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Development of Premium Connection "KSBEAR" for Withstanding High Compression, High External Pressure, and Severe Bending*

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Synopsis:

For the connection of oil well tubes used in increasingly severer environments, special screw joints equipped with metal-to-metal seals, excellent in resistance to leakage, are generally used. However, there are increasing in number, stricter oil well designs whereto screw joints of conventional properties have bacome inapplicable any longer. Under the circumstances, oil well screw joints, having anti-leakage property, bearable specifically in an environment of the burdens of compression, external pressure and bending have become strongly demanded. To satisfy the above-described demands of customers, Kawasaki Steel has developed "KSBEAR", substantially exceeding the properties of conventional tubular joints. Through the unique advanced design concept of a new screw thread, the development of a screw joint outstandingly surpassing the level of API Class 1 has been achieved.

1 Introduction

In recent years, much emphasis is placed on profitability in oil well development and subsequent oil production, yet successive mergers between major oil companies and other structural changes have led the world oil industry into fierce cost competition. In response to these changes, oil wells are getting deeper, and the numbers of directional wells[1] and horizontal wells are increasing. Accordingly, the condition in which threaded connections are used for connecting oil and gas well tubes is becoming increasingly severe.

The method of evaluating special threaded connections for oil well tubes is stipulated in API RP (American Petroleum Institute: Recommended Practice) 5C5. Even in the highest-ranking Class 1 requirements, the stipulated test conditions are only up to the compression of 40%PBYS (pipe body yield strength) and the leak test under bending is not stipulated.[2] On the other hand, some of the test methods recently adopted by individual oil companies take into account the actual usage environment and incorporate severe conditions such as high compression of 80%PBYS and bending of 39.4°/30 m (equivalent to the bending radius of 43.7 m). Conventional oil well tubing threaded connections for OCTG (oil country tubular goods) can not meet these severe test conditions. Further, in view of global environmental protection, the ratio of gas wells is increasing, and so leakage resistance is becoming more important. There is strong market demand for special threaded connections, premium joints which have far better performance compared with conventional connections. In order to meet this demand, Kawasaki Steel has developed the premium joint for oil well tubes "KSBEAR" that has excellent leakage resistance under high compression, high external pressure, and severe bending. This report outlines the KSBEAR threaded connection, its performance evaluation using FEA (finite element analysis), a test method for evaluating the connection performance, the results of the evaluation, and its production technology.

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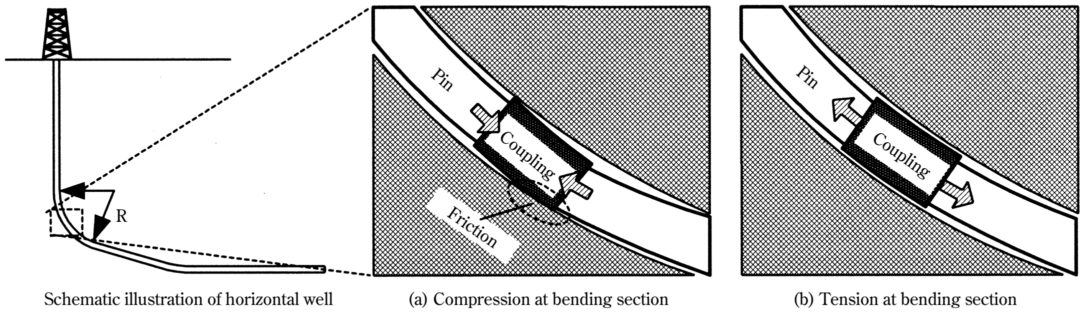


Fig. 1　Force to thread joint in well

2 Performance Required for Oil Well Tubing Threaded Connections

2.1 Leakage Resistance

Oil well tubes and their connections are subjected to various loads while being installed and subsequently used for oil production. During and also after installation, tensile load acts on the connections due to the self weight of the tubes; external pressure acts on the connections from the wall of the oil well; and internal pressure acts from within the tube due to the fluid being produced.

With regard to a horizontal well as shown in **Fig. 1**, compressive load acts on the inside of the bending section and tensile load on the outside. Compressive load also acts on it due to friction at a point where the tube contacts the oil well wall while being installed. When it is released from the friction with the wall, tensile load starts acting on it again. Therefore, the threaded connections used in oil wells require leakage resistance under the following conditions.

(1) Compression and tension,
(2) External and internal pressure,
(3) Bending, and
(4) Combined load of (1) to (3).

