Production Process Improvements in Large-Scale Pipe Spool Fabrication Plants Using Laser Radar

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Abstract

The main plant of Hitachi Engineering and Services (HES) has produced pipe spools for large scale plants. These pipe spools have complicated shapes and are made by various types of materials. In the process of these pipe spools fabrication, high accuracy and high throughput are required. Especially the bending process, assembling process, and the welding process are required skilled workers who have many experiences and know-how because of the particularity of these fabrication processes and have difficulties to be automated. (pipe spool: assembled pipe shipped as one unit)

In recent years, the facilities of power-generating plants and chemical plants are becoming larger. The pipe spools for these plants are also becoming larger and the shapes are becoming complicated. It becomes increasingly difficult at each production process of pipe spools to perform the accurate dimensional inspection and precise scribing even by the skilled worker. But these works within the short time period are strongly required from the view point of quality control and productivity.

HES has introduced non-contact precision 3D Laser Radar (LR) measurement system (from Nikon Metrology Inc.) to solve above mentioned issues and realize the process improvement. It has been done to establish the high efficiency production process of the pipe spool fabrication and machining works based on our wide experience of automatic measurement and data analysis system using the non-contact 3D measurement technology. Then we succeeded to shorten a period of pipe spool production by improving the accuracy of shape and dimensional inspection and scribing.

The followings are the improved functions established by this 3D measurement system.

1) The Laser Radar was applied to high accuracy dimensional measurement after the bending process as well as high accuracy scribing works at the cutting position of the pipe edge. We investigated the most appropriate measurement settings and reduced the work time significantly. It automated dimensional calculation like bending angles using scan data of pipe surface and scribing to indicate the cutting position by laser.
2) We established the easy method of measuring assembled pipe spools. The dimensional measurement time of the assembled pipe spool had been required a large amount of labor by the conventional method. It was reduced.
3) We established the automatic alignment method of the infrared (IR) and red lasers of the LR. The misalignment of the IR and red lasers were investigated. The IR laser is used for measurement and the red laser for scribing. And we established the software alignment method.

Our pipe spool production process has been streamlined and the production quality improved. This paper describes the innovatively streamlined production process by the application of these methods.

1. Nomenclature

- AMM: Automatic Metrology system for Mieruka
- HES: Hitachi Engineering & Services
- IR: infrared
- LR: Laser Radar by Nikon Metrology
- TB: Tooling ball, Grade25 0.25-in. diameter steel ball

2. Introduction

In recent years, the facilities of power-generating plants and chemical plants are becoming larger. The pipe spools for these plants are also becoming larger and the shapes are becoming complicated in order to improve the production process from the view point of construction period and construction cost reduction. On the other hand, the number of the skilled workers who have sustained productivity continued to decrease because of the aging.

In rationalizing of machining and assembling work of large-sized and complicated form products, high accurate dimensional inspection, surface measurement and scribing work are indispensable. But these works are becoming difficult even if the works are carried out by the skillful workers. Then we examined attaining rationalization of a production process and skill free production process utilizing the newest 3D measurement technology which could be made visible in whether it is manufactured as it meant in each process. That is called Mieruka (visualization), identifying problems and bringing them to the foreground.

Figure 1 shows the life cycle of the general products. We have tried to systemize the automatic measurement and evaluation process as AMM (Automatic Metrology System for Mieruka) for realizing visualization of the quality in each process. And we have applied AMM effectively to the production processes of various fields.

In this paper, we present the samples of AMM in the manufacture and inspection processes of a pipe spool.

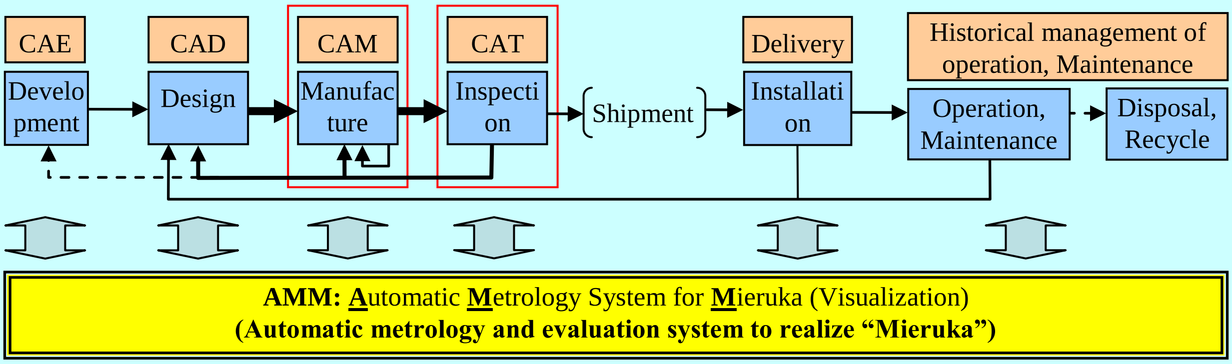


Figure 1. Life cycle of the product and AMM

3. Production process of large size pipe spool

As shown in figure 2, various sizes and shapes of the pipes are used in the complicated layout in the construction of the power plants and chemical plant. Huge numbers of pipes are welded for the layout. If the welding points increase in number, the risk on construction would increase, and a construction period would become long and construction cost would also increase. Therefore, in order to reduce welding places and to raise reliability the numbers of bended pipes used in these plants are increasing. These pipes are bent by the high frequency induction heating technology. Bended pipes which are bent at two or more places in different directions are called 3D bended pipes. Figure 3 shows the sample of the 3D bended pipe.

