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Failure analysis of pipeline indents using steel precision balls under subsea conditions

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ABSTRACT

Mechanical connectors used to repair sub-sea pipe lines can use balls to achieve grip on the pipe surface. While designed to indent the pipe surface, it has been found that some balls skid instead which reduces the connection integrity.

This work was aimed at finding important features which relate to rolling and skidding of precision balls on the surface of pipes. A skidded ball is associated with a failure and a rolled ball is associated with success. Experiments simulating the activation were performed and compared with analytical models. Several features such as friction, ball size, material hardness and surface finish were identified as important for understanding the transition of the ball from roll into skid. The results of the surface and subsurface analysis correlated well with the model output. Once the important features are verified, progress can be made to achieve production of more robust connectors (from successful activations) leading to better customer confidence in buying mechanical pipeline connector products.

1. Introduction

Sub-sea pipe-lines may require mechanical connectors as part of a repair strategy. In such connectors, a series of precision balls arranged circumferentially around the pipe in axial rows are used to achieve a mechanical grip (Fig. 1a). As the connector is actuated the balls roll along a taper housing (Fig. 1b), leading to an increasing radial force. The taper housing angle is kept at 10° with the respect to the x-axis in the Figure. This radial force causes the ball to indent the pipe material, leaving a teardrop (Fig. 1c) shaped impression, and results in the connector gripping the pipe [4]. The scale of the teardrop (0.5 mm indent depth) in Fig. 1c is proportional to the size of the precision ball used (ϕ 30 mm). Unfortunately the teardrop formation does not always happen, and in some instances it has been noted that the balls skid instead of rolling along the taper and indenting, resulting in the connector not gripping the pipe. In this case, a witness mark is evident on the pipe surface, though no actual deformation or radial load increase occurs.

Previous investigations by Hydratight have linked the probability of a skid to factors such as the taper angle (>11°), along with pipe tolerance and surface finish [1].

In this study, the contact conditions occurring between the ball and pipe material have been simulated using a Bruker® UMT 3 Tribometer, with the aim of investigating the factors that lead to the ball either rolling and indenting, or skidding. This approach has been coupled with analytical modelling of the contact conditions present, in order to assess the likely impact of factors such as the mechanical properties of the materials, surface roughness and friction coefficient. The outcomes of this study will then be used by Hydratight to identify conditions when skidding is likely, helping make failure predictions more robust.

Similar work (related to ball indent analysis) was reviewed for background research purposes. Kaneta et al. modelled the surface roughness by engineering a constant height and wavelength bumps on smooth steel surface [20]. Bhushan proposed a 3-D model which could produce a surface of varying size and height asperity distributions, which would replicate a real surface. The asperities were noticed to be elastically and elastic-plastically deforming by an elastic sphere in motion depending on the contact mechanics and the asperity shape and orientations [22]. The chrome steel has a high hardness value and is almost 3–4 times harder than the pipe surface. This is equivalent of using a rigid sphere in motion over a model replicating a real surface. In the initialization process, the ball would deform the asperities elastically but would eventually plastically deform all asperities in contact.

A FEA model using frictional contact was presented by Kogut wherein the deformations were in the elastic-plastic region. The two rough

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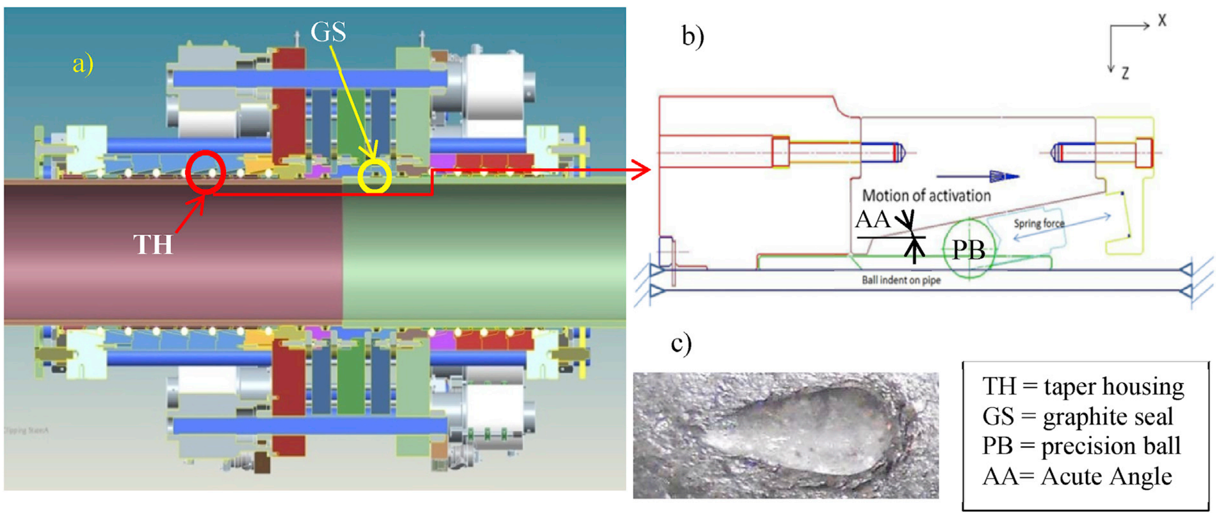

Fig. 1. a) Illustration of a typical mechanical connector. b) Ball activation mechanism; Angle $= \frac{\pi}{18}$ rad. c) A typical teardrop formation on a pipe wall after indentation.

surfaces in contact were tested in a sliding motion [21]. The friction was found to be affected by the amount of permanent deformation and adhesion between the two surfaces. The adhesion between the chrome steel precision ball and carbon steel material is negligible.

