Design of a novel grinding end-effector for spiral welded pipe

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Abstract. In the spiral welded pipe manufacturing process, grinding is one of the production processes, this process proceeds by hand grinding and fixed machine grinding. Usually, those methods have impacts larboard intensive, long production cycle and unstable product qualification rate for the final product. To prevent those factors from this paper, present a newly-designed grinding machine for a spiral welded pipe manufacturing industry, the machine has equipped with a special grinding machine with the ability to grind the spiral welded pipe the inner and outer surface simultaneously of the pipe and equipped with 6DOF grinding robot. The kinematics model of grinding robot is derived and the robot joint trajectory is calculated. The simulation result shows that the grinding mechanism can perform the job without failures under the external torque, and also trajectory graph of the robot kinematics shows there is no vibration on the robot movement to perform the job.

1. Introduction

To ensure the automatic welding of the girth welds during the construction of long-distance pipelines. The standard requirements for spiral submerged arc welded pipes are required. The standard of submerged arc welding pipe to grind the end of the pipe both inside and outside weld less than 0.5mm. Currently, they use a two-sided fixed grinding machine, this innovation has some scarcities, manual control, and manual operation, Poor leading time and require a highly experienced employer, Spiral welded pipe standards require a smooth transition. At present, the grinding quality of the grinding machine can not meet this requirement. Seeking, you need to manually find the edge and other parts. To achieve fully automatic control, to get the desired quality of the weld must be repaired.

In recent years, many scholars have studied robot grinding. J.A. Diestea, 2013 developed an automatic bending machine using a spherical robot for surface material automatic process. They can reach roughness values less than 0.1μm [1]. Kaiwei Ma et.al (2018) developed a robotic belt grinder a robotic belt grinding control system is setup by using field bus and serial port. The system has a constant grinding force control module. In this research, they can reach roughness of fine grinding are below 0.9 microns [2]. Yixu et.al (2013) proposed an intelligent control method for the industrial robot [3]. Tian et.al (2016), built the relationship between the polishing force and the tool gravity compensation to help realize the actual polishing force control on the machined surface, which is for eliminating gravitational disturbance of polishing tool during the polishing process. The proposed polishing machine can improve the accuracy of the material removal amount and decrease effectively surface roughness [4]. Xie et.al (2017) proposed a robot flexible grinding system composed of robot and control cabinet, ACF flexible force controller, spindle, grinding tools and workbench. It is proven to be able to achieve automatic grinding and improve the A grinding process is proposed based on the...
robot grinding platform, and a suitable grinding condition and process parameters are obtained. The texture left after the milling of the blade is substantially eliminated and the minimum roughness Ra can reach 0.16 μm grinding efficiency [5]. To increase product quality and manufacturing flexibility Michael N. Morgan and Rui Cai (2007) proposed an intelligent grinding assistance system integrated with the grinding machine [6]. Mohammad et.al (2018) built up a new automated polishing using the design a force-controlled end-effector for automated polishing, the proposed end-effector is to be integrated into a macro-mini robot polishing cell [7]. Mahfouz et.al (2018) utilized artificial intelligence (AI) technique to predict surface roughness in turning, surface roughness measure is divided into three classes; smooth; medium and rough surface finish [8]. To predict robot belt grinding depth of cut, Wang et.al (2017) proposed a new framework. It includes a local stress model and a local material removal model, both of which factor in contact wheel deformation. This method can be applied to robotic grinding applications and has a prediction error of less than 3% when the cutting depth is about 0.3 mm. Transient grinding at the cut-in and cut-out points results in greater prediction error. Pipeline systems in industrial facilities are connected and installed by welding, and weld position most prone to damage [9]. Canhui YIN, Dewei TANG et.al (2017) developed robot implementing Y-ray non-destructive to detect and automatic grind for the inner girth weld seam of the thick wall pipe. This robot can be adapted to pipes with an inner wall diameter ranging from 270mm to 380mm [10]. Jijian (2015) built up a double-sided spiral welded pipe end grinding machine. Researchers have been adding tools overcome to solve those scarcities in these sectors. This new technology incorporated with an industrial robot, newly designed double-sided grinding machines which is the ability to grind the spiral welded pipe simultaneously the inner and outer surface of the pipe. The grinding mechanism also has a 3D lesser sensor which is to identify the welding lines and also doing analyze the surface roughness. Thus, the implementation of the newly grinding mechanism analyzing the grinding mechanism of the belt and drive the Euler formula for the belt transmission considering the centrifugal force, and applied abrasive belt mechanism. The grinding force, pre-tightening force and the servo motor pressing force during the grinding process having established the grinding process of the spiral welded pipe. The grinding machine structure to analyze the Max von mises stress stimulation proceeds by using solid work version 2017 software, Also, use MATLAB toolbox software to do the kinematics analysis and the trajectory planning of the required 6DOF KUKA KR360 robot. In the final manufacturing procedure of spiral welded need to grind the pipe end part to prepare the pipe for installation on field site, however, those researchers develop new grinding robot and they got a good result for surface finishing and improve machining time but for the spiral welded pipe manufacturing industry is not applicable because of the grinding machine mechanism structure is not compatible to grind the specified spiral welded pipe and also the other machine to work with spiral welded pipe have the limitation to the quality problem and machining time also.