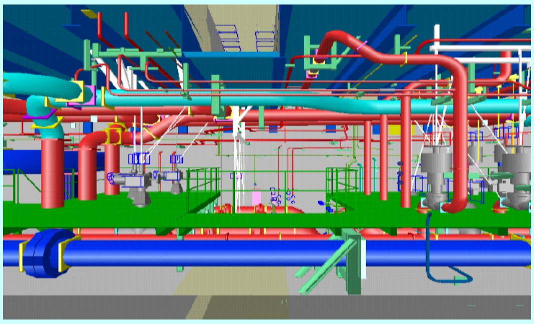


Figure 2. Sample of the complicated piping layout in power plant

Figure 3. Three-dimensional bended pipe

Figure 4 shows the typical pipe spool using the 3D bended pipe manufactured in our plant. The meaning of pipe spool is the assembly piping partially manufactured at the factory by the size which can be conveyed and carried in. This pipe spool is bended at two places, carries out beveling of a both-ends side that is the edge preparation for welding, and a branch pipe is welded to one side.

Figure 5 shows the production work flow of the pipe spool using the 3D bended pipe and figure 6 shows the summary of each work and the required time divided into work by manual and automated work.

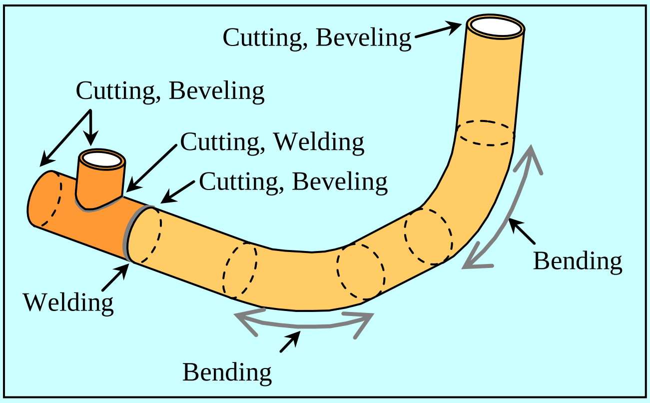


Figure 4. Typical pipe spool using 3D bended pipe

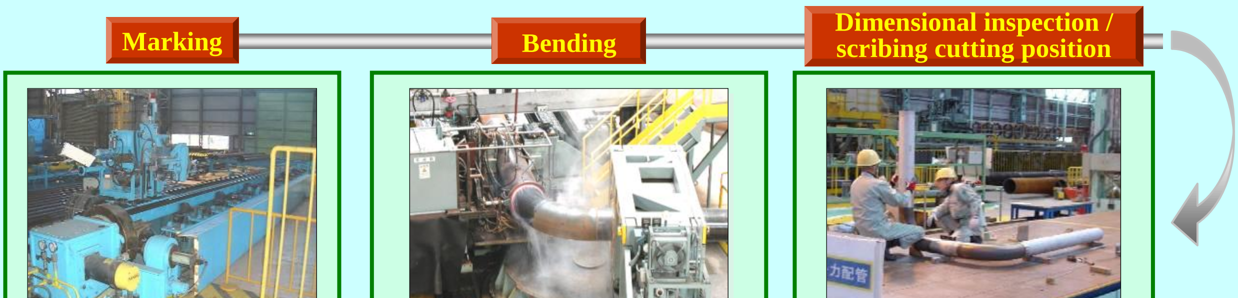


Figure 5. Production work flow of the typical pipe spool

Production work flow	Summary of the work	Time (h)	
		Manual	Automated
Marking	To identify the pipe, mark the material number, and the spool number to the pipe.	0.1	0.1
Bending	Bend the pipe by the high frequency bending machine according to the designed bending radius and angle.	0.5	4
Dimensional inspection, scribing cutting position	Measure the bending angle, straight part length, interface length using the drawings and measurement tools and mark the cutting position so that the lengths should be equal to the designed values.	6 h by 2 persons	0
Cutting	Cut at the indicated position scribed in the dimensional inspection.	0.1	0.2
Beveling	Bevel the edge of each pipe end to prepare welding.	1	3
Assembling	Assemble the bended pipe, straight pipe, joint and so on, and perform tack welding.	0.7	0
Welding	Perform welding, and heat treatment for the welding places.	1.5	1.5
Dimensional Inspection	The dimensional inspection after welding was not performed, but dimensions were judged in the inspection after assembling and these data collateralized the product dimensions.	> 10	-
Non-destructive inspection	Inspection for the welding places and beveled places.	1	0.2
Finishing	Removal of rust and a scale, perform paint and curing.	1.0	0.1
Shipment	Ship the pipe to the plant or assembly factory.	0.2	0

Figure 6. Summary of the work of the pipe spool production and the required time

As shown in figure 6, long hours of the manual working are required in the dimensional inspection and scribing work after the bending process. And these works depend on the skilled workers, but the number of skilled workers is decreasing. Therefore we considered the automatic measurement method of these works by application of a 3D measurement system so that these works would not need the skill.