Bogy et al. found, using a point contact microscope, that the hardness of a material increases with small indent depth and loads but the hardness becomes insensitive once a limit has reached [23]. The indent depths discussed in this paper are higher than the range tested by Bogy (50–100 nm). This means the hardness value would not change much for the higher range of indents but will change during the indent initialization process.

A UMT 3 tribometer with slow reciprocating module was used to analyse the rolling friction of balls rolling friction dependence on rotational speed in dry contacts [2]. The results were then compared to an analytical model which showed high correlation with the experimental results. The analytical model predicted the values and location of the maximum shear stress based on the mechanical properties of the materials in contact and friction/traction coefficients. If the location of the maximum shear stress is away from the centre of the ball and close to the surface, it means the ball is sliding opposed to rolling when the maximum shear stress is located subsurface towards the centre of the ball.

There were also comparisons done on the rolling friction of balls on micro and macro levels in dry and lubricated or wet conditions for which the results fitted well with the analytical models [3].

The main objective of the work outlined in this paper was to understand the complex contact mechanics between the balls and the pipe and identify the key parameters that cause the balls to skid from rolling conditions. This information can be used to ensure better integrity of the connector and eventually of the pipeline system.

To our knowledge, Hertzian contact models have been rarely compared against experiments using precision balls in sliding and rolling motion. The key novel aspect of this paper is the validation of the analytical theory for this scenario allowing improved confidence in using the model for the ball 'skidding' problem.

2. Connector ball-pipe contact mechanics analysis

2.1. Activation of mechanical connector

Activation is the process of closing the connector to effect a pressure seal and create a firm grip onto the concerning pipe. During the process, precision balls are used to indent onto the pipe surface while they roll using a taper housing which traverses axially, as illustrated in Fig. 1b. The ball rolls in the direction of the activation and progress to move to the lower part of the inclined surface (10°) under generation of radial force from the taper geometry. The spring is to ensure all balls are in contact with the pipe considering that gravity will affect some of the balls. Once the ball has touched the pipe and the ball starts rolling, the spring-force is no longer required. The activation process was modelled using an analytical approach which was compared with the results from physical testing. The comparison will gave a sense of how well the model actually operates in terms of accuracy.

2.2. Mechanics

In order to find which features of the ball indent mechanism lead to ball skidding, a full mechanical assessment of the ball indentation process was carried out The forces acting on the ball while it is forced to indent into the pipe material can be divided into vertical ($\boldsymbol{F_v}$) and horizontal forces ($\boldsymbol{F_h}$) respectively as shown in Fig. 2. These forces on the ball are resisted by the reactions at the contact and due to friction arising from the rolling or skidding motion. If the ball is rolling (due to rolling force $\boldsymbol{F}$ in Fig. 2), there is a frictional force opposing this motion defined as $\boldsymbol{F_{\mu\ roll}}$. On the other hand, if the ball is sliding, the force of sliding $\boldsymbol{F_{skid}}$ is opposed by $\boldsymbol{F_{tan}}$.

Note that the $\boldsymbol{F_{tan}}$ and $\boldsymbol{F_{roll}}$ are different in the sense that one is due to sliding and the other is helping the rolling motion respectively. The sliding resistance is always higher than the *'elastic'* rolling friction. As the ball starts rolling down the taper, it has to indent the pipe material with an indent radius $\boldsymbol{r}$. The indent radius keeps changing with the amount of indent depth, δ. Since the ball is spherical and the outer surface of the

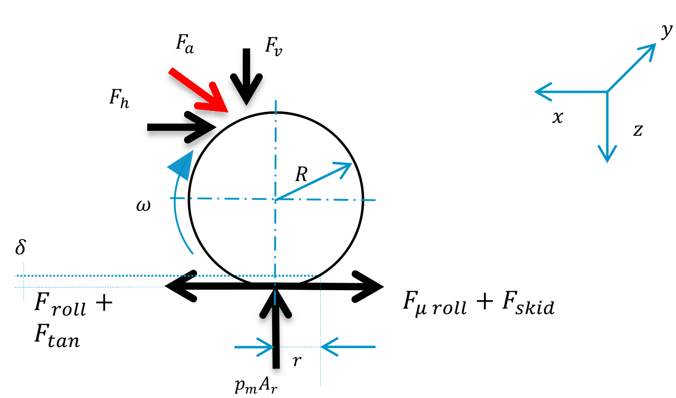

Fig. 2. Illustration of the ball indent mechanics involving forces leading to roll/skid.