.080</td>
<td>0.063</td>
</tr>
<tr>
<td>4-6 D</td>
<td>6.575</td>
<td>6.615</td>
<td>0.118</td>
<td>0.078</td>
</tr>
<tr>
<td>7-8 C</td>
<td>6.567</td>
<td>6.609</td>
<td>0.126</td>
<td>0.084</td>
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<tr>
<td>9 B</td>
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<td>6.654</td>
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<td>0.039</td>
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<tr>
<td>10 B</td>
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<tr>
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<td>6.561</td>
<td>6.656</td>
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</table>

During the outage, the mold, discharge rack, bender, and eighteen segments were removed. A photograph of the caster structure with all components removed is shown in Figure 5. The locations of the FLT and the 3D Laser Scanning Machine used to measure the caster frame and rails can be seen in this image. The caster component mounting locations on the frame consist of saddles, pins, and pads. The mounting locations were inspected and repaired as needed.

At the top of C-Line, the discharge rack sits in the quick-change oscillator frame and is located by a saddle. The oscillator sits on top of the oscillator frame. The mold and the oscillator are aligned with respect to each other with the help of mold alignment pins. The oscillator frame is located in the east-west direction by keyways on the north and south sides of the caster frame. There is a bolt which holds the frame from moving in the north-south direction. The oscillator frame sits on four T-blocks which determine the elevation. Several photographs of the keyway and the T-block are shown in Figure 6.

The bender and segments mount to the frame with saddles on the entry side and mate against flat seating pads on the exit side. The saddle is held in position by keepers. If a segment trunnion pin wears, there is no mechanism to keep the segment from moving tangentially in the casting direction by the amount of wear. Images of the Bender saddles and pads are shown in Figure 7. Using a calibrated cylindrical block to simulate a new segment trunnion pin, the center point of each saddle was measured. An SMR was placed on each pad corner to define the location and orientation of the pad.

Once the FLT measurements were obtained, the segment saddle and pad locations in the roller apron section were used to determine machine radius and center. The rolls in the vertical and horizontal sections of the machine were then located based on the machine center. In this caster, the coordinates of the rolls in the bender and straightener are also defined with respect to the machine center. The dimensions based on the FLT survey were then compared to the OEM design dimensions to generate a shimming recommendation.

During alignment of the line, there is a need to move each segment both in the casting direction and perpendicular to the casting direction to adjust it to the machine radius and the center. Each segment is located by adjusting shims to move the saddles. C-Line has 5 mm nominal shims on the front and rear of each saddle to move the associated segment up a maximum of 10 mm in the casting direction. It also has a nominal 10 mm shim underneath to adjust the back face of the strand. The saddles seat in the caster frame in keyways built into the saddle holder. Example images of a frame pad and keyway, along with images of new pads and a new saddle, are provided in Figure 8.
Figure 5. No. 2C Caster frame after segments were removed, showing the FLT and the 3D Laser Scanning Machine.

Figure 6. Quick change frame adjustment points -- guide key and the T-block.
The original saddles and pads were removed along with the shims underneath. The thickness of each original shim was also measured. Shim corrosion could affect this measurement, but the measurement provided an estimate for the initial shim thickness needed in each location. Once the preliminary numbers were agreed upon, the shim underneath each saddle and pad was adjusted. The saddles and pads were measured again, and a final adjustment was made to bring each segment pad within 0.005 inch of the recommendation from the FLT survey. The saddles were then installed and similarly adjusted to within 0.005 inch in the passline direction to the FLT survey.

It should be noted that during the segment shimming process, the measurement tool sets used to determine the thickness of shims were found to result in different shim combinations. Each repair crew used their own shim measuring tools, and conflicting moves were generated when finalizing the positions of the saddles and the pads. Once this issue was identified, a review of the data indicated that the conflict was the result of different tooling being used by each crew. Based on this finding, all of the crews began using a common set of tooling to eliminate this confusion.
Finally, after all of the segments were installed, the Sarclad gap sled was run. The gap sled measured the segment roll gaps and segment-to-segment alignment angle. The gap sled data were used to compare the result of the current alignment with previous alignments.