2. Design of grinding end-effector

2.1. Structure design

The designed grinding machine can grind the inner and outer surface of the pipe. The grinding mechanism should be able to grind the spiral submerged arc welded pipe the inner and outer welds of the pipe end, grinding from 0 to 200mm from the pipe end internal and external welds. Application steel pipe specification is outer diameter 508~1420mm, wall thickness 6.4~185mm.

The designed grinding machine can grind the inner and outer surface of the pipe, the whole system is shown in figure 1.

The grinding machine can be integrated with an industrial robot. The detail components of the designed grinding machine are shown in figure 2. The grinding machine has 7 components.

Those are: - linear actuators to control the belt-tightening, the rotational motion transmission mechanism between the grinding belt and the grinding motor through flexible shaft will be transmitted. The rotational speed of the motor is 3000RPM. The link mechanism simultaneously grinds the inner and outer side of the pipe through lifting mechanism, to do this job the link mechanism the ability to lift and control of the pipe thickens using the torque of the servo motor is 1200Nm. The mechanism
torque is 57.6N/m. The ability to grind the pipe of the proposed model employ with industrial robot KUKA Kr360 model high efficiency and flexible movement. To ensure grind and inspect we employ a 3D lessor sensor to track to identify the welding seam and inspecting the grinding processes.

![Figure 1](image1.png)

**Figure 1.** A new proposed grinding mechanism for spiral welded pipe integrated with KUKA kr360 robot.

![Figure 2](image2.png)

**Figure 2.** Components of the designed grinding machine.

2.2. **Strength check of key components**

Solid work is used to check the strength of key components, Max von mises stress this failure criterion is used for ductile material (aluminum, steel brass, bronze, etc.). it consider the best predictor of actual failure in ductile material and as such provides a good indication of the true safety factor, this criterion is also referred to as “distortion energy theory”.

\[
\frac{\sigma_{\text{Mises}}}{\sigma_{\text{Limiting}}} < 1
\]  

(1)

The equation currently set to identify the locations in the model where the ration of Von Mises stress to the limiting value stress (i.e. the yield strength)< 1.

Safety factor =n=Strength /Stress

The model of the grinding machine simulation analysis results as we can see from figure 3. To do this simulation analysis first we selected the material type of the part, (ISO1023 Carbon steel sheet(ss) and ISO Alloy steel), finally, we assure the model can perform the grinding job without any failures.

![Figure 3](image3.png)

**Figure 3.** Grinding mechanism stress simulation result using Solidworks 2017.
2.3. Design and analysis the grinding head
The selected pulley and belt setup geometry for the designed grinding mechanism open belt geometry as we can see from figure 4.

\[ L = \sqrt{\frac{4}{a^2} \cdot (D_1 - D_2)^2 + \frac{\pi}{2} (D_1 + D_2)^2} \Delta D \]  \hspace{1cm} (2)

where, \( \beta = 2 \sin^{-1} \frac{D - d}{2a} \) \hspace{1cm} \( \theta = \pi + \beta \) \hspace{1cm} \( Y = \pi - \beta \)

According to the above belt equation, we can get the belt length. The new model of the grinding machine is double side grinding as we can see from figure 5 both sides of the pipe we can grind simultaneously by this method we can improve the grinding efficiency.

2.4. Belt grinding parameters
✓ Structural form: two-wheel active grinding
✓ Abrasive belt: SK840X, 36, width 50mm, In general, choosing a wider bandwidth will reduce the wear of the belt per unit area and increase the grinding cutting efficiency. However, for spiral weld grinding, the weld is in the sand due to the weld width and the helix angle. The contact area of the (cylinder) surface is constant, so the width of the belt is should able to touch the width of grinding seem onetime travel, so the 50mm belt width is sufficient to ensure the tracking range.
✓ Pulley: Diameter 150mm Driving wheel, and Passive wheel: cast steel perform grinding in the steel pipe, the pulley should not be too large when designing the inner grinding head.
✓ Line speed / angular velocity, To give full play to the belt drive capability, the belt speed is optimally designed to be about 20 m/s.