And the dimensional inspection after the welding process was not fully completed but had substituted the inspection on the part level before welding because there was no effective measurement method. However, the necessity for the dimensional inspection after the welding process increased while the pipe spools are enlarged and complicated in recent years. We investigated the 3D measurement technique in which the dimensional inspection of the large sized pipe spool after welding process is possible. Hereafter, the contents which applied the 3D measurement system to these two processes are introduced.

4. Applying 3D measurement system for dimensional inspection of bended pipe and scribing cutting position

4.1 Conventional work of the dimensional inspection of bended pipe and scribing

When the 3D bended pipe is welded in the plants, the angle of the both ends side which makes welding connection and the length between centers of both ends which is called interface length are important. That is, when the accuracy of manufacturing is not good, a large gap arises at the places where would be going to be welded. In such case, the adjustment work is required. As a result, increase of a construction person-day and the reliability degradation are caused. Therefore, the dimensional inspection of the bended pipe and the scribing at the cutting position which determines the positions and angles of both ends with a high degree of accuracy are important.

Figure 7 shows the dimensional inspection items of the 3D bended pipe. Each end has surplus length which is cut in the post-process to be same length as the designed value. The followings are the dimensional inspection items of the 3D bended pipe.

(1) Bending angle between straight part A and B (θ1)
(2) Bending angle between straight part B and C (θ2)
(3) Tilt angle (θ3): Angle between straight part C and vertical line, horizontal plane is set by straight part A and B.
(4) Length of the straight part B (L2): Distance of two intersection points, intersections of straight parts A-B and B-C.
(5) Interface length (K): Distance between the centers of both ends.
(6) Length of straight part A (L1)
(7) Length of straight part C (L3)

And the form, ellipticity and thickness of the bended places are also inspected.

Here, (5) Interface length K, (6) Length of straight part A L1, (7) Length of straight part C L3 are calculated by the interface length adjustment. The procedures of the interface length adjustment are described next.

(i) Set the designed value of straight part A to L1, straight part C to L3. The distances from the intersection points to the cutting planes are set to L1 and L3, and then calculate the interface length. The calculated interface length is different from the designed value because the bending angles are actual values.
(ii) Adjust the length of L1 and L3 within tolerances to interface length be equal to the designed value. For instance, when the interface length is larger than designed value, make the length of L1 and L3 be shorter to K be equal to the designed value. In case that K would be equal to the designed value by adjusting L1 and L3 within the tolerances, the adjusted L1 and L3, and the K which is equal to the designed value are output.
(iii) In case that the interface length would not be equal to the designed value by adjusting L1 and L3 within tolerances, set the L1 and L3 to the tolerance limit values and calculate K. And these values are output.

After the interface length adjustment, scribing is performed at the cutting plane A and C. The cutting plane A and C should be parallel to the designed cutting planes. Therefore the actual cutting plane would not be perpendicular to the center axis of the pipe, which is called miter cutting.

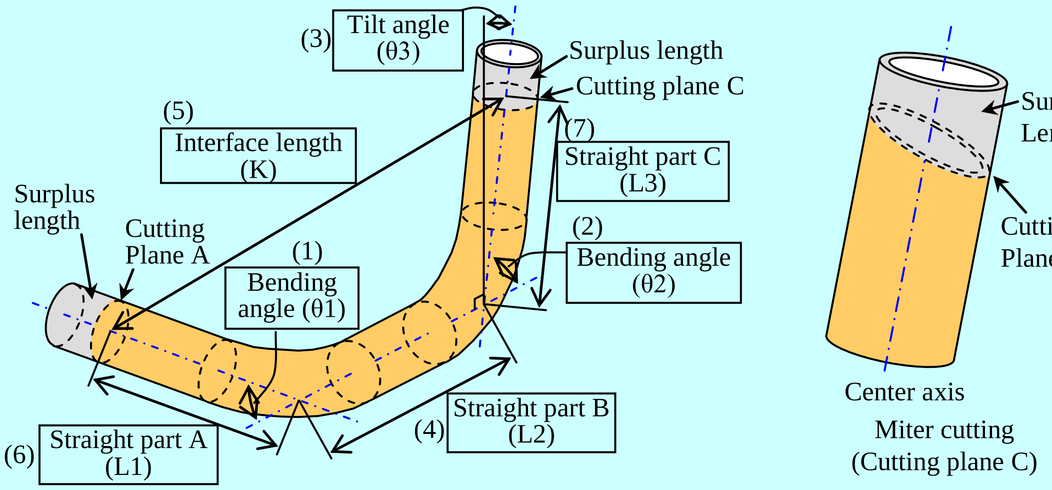


Figure 7. Dimensional inspection items of 3D bended pipe and Miter cutting

Figure 8 and figure 9 show the conventional dimensional inspection of the bended pipes using the measurement tools. The bended pipe should be set along a nominal line on the surface plate, and measured linear dimensions by gauges and bench rules, and measured bending angles by comparing with the drawings on the surface plate. Scribing the cutting positions was performed by drawing the center axes of the straight parts of the pipe on the surface plate and using designed values of the straight part length and bending angles.