**RESULTS AND DISCUSSION**

Review of the FLT data determined:

1. The locating key for the discharge rack located on the north and south sides of the frame was offset in the east-west direction.
2. The north side of the line was consistently higher than the south side of the line in the roller apron section.
3. Segment location along the casting direction was off by about 0.1 inch. While this makes a small difference, all segments were adjusted.

Based on the shimming requirement for the segments, a tilt was observed on the flat segment pads toward the south side of the north pad and toward the north side of the south pad. In other words, the segment feet were not completely in contact with the pads. An average of the pads was chosen to determine the shims needed. At times, the amount of tilt toward the strand was greater than 0.040 inch, yet it was not chosen to shim the strand using half shims due to a concern regarding subsequent movement of the half shims.

Based on previous internal discussions, Segment 1 was installed and the entry roll was measured, as it was the location of the main misalignment issue. The FLT determined that Segment 1 entry roll was still below the passline. It was thought that the weight of Segment 1 led to this discrepancy. As a result, the location of the SMR at a reference point was measured under two conditions: with and without Segment 1 installed in the line. A maximum deflection of 0.02 inch was determined. It was then decided to install all of the segments in the line. After all of the segments were installed, the gap sled run confirmed that the Segment 1 entry roll was not aligned with the Bender exit roll. The gap sled data matched the amount of misalignment measured by the FLT after all segments were installed. The misalignment of the Segment 1 entry roll was similar to the historical angular alignment data for this roll.

The ongoing angular misalignment may be due to the method used to seat the segments in the saddles. Prior to this study, known issues with trunnion pin wear and saddle design had not been associated with angular misalignment between the segments. The flat areas on the trunnion pins and saddle gouges indicated that a new saddle design may be needed to improve the ability to secure the segments to the frame. Gouges were observed in new trunnion saddles from several segment insertion cycles, as shown in Figure 9.

A flat saddle bottom design would improve the ability to position the segment, and this would reduce misalignment of the segments in the roller apron area. Figure 10 shows a diagram of the original and a redesigned saddle with a worn segment trunnion pin. The bottom of the trunnion is used as reference when a segment is rebuilt. Therefore, a flat bottom in the saddle should not cause an issue. In addition, the flat bottom would eliminate sliding the trunnion pin up against gravity as it is moved to the final position at the bottom of the saddle. A minor adjustment would be required in the casting direction, but this adjustment is not expected to cause a misalignment issue with this design because the segment movement would be tangential to the caster curve. A decision was made to fabricate new saddles based on this design for a future trial.

![Figure 9. New trunnion saddle wear observed after a segment was inserted in and removed from the cast line a few times.](image-url)
After C-Line was aligned, production data were reviewed and slabs were inspected to understand the impact of the alignment on slab surface quality. Slabs are probed using a torch on the slab corners and the broad face at the head and tail locations. After cooling, the scale is cleaned using a brush or a metallic tool. Figure 11a shows a typical probed slab. A problematic steel grade was selected to evaluate the effect of the alignment. Slabs of this steel grade were probed, and a standardized slab grind rate was plotted as a function of time. The trend of slabs ground by month is shown in Figure 11b. The figure shows that alignment, in conjunction with other process changes, led to significant improvements in the slab surface quality.

Finally, it should be noted that the caster frame deflection and segment movement can be measured by installing proximity transducers. Turck inductive proximity sensors were installed for this purpose in the U. S. Steel Canada Lake Erie Works and Hamilton Works casters. Since the Turck sensor is a non-contact measurement, excessive movements do not lead to sensor failure. In addition, the sensors have lasted for more than several months in the cast line. Understanding segment movement over time may help improve the effort to maintain strand alignment.
CONCLUSIONS

The following conclusions were identified from experience with laser alignments.

1. All caster components should be removed. This includes the mold, top zone/discharge rack, and all segments to expose the full frame of the caster;
2. Laser survey data should be compared with commensurate plan dimensions;
3. Common measurement tooling should be utilized by all personnel;
4. All shims should be changed and caster mount locations reset using the plan dimensions and the laser survey data;
5. Gap sled angular misalignment data from the entry/exit of each segment should be tracked; and
6. Laser-based alignments should be conducted on a scheduled basis to track caster movement.

Finally, it is recommended that new machines should be measured with a laser tracker to obtain a baseline for future alignments.

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