2.2 Workability of Threaded Connections

If some troubles occur in peripheral equipment or somewhere in the installation system while running, it is necessary to pull out the tubes to the rig, and break out the threaded connections, and make up again before resuming the running. Therefore, the threaded connection needs to have galling resistance for withstanding multiple cycles of make up and breakout. In recent years, environment-friendly "green" dope that contains no heavy metals such as lead is increasingly being used to prevent environmental pollution, which makes the galling resistance of the connections more important.

Further, in order to shorten the running time, it is important to prevent cross threading between pin and coupling, and to improve the operating efficiency.

The properties required for make up are:

(1) Anti-galling performance
(2) Operating efficiency

3 Features of KSBEAR

Figure 2 shows the design of the KSBEAR, and **Table 1** summarizes its design features.

3.1 Adoption of Hooked Thread

Figure 3 shows the modified buttress thread form

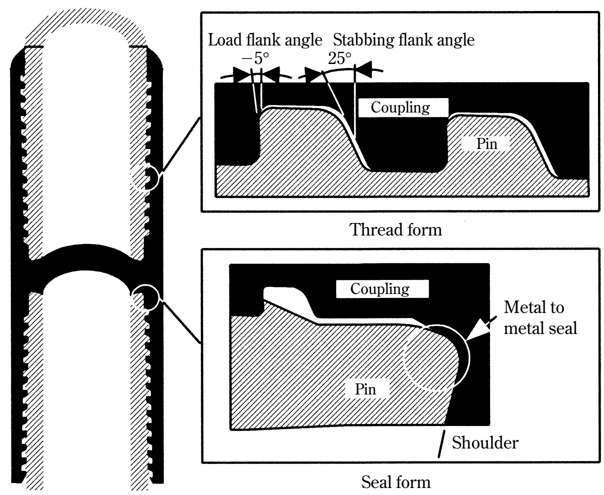


Fig. 2　KSBEAR design

Table 1　Design features and resulting improvement

Design feature	Resulting improvement
Negative load flank angle on thread	Increased tensile capacity
	Increased bending capacity
	Increased external pressure capacity
Optimized gap between stabbing flanks on pin and coupling threads	Increased resistance to compression loads
Different corner radius on load flanks on pin and coupling threads	Increased resistance to galling
Different load flank angles on pin and coupling threads	Increased external pressure capacity
	Increased resistance to galling
25° angle on thread stabbing flank	Fast make-up and increased resistance to cross threading

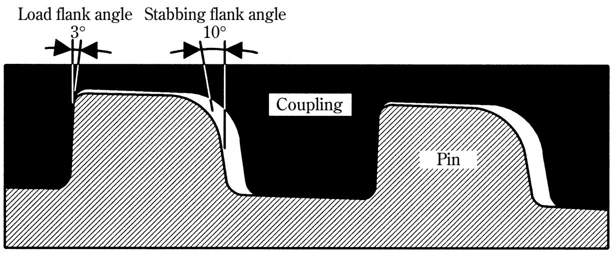


Fig. 3 Form of modified buttress thread

used for normal premium joints. When tensile load, bending load, and external pressure act on a connection that has a modified buttress thread form, these loads generate a force that moves the pin thread and coupling thread away from each other in the radial direction. In the KSBEAR, the hooked thread form was adapted, which significantly reduced the force that moves the pin thread and coupling thread away from each other in the radial direction when tensile load, bending load, or external pressure acts on it.

3.2 Optimization of Gap between Stabbing Flanks

The surfaces of the threads that work as guides in the process of making up the pin and coupling are called stabbing flanks, and the surfaces of the threads that come in contact with each other when the pin and coupling are tightly made up are called load flanks. When the pin and coupling are made up, there is a space between the stabbing flanks facing each other. When a compressive load acts on the connection, the load flanks of the pin and coupling are separated. **Figure 4** shows the results of FEA for investigating the thread condition when a high compressive load of 90%PBYS acts on the connection. The figure shows that the stabbing flanks contacting each other carry the compressive stress in the KSBEAR thread. Conversely in the modified buttress thread, there is a wide gap between the stabbing flanks of the pin and coupling threads and, even when a high compressive load of 90%PBYS acts, the stabbing flanks do not come in contact with each other. Therefore, all the stress in the axial direction of the tube needs to be carried by the sealing section and torque shoulder, and plastic deformation is caused there. When a tensile load is applied after compression, the contact pressure at the sealing section is lowered, resulting in leakage. In contrast, in the KSBEAR, the gap between the stabbing flanks is optimized so that the stabbing flanks come into contact with each other when high compression is applied. Approximately 19% of the total compressive load is carried by the stabbing flanks in contact with each other (in case of 80 ksi 7″ × 32.0 lb/ft). Accordingly, the loads acting on the shoulder and sealing section are reduced and plastic deformation at these sections is significantly suppressed. As a result, the leakage resistance is markedly improved when a tensile load is applied after compression.