Figure 8. Conventional dimensional inspection of bended pipe. Setting on the surface plate.

Figure 9. Conventional dimensional inspection of bended pipe. Measuring length between intersections using measurement tools.

The interface length which is defined the distance between centers of both ends could not be measured easily by the measurement tools. Instead, the distance between the side surfaces of the both ends was measured with the steel measure tape. For this reason, not only highly accurate measurement was difficult, but the interface length adjustment required repetition work and it had taken time and effort.

The above mentioned conventional methods of the dimensional inspection of the bending pipe and the scribing the cutting position had the following problems.

- Since the workers are carrying out by manual operations, measurement takes a long time.
- Measurement accuracy is dependent on the worker's skill and the accurate measurement is not easy if it is not done by the skilled worker.

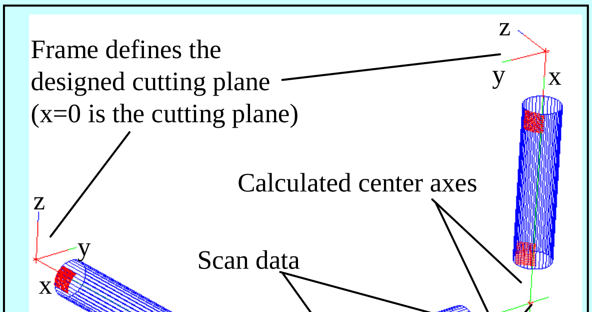
Then, we investigated applying a 3D measurement system to a dimensional inspection and scribing cutting position as a means to solve the above mentioned problems.

4.2 Dimensional inspection of the bended pipes using the LR

As for the 3D measurement system for the dimensional inspection of the bended pipe and scribing the cutting position, it is required to measure bended pipe of approximately 5m size within the accuracy of 0.1mm. And a function for scribing the cutting position is desired. We used the Laser Radar (LR) of Nikon Metrology Inc. because the LR could measure 10m range within the accuracy of 0.1mm and it has the red laser for visual confirmation which could be used for scribing other than IR laser for measurement. Moreover, since the non-contact measurement by laser is possible, the automatic measurement which does not need manual operation becomes possible. Next we examined how to use the LR to carry out the dimensional inspection of bended pipe and scribing cutting position.

At first, to calculate the values of bending angles it is necessary to search for the center axis of the straight part A, B and C. To get the center axis of the straight part for a short time accurately, we set the measurement areas as two places which are positions of both ends of the straight part, and one measurement area is a square which has the pipe radius length on the side as shown in figure 10. To measure by the LR, measure 6 center points of each measurement area, then auto-measure by the vision box scan mode. The scan size and the scan pitch are defined preliminarily.

Construct cylinders from the measured data from two measurement areas for each straight part, and get the center axes of the cylinders. Calculate the bending angle and the tilt angle from the center axes. The length of the straight part B (L2) would be calculated from the intersections of the center axes. Then input the designed values of the straight part length L1, L3 and calculate interface length K. Perform the interface length adjustment and output the adjusted L1, L3 and K.



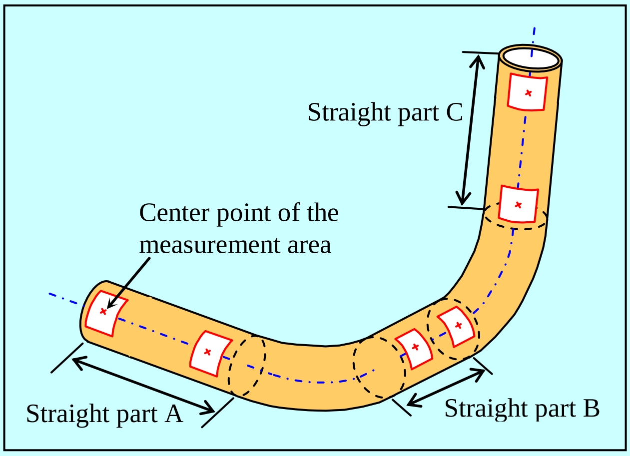


Figure 10. Measurement Areas of each straight part

Figure 11. Sample of the scan data of 3D bended pipe

After the dimensional inspection, the scribing of the cutting position is performed. In order to make each cutting plane parallel with the designed cutting plane, the designed cutting planes are defined on the center axes of straight part A and C in the position where the length of the straight part A and C becomes L1 and L3 respectively. As shown in figure 11, cutting planes are defined by the frames constructed on the straight part A and C where the designed cutting plane and the plane x=0 should become parallel. The intersection between the defined plane and the actual pipe surface would be measured using the section cut function of the LR. After the section cut measurement, the red laser is aimed to the measured points and the worker makes marking at the indicated points. At least 3 points are marked to define the plane.

We accomplished the automatic measurement of the above mentioned measurement and analysis work using the Measurement Plan of SpatialAnalyser. Thereby, the person-day which required in the dimensional inspection and the scribing the cutting position work reduced to 30 minutes by one- person work. It was shortened significantly with 1/24 as compared with the conventional work.