\[ V = \frac{\omega \pi D}{60} \cdot \frac{60}{60} = 23.56 \text{ m/s} \]  \hspace{2cm} (3)

where: \( \omega = \) speed, rpm. \( v = \)linear velocity, m/s. \( D = \)diameter of the pulley m,
✓ Grinding power/belt speed and motor. \( P = 17.49 \text{kw} \)

\[ P = F_r \cdot \lambda = \lambda v F_r \]  \hspace{2cm} (4)

\[ F_r = \frac{[F] \cdot q v^2}{\Delta} \left(1 - \frac{1}{e^{\Delta \pi}}\right) \]  \hspace{2cm} (5)

\[ P = v \left([F] \cdot q v^2 \right) \left(1 - \frac{1}{e^{\Delta \pi}}\right) \]  \hspace{2cm} (6)

✓ Belt length, The design of the center distance mainly considers the size of the pulley, the adjustment gap, the design spacing of the tensioning mechanism/support mechanism. When designing, be careful not to exceed the minimum pipe diameter processing range. The length of
the belt is based on the center distance and belt the wheel size is determined. This paper selects according to the structural design: \( L=1043.75\approx1044\text{mm}, a=286.26\text{mm} \)

- Motor torque, The motor output torque is 12Nm the gearbox 1:10 ratio the gearbox 100rpm.
- Belt length, The design of the center distance mainly considers the size of the pulley, the adjustment gap, the design spacing of the tensioning mechanism/support mechanism. When designing, be careful not to exceed the minimum pipe diameter processing range. The length of the belt is based on the center distance and belt the wheel size is determined. This paper selects according to the structural design: \( L=1043.75\approx1044\text{mm}, a=286.26\text{mm} \)

To calculate the torque first we need to know the centroid distance of the grinding mechanism and mass of the grinding head, so we can get from those variables of grinding mechanism model from figure 6.

\[
\text{Torque} = d \times mg = 0.3848 \times 13.5 \times 9.81 = 50.96\text{Nm}.
\]

![Figure 6. New proposed grinding mechanism model](image)

**Figure 6.** New proposed grinding mechanism model.

\[ T = d \times mg = 0.3848 \times 13.5 \times 9.81 = 50.96\text{Nm}. \]

3. Kinematic models

Kinematics is the study of motion without regard to the force which causes it. Kinematics is the most fundamental aspect design, analysis and control simulations. The kinematics of the manipulator involves the study of geometric and time-based properties of the motion and a particular how the various link moves concerning one another with time. The typical robot is a serial link manipulator compressing a set of the body called the link in a chain connected by joint. Each joint has one degree of freedom either translational or rotational. The link offset is the distance from one link to the next along the axis joint.

As we can see from figure 7, KUKA KR360 R2830 has a serial 6DOF robot arm with all revolute joints.

![Figure 7. Selected Robot KUKA KR 360 R2830 Direction of rotation of robot axes.](image)

**Figure 7.** Selected Robot KUKA KR 360 R2830 Direction of rotation of robot axes.

![Figure 8. Denavit-Hartenberg analysis (DH) Parameter for KUKA kr360 Robot.](image)

**Figure 8.** Denavit-Hartenberg analysis (DH) Parameter for KUKA kr360 Robot.
The selected KUKA KR360 R2830 robot is designed for a related payload of 360 Kg, and the pose repeatability 0.08mm and the arm extension of up to 500 mm. To perform forward kinematics analysis for KUKA KR360 R2830 numbered link and joints and its attached local coordinate reference frame in figure 8.

Table 1 summarized the Denavit-Hartenberg analysis (DH) parameter for each link according to DH rules.

| i | $\theta$/$^\circ$ | $d$/mm | $a$/mm | $\alpha$/$^\circ$ | $\theta_{\text{min}}$/$^\circ$ | $\theta_{\text{max}}$/$^\circ$ |
|---|---|---|---|---|---|---|
| 1 | $\theta_1$ | $d_1$=1045 | $a_1$=500 | -90 | -185 | 185 |
| 2 | $\theta_2$ | 0 | $a_2$=1300 | 0 | -130 | 20 |
| 3 | $\theta_3$=-90 | 0 | $a_3$=55 | -90 | -100 | 144 |
| 4 | $\theta_4$ | $d_4$=1025 | 0 | 90 | -350 | 350 |
| 5 | $\theta_5$ | 0 | 0 | -90 | -120 | 120 |
| 6 | $\theta_6$ | $d_6$=290 | 0 | 0 | -350 | 350 |

The Denavit-Hartenberg homogenous transformation matrix of KUKA KR360 R2830.