3.3 Optimization of Corner Radius of Load Flank of Pin Thread

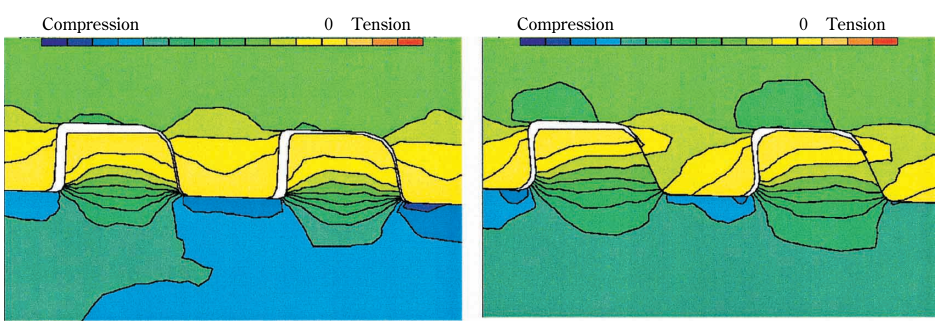
As stated in Section 3.1, the hooked thread offers good leakage resistance. However, galling tends to occur when the threads are being made up, particularly at a position where stress concentrates: that is, the upper portion of the load flank of the pin thread. In the KSBEAR, the radius of the upper corner of the load flank was made larger to prevent stress concentration that causes galling. As a result, the KSBEAR has excellent galling resistance.

3.4 Optimization of Load Flank Angles of Pin and Coupling Threads

As stated in Section 3.3, stress tends to concentrate at the crest of the hooked pin thread and cause breakage there. In the KSBEAR, the angle of the load flank of the pin thread against that of the coupling thread was modified so as to make the stress concentrate at the lower portion of the pin thread that has the highest strength. **Figure 5** shows the stress distribution obtained by FEA. The galling resistance was further improved.

3.5 Stabbing Angle of 25°

In the running of connection at an oil well, a pipe lifted up is lowered and a pin end of the pipe is inserted into a coupling. If cross threading occurs in this process,



(a) Modified buttress thread
(b) KSBEAR thread

Fig. 4 Axial stress distribution by FEA at 90%PBYS compression (13 Cr-80 7″ × 29.0 lb/ft)

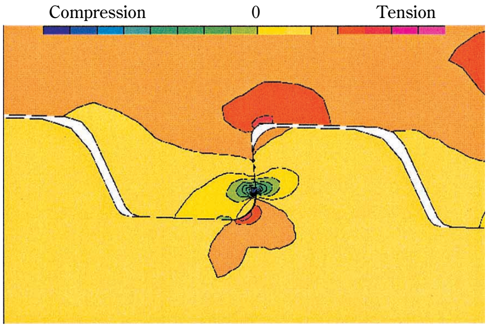


Fig. 5　Axial stress distribution by FEA at make-up (KSBEAR)

the work efficiency is decreased significantly. Therefore, the stabbing angle was increased to 25° in the KSBEAR from 10° in the modified buttress thread to improve the make-up efficiency.

4 Development of FEA Models

FEA is an effective means to estimate the amount of elasto-plastic deformation in the threaded connections and the contact pressure at the sealing sections in the physical test quantitatively. However, conventional FEA models cannot simulate results of the physical test carried out under severe conditions not previously experienced, such as extremely high compression, high external pressure, and severe bending. Therefore, two models were newly developed as described below.

4.1 Successive Make-up Model

Leakage tests of threaded connections are generally performed after multiple cycles of make-up and break-out of the threads. It is necessary to evaluate the amount of strain generated in the axial and radial directions of the tube when multiple cycles of make-up and break-out are successive performed. Conventional FEA models can only be used to analyze a single make-up. In the newly developed model, imaginary thermal strain is given in a region where the coupling is located as shown in **Fig. 6**, and allowed to expand and shrink in the axial direction in order to model the thread make-up and break-out. **Figure 7** compares the values of axial strain and hoop strain calculated by FEA and with those measured in the experiment. Evaluated points at make-up are shown in **Fig. 8**. The values calculated using the new FEA model and observed values are in good agreement, thus confirming the high accuracy of the new model.