4.3 Issue of the LR when it is used to indicate scribing position

The LR has the IR laser (wavelength 1550nm) and the red laser (wavelength 660nm). These two lasers are oscillated from each oscillator and passed through same optical fibers and lenses. Then reflected at the scanner mirror and aimed to the target (as seen in figure 12). The focus positions of the IR and red lasers are different so the focus lens position is properly adjusted depending on the measuring distance. The IR laser is focused during measuring and the red laser is focused during not measuring.

The centers of the IR and the red laser spots are not aimed to the same position because of the slight difference of the incident angle to the optical fiber end. The red laser is used to indicate the scribing position so the point difference of IR and red lasers would cause the error. We asked the LR manufacturer (Nikon Metrology Inc.) about the point difference and they developed the software alignment. The followings are the summary of the alignment method. The point relationship of the IR and the red lasers is dependent on the azimuth angle of the LR because of the LR configuration (as seen in figure 13). When we set the nominal of the IR laser direction from the red laser position in case that the azimuth angle equals zero, the IR laser direction would rotates by θ counter-clockwise in case that the azimuth angle equals θ. Incidentally, the position relationship of the IR and the red lasers is not depend on the elevation angle of the LR.

The offset of the IR and the red lasers and phase angle are depend on the LR unit, so these parameters should be acquired and set to each LR unit. The parameters are Angular offset ψ which is acquired by the offset width δ, and the phase angle φ which is the angular rotation of the IR laser from red laser in case that the azimuth angle equals zero.

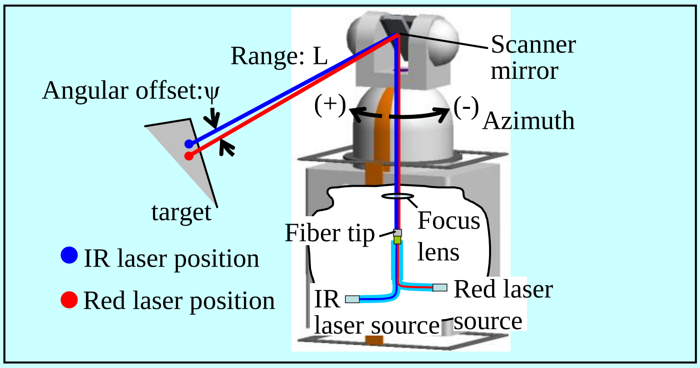


Figure 12. Angular offset of the IR laser and the red laser of the LR

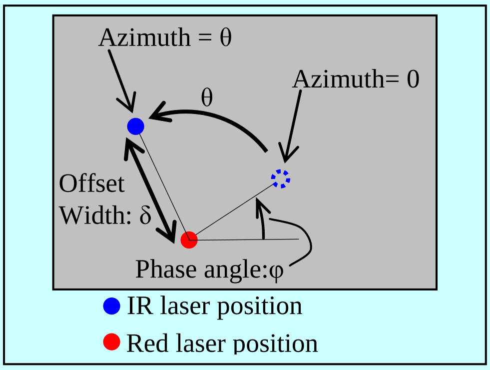


Figure 13. IR laser offset directions when the Azimuth angle is equal to 0 and θ.

During the measurement, the IR and red lasers alignment is not applied and the focus lens position is set where the IR laser is focused. The period of not measuring, the IR and the red lasers alignment is applied and the focus lens position is set where the red laser is focused. The offset angles of azimuth and elevation are calculated by the following formulas.

$$\text{Azimuth Offset} = \arctan(\tan\varphi \cos(\varphi + \theta)) \qquad \text{(Equation 1)}$$

$$\text{Elevation Offset} = \arctan(\tan\varphi \sin(\varphi + \theta)) \qquad \text{(Equation 2)}$$

4.4 The evaluation of the IR and the red lasers alignment

We tested the IR and the red lasers alignment of the LR to evaluate the properness of the above mentioned alignment method and to determine the alignment parameters. Figure 14 shows the test conditions. The IR viewer was used to see the IR laser position and set at the position 5m from the LR. The IR viewer was taken pictures by the digital camera once the IR laser was focused and then the red laser was focused. The center of the laser spot was measured by pixels for horizontal and vertical directions and the offset width was calculated by the differences. That is the horizontal and vertical offsets (α_d, β_d), are calculated by

$$(\alpha_d, \beta_d) = (\alpha_{IR}, \beta_{IR}) - (\alpha_{Red}, \beta_{Red}) \qquad \text{(Equation 3)}$$

where (α_{IR}, β_{IR}) is the center of the IR laser spot, (α_{Red}, β_{Red}) is the center of the red laser spot.
To convert pixel to distance, the stainless ruler was taken within the pictures. We evaluated two LR units (SN8626, SN9704). The used digital camera was Nikon COOLPIX S3100 and number of pixels was 4320x3240.