$$H_i = [\begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & a_i \cos \theta_i \\ \sin \theta_i \cos \alpha_i & \cos \theta_i \cos \alpha_i & a_i \sin \theta_i \\ \sin \alpha_i & 0 & 1 \end{bmatrix}]$$

**Figure 9.** Design simulation result on new grinding mechanism pose 1.

**Figure 10.** Design simulation result on a new grinding mechanism pose 2.

The Toolbox is representing the kinematics and dynamics of robot manipulators. Creating a model in the robot toolbox. To perform the robot motion trajectory, first, we select two positions of the robot the initial position and the final position. Pose1, figure 9, is the initial position or robot setup position and pose2, figure 10, is a final position or the desired position of that the end effector to reach the position and performing the grinding job.

### 4. Trajectory planning

Trajectory generation computes the time of the motion for the robot, trajectory defines in the joint space in Cartesian space. Using MATLAB toolbox to track KUKA KR360 grinding robot the trajectory planning has two functions is known to initial and terminate the joint angle using the fifth-order polynomial to plan the trajectory known initial and terminated position the use of uniform acceleration and uniform deceleration movement to plan the trajectory. Assume that the initial variable of the end grinding robot.

$\mathbf{q}_{\text{initial}} = [0, -90, 90, 0, 0, 0]$ this joint angle value is the mastering position (pose 1) of the robot.

$\mathbf{q}_{\text{final}} = [0, -40, -50, 0, 0, 0]$ this joint angle value we got from robot toolbox command with r.teach the desired position (pose 2), of the robot joint angle value. set the running time $t=3s$ and the interval time 0.025s with the fifth-order polynomial interpolation that is,
\[ (\theta) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \]  
\( (\dot{\theta}) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4 \)  
\( (\ddot{\theta}) = 2a_2 + 6a_3 t + 12a_4 t^2 + 20a_5 t^3 \)

By differentiating Equation (7) the velocity profile is obtained as shown equation (8),

By differentiating equation (8) the acceleration profile we obtained as shown equation (9),

\[
\theta(t_0) = \theta_0 \quad \dot{\theta}(t_0) = \dot{\theta}_0 \quad \ddot{\theta}(t_0) = \ddot{\theta}_0 \quad \theta(t_f) = \theta_f \quad \dot{\theta}(t_f) = \dot{\theta}_f \quad \ddot{\theta}(t_f) = \ddot{\theta}_f
\]

To achieve the smooth transition from one phase to another, the boundary conditions for the initial and final position, velocity and acceleration must be satisfied.

Those values we gate from MATLAB toolbox, the time interval \( t=3 \) interval with 0.025s, pose 1 joint angles \([0, -90, 90, 0, 0, 0]\); Pose 2 joint angles \([0, -40, 50, 58.5, 67.12, 0]\);

![Figure 11. Position Simulation of the motion trajectories of the joints in the kinematics of the robot.](image)

![Figure 12. Velocity Simulation of the motion trajectories of the joints in the kinematics of the Robot.](image)

![Figure 13. Acceleration Simulation of the motion trajectories of the joints in the kinematics of the robot.](image)

In the MATLAB environment through the robotics toolbox to establish a three-dimensional model of the robot. As shown in the figure for the final state of the robot model. The trajectory function used to plot the joint trajectory in the joint space, the joint of the robot changes smoothly speed and acceleration changes smoothly can successfully from the initial state to the final state (reach the target), that based on the D-H theory to establish of the robot link parameter are correct, based on joint space trajectory planning is feasible and the robot movement without vibration.

The trajectory simulation plot result figure 11 to figure 13 show that the joints of the robot change smoothly, speed and acceleration changes, can successfully from the initial state to reach the target state, that based on the D-H theory to establish Of the robot link parameters are correct, based on joint space trajectory planning is feasible, and the robot movement without vibration.

5. Conclusion

This paper present a newly-designed grinding machine for a spiral welded pipe manufacturing industry, the machine has equipped with a special grinding machine with the ability to grind the spiral welded pipe the inner and outer surface simultaneously of the pipe and equipped with 6DOF grinding
robot. The kinematics model of grinding robot is derived and the joint trajectory is calculated. The simulation results show that the grinding mechanism can perform their job without any failures under the 50.96N/m external force, and also as we see the trajectory graph of the robot kinematics simulation, we can know there is no vibration on the robot movement to perform the job. This new design machine improves manufacturing flexibility, weld grinding quality, and consistency. The study implies a spiral welded pipe manufacturing industry and future researchers.

**Future scope**

On this new intelligent system of grinding mechanism, we employ a3D lessor sensor, in the next job we will perform the lessor sensor communicate with the robot and the grinding mechanism using a PLC control system then experiment.

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