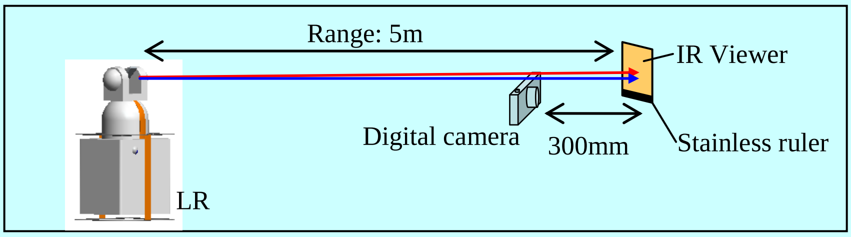


Figure 14. Test conditions to evaluate the IR and the red lasers alignment

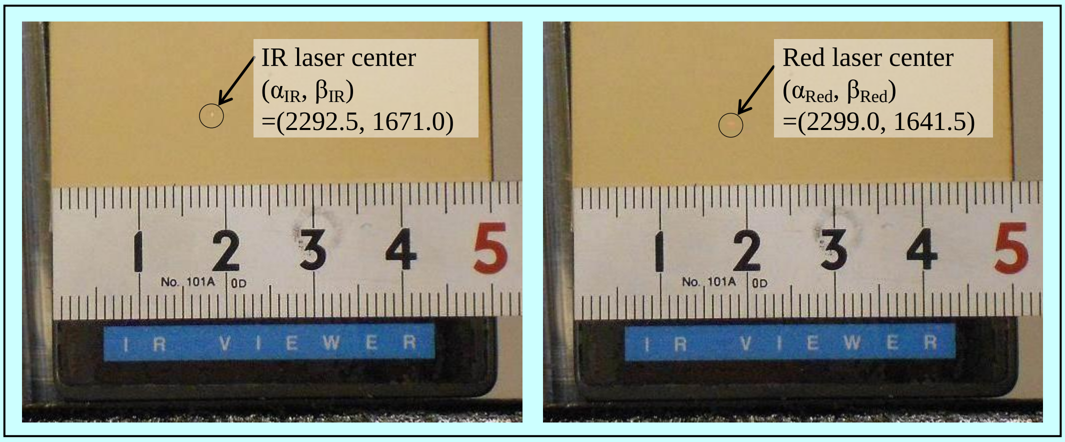


Figure 15. Pictures used in the evaluation test of the IR and the red lasers alignment

Angular offset ψ and the phase angle φ are calculated from the horizontal and the vertical offset (α_d, β_d) by the following formulas.

$$\psi = \arctan\left(\sqrt{\alpha_d^{\,2} + \beta_d^{\,2}}/L\right) \qquad \text{(Equation 4)}$$

$$\varphi = \arctan\left(\beta_{d(-\theta)}/\alpha_{d(-\theta)}\right) \qquad \text{(Equation 5)}$$

Where θ is the azimuth angle of the LR, L is the distance from the LR to the IR Viewer, and

$$\begin{pmatrix} \alpha_{d(-\theta)} \\ \beta_{d(-\theta)} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \alpha_d \\ \beta_d \end{pmatrix} \qquad \text{(Equation 6)}$$

Tests was performed at each LR azimuth angle 0, 90, 180, 270 degrees, and the parameters were calculated at each angle. The parameters for the settings were calculated by averaging these results. And the same test was performed using the alignment function with the acquired setting parameters to confirm the function of the laser alignment. One pixel c

using t

(1) SN8626

Azimuth (deg)	Offset width without alignment (pixel)		Offset width without alignment (mm)		Calculated parameters (deg)		Offset width using alignment (pixel)		Offset width using alignment (mm)	
	α_d	β_d	α_d	β_d	ψ	φ	α_d	β_d	α_d	β_d
0	-6.5	29.5	-0.22	1.02	0.0119	77.6	-1.5	-2.0	-0.05	-0.07
90	29.5	7.0	1.02	0.24	0.0120	76.7	-0.5	1.5	-0.02	0.05
180	5.5	-29.0	0.19	-1.00	0.0117	79.3	-2.0	-1.0	-0.07	-0.04
270	-28.5	-4.5	-0.98	-0.16	0.0114	81.0	-1.5	-1.5	-0.05	-0.05
				Average	0.0117	78.6				

Figure 16. Test results of evaluation of the IR and the red lasers alignment

Figure 16 shows that the IR and the red lasers alignment worked properly and the offset width could be less than 0.1mm. By using this alignment, the accurate scribing by the LR should be possible within 0.2mm errors combined with the LR measurement accuracy.

5. Applying 3D measurement system for dimensional inspection of the pipe spool after the assembling and welding process

5.1 Dimensional inspection after the assembling and welding process

It takes huge amount of time to inspect dimensions of the large size and complicate shaped pipe spool after the assembling and welding process. And this dimensional inspection is performed manually so the accuracy and the inspection time rely on the skill of the workers. The pipe spool over 10m size as shown in figure 17 has been also manufactured especially in recent years. The pipe spool of this large size had been confirmed the manufacturing accuracy by measuring each segment of the pipe spool (Segment A, B, C). And the dimensional inspection after the welding process was performed by marking the drawing of the spool on the floor etc., measure the offset using the steel measure tape.

However, the necessity for the dimensional inspection after welding increases with the size of the pipe spool becoming larger and the shapes are getting complicated. We investigated the 3D measurement method for the pipe spool of the large size. It could also shorten the measurement time and increase the measurement accuracy for the measurement of the pipe spool segments.

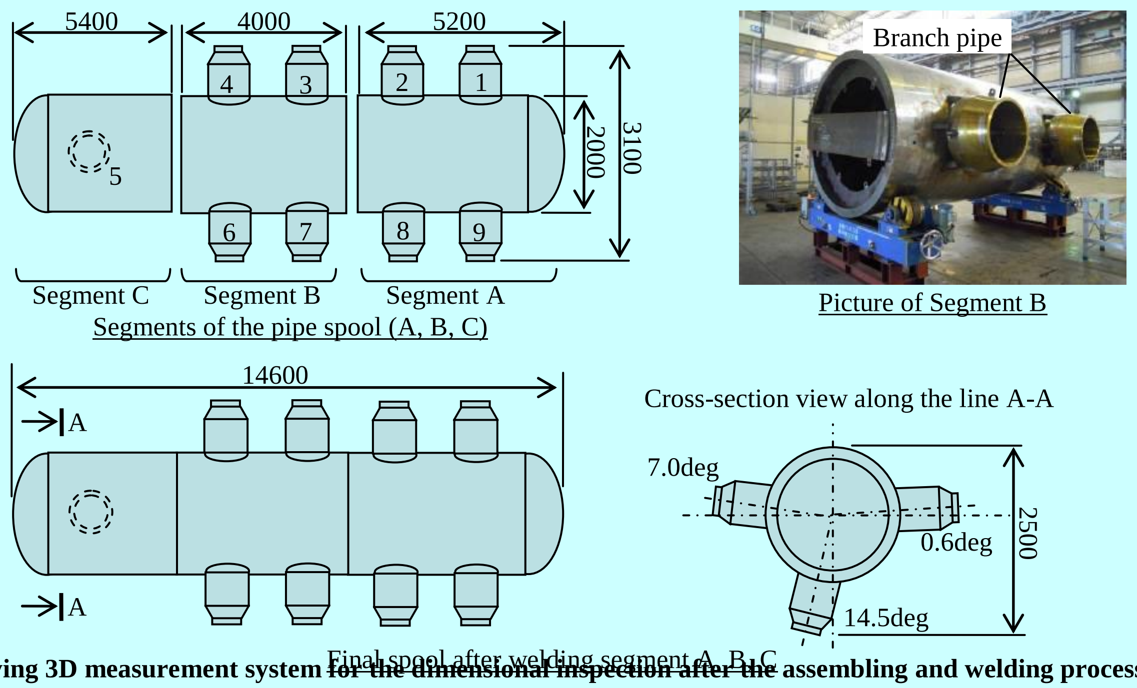


Figure 17. Outline dimensions of the large size and complicate shaped pipe spool

5.2 Applying 3D measurement system for the dimensional inspection after the assembling and welding process

(1) Measurement procedures

We investigated the measurement procedures of dimensional inspection of the pipe spool after the assembling and welding process using the LR. To measure the position and the angle of the branch pipe, side surface of the branch pipe should be measured and the center axis be calculated. Most branch pipes have shorter length than the 3D bended pipe. It is not easy to set the scan area properly to get the appropriate data for fitting the cylinder. So we would use the surface point measurement mode. And to detect the pipe edge position, perform the line scan and get the edge position. The followings are the measurement procedures.

(a) Manually measure two points, Point Near Edge (Pn) and Search Edge Direction (Pd).

(b) Automatically perform 3 line scans and detect 3 edge points from scan data. And calculate rough position of the branch pipe.

(c) Automatically measure 15 points on the side surface of the branch pipe to calculate the center axis.

(d) Automatically perform 3 line fine scans at the detected 3 edge points precisely to detect the position and the angle of the end surface.

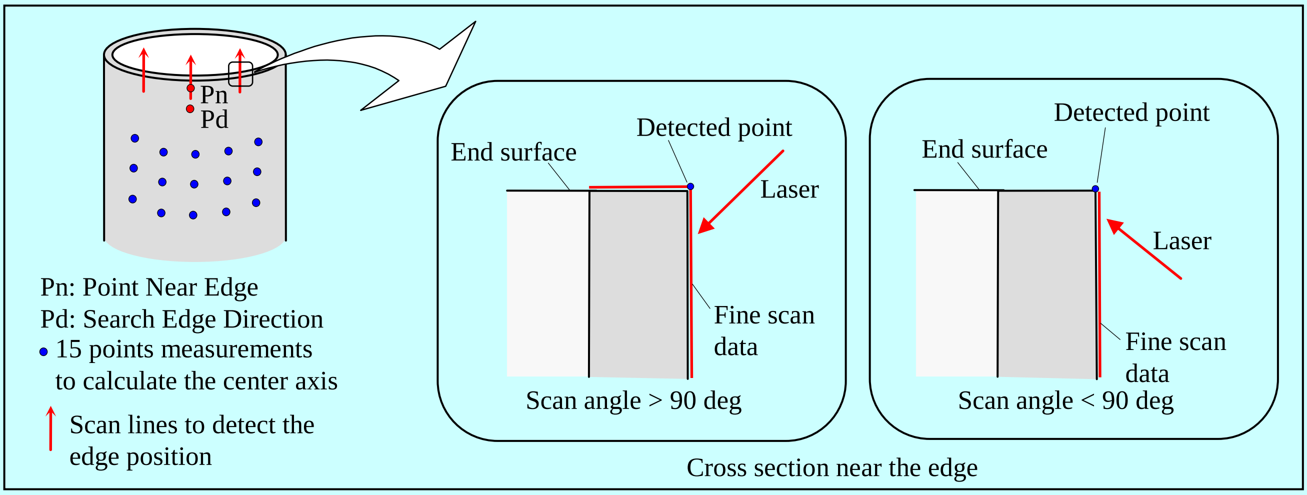


Figure 18. Measurement procedures of the branch pipe using the LR

(2) Evaluation test for applying the LR to the dimensional inspection after the assembling and welding process

In order to verify the measurement accuracy and measurement time of the above mentioned measurement method, the examination was carried out using a sample of branch pipe as shown in figure 19. It was measured in various angles supposing measuring the pipe spool after an assembling and welding process. To confirm the measurement accuracy, set a sample of branch pipe on a turn table, and put the 6 TBs on the side surface and three TBs on the end surface and make the nominal values of the angles of the center axis and the center position of the pipe end. The TBs were measured from 2m range in order to measure with high precision (LR position1). The sample of branch pipe was measured from 10m range supposing measuring pipe spool of large size (LR position2). Figure 20 shows the test results.

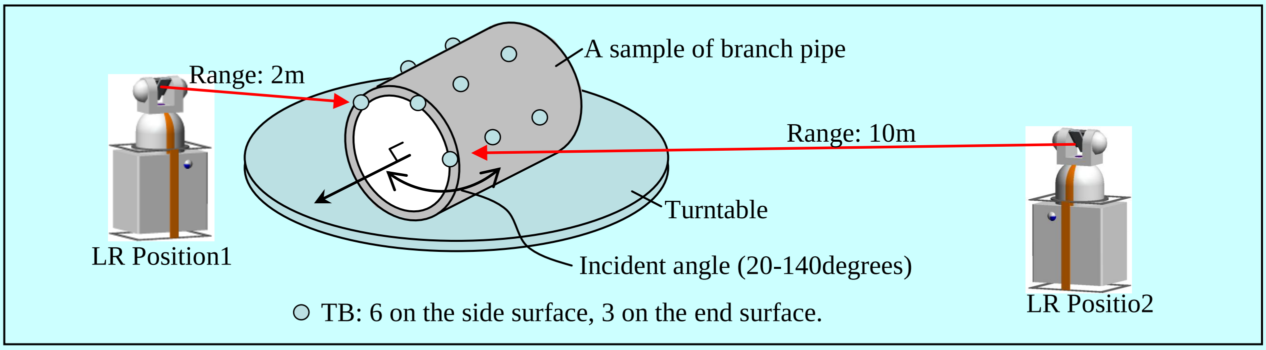


Figure 19. Evaluation test for applying the LR to the dimensional inspection after the assembling and welding process

Incident angle (deg)	Deviation of the center position of the pipe end (mm)	Deviation of the center axis angle (deg)
30	0.229	0.218

50	0.223	0.225
70	0.196	0.125
90	0.090	0.125
110	0.216	0.149
130	0.251	0.204
150	0.277	0.257

Figure 20. Test results for applying the LR to the dimensional inspection after assembling and welding process

The deviation of the center position of the pipe end was 0.277mm at the maximum, and the deviation of the center axis angle was 0.257 degrees at the maximum which were less than the tolerances (+/- 0.5mm and +/- 0.5 degrees). The tests at the incident angle 20 and 160 degrees were performed, but could not detect edges properly. And the measurement time for one branch pipe was less than 60 seconds. By using this measurement method, the dimensional inspection of the pipe spool after the assembling and welding process which has a complicated shape as shown in figure 17 could be considered that the inspection becomes possible within a short time by setting LR in the positions where the incident angles to the branch pipes are set from 30 to 150 degrees.

6. Conclusion

High-accuracy and non-contact three-dimensional laser radar measurement technology was applied to the pipe spool assembling and inspection works aim to establish the efficient and high quality manufacturing system.

1) The LR was applied to the dimensional inspection and the scribing cutting positions after the bending process. These works had required two persons for 6 hours conventionally. Now it takes 30 minutes of one person.
2) We established the automatic alignment method of the IR and the red lasers of the LR evaluating the setting parameters of the alignment in order to apply the LR to the scribing works.
3) We established the easy method of measuring assembled pipe spools which could shorten the required working time significantly. The dimensional measurement time of the assembled pipe spool had been required a large amount of labor by the conventional method.

The accuracy of dimensional inspection of the pipe spool has improved by using these methods and then the pipe spool production process has been streamlined and the production quality has improved.

We will investigate the validity of the developed methods applying to the various types of the pipe spool. And we are trying to continue developing the automatic 3D measurement technologies to expand the applicable fields of the 3D measurement system. As an example, the slide calipers etc. are used for inspecting the beveling process, but the production quality would improve if we could use 3D measurement technology for this process.

We intend to contribute willingly to promote the streamlining and improve the quality of design, manufacture, assembling, inspection, installation, operation and maintenance processes by applying effectively our 3D measurement technologies obtained during the development of the 3D measurement methods for the assembling and inspection process of the pipe spool.

7. Acknowledgements

We would like to express our appreciation to Nikon Metrology for developing the laser alignment function of the LR. And New River Kinematics, we used SpatialAnalyzer to automate the measurement and analysis process, and to perform the evaluation tests.