4.2 Bending Model

Almost no FEA has been carried out for analyzing the results of bending tests so far. A bending load is axially non-symmetrical; therefore conventional axially symmetrical models are not applicable. For analyzing bending behavior, a 3-dimensional model is needed, but developing a 3-dimensional model is too laborious and the calculation time is too long, so it is not a practical solution. Therefore, a new bending model was con-

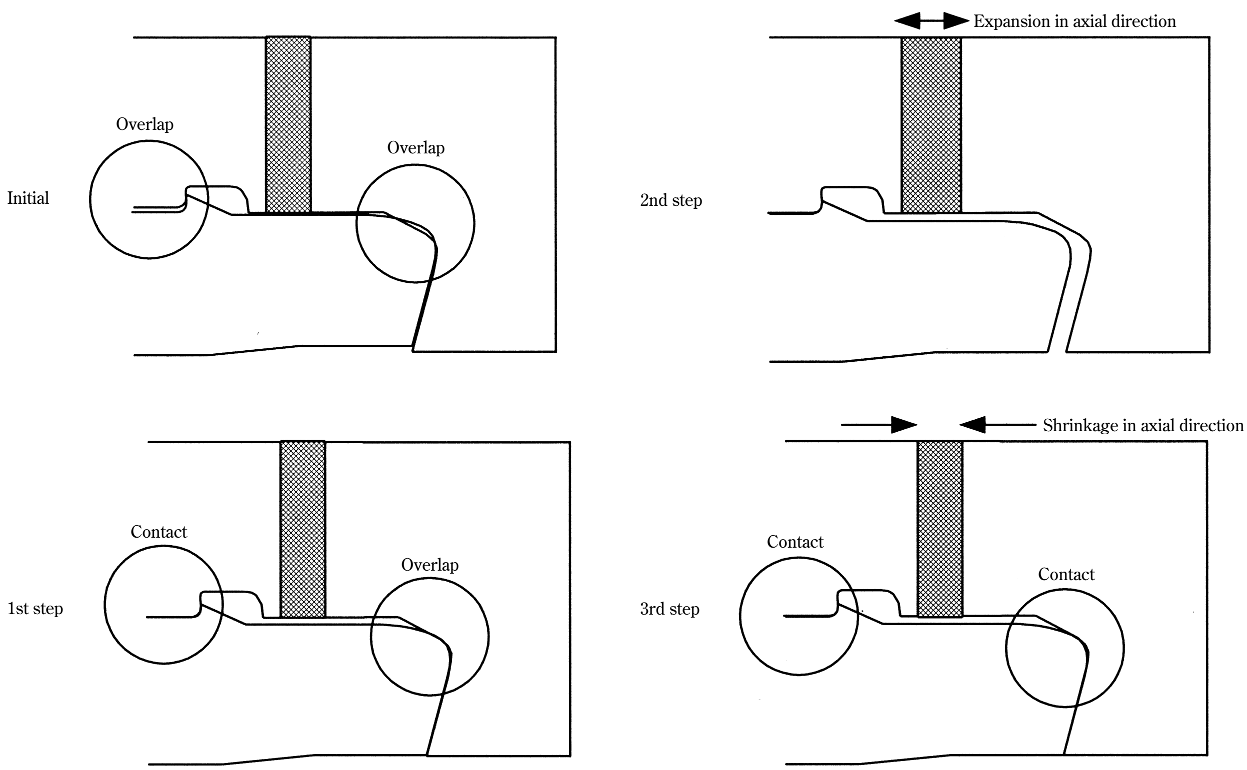


Fig. 6　Make-up model in FEA model

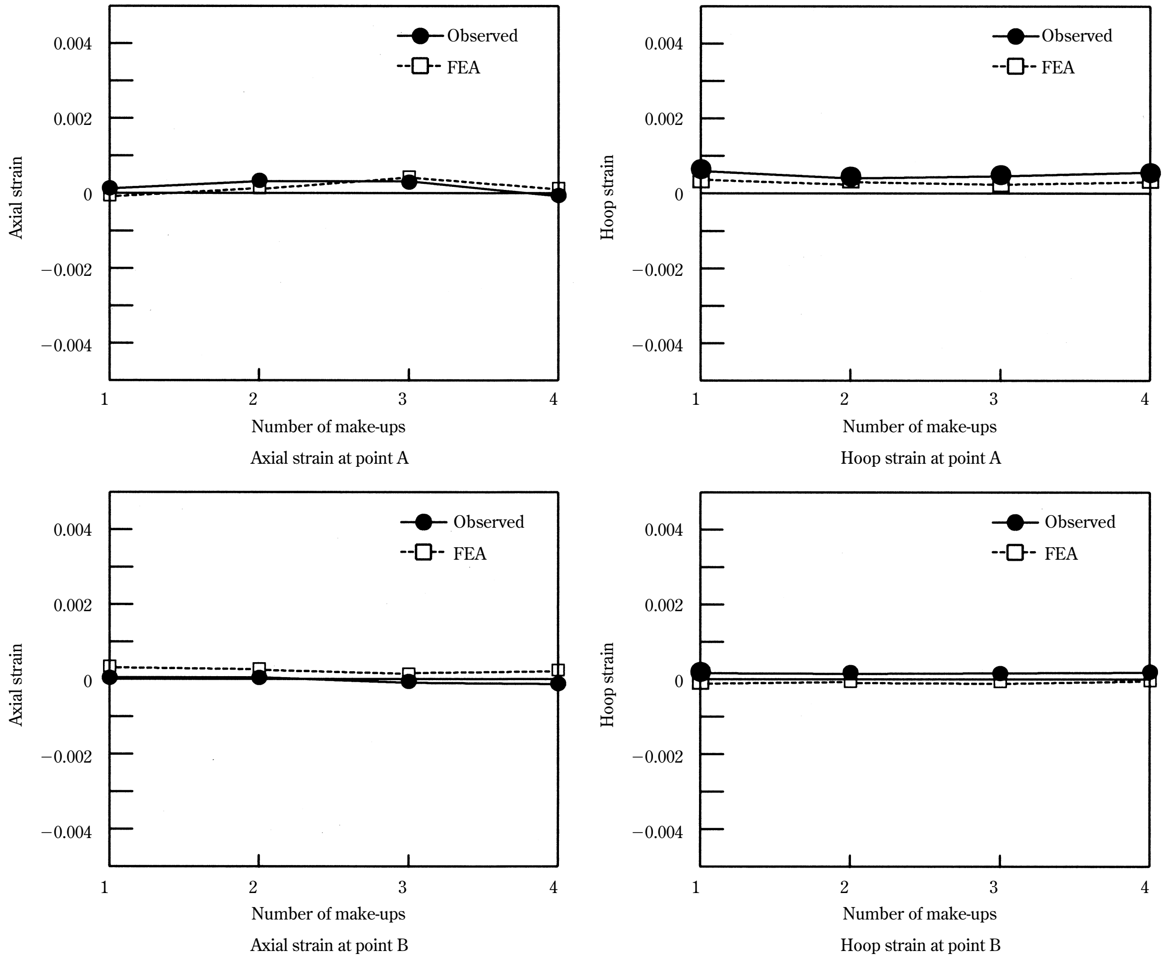


Fig. 7 Change in strain by number of make-ups

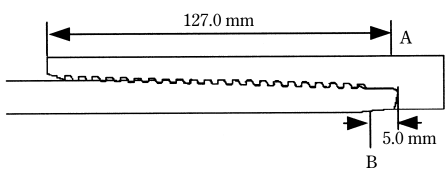


Fig. 8 Evaluation point for stress at make-up

structed employing axially symmetrical elements that permit non-linear, axially non-symmetrical deformation; hence 3-dimensional analysis can be performed using an axially symmetrical model. These elements have independent nodal points in the hoop direction. Nodal point displacement is calculated from the equation of equilibrium of force at each nodal point. Displacement at an arbitrary point is given by Eq. (1).

$$\begin{Bmatrix} u_r \\ u_z \\ u_\theta \end{Bmatrix} = \sum_{m=1}^{M} H^m(g, h) \times \left(\sum_{p=1}^{P+1} R^p(\theta) \begin{Bmatrix} u_r^{mp} \\ u_z^{mp} \\ 0 \end{Bmatrix} + \sum_{p=1}^{P} \sin p\theta \begin{Bmatrix} 0 \\ 0 \\ u_\theta^{mp} \end{Bmatrix} \right) \cdots (1)$$

Where u_r^{mp}, u_z^{mp}, u_θ^{mp} are respectively the displacement component in the radial direction, axial direction and hoop direction at $\theta = \pi(p\text{-}1)/P$; $H^m(g, h)$ is the interpolation function in the r-z plane at $\theta = 0$; $R^p(\theta)$ is the interpolation function in the hoop direction; M is the number of nodal points in the element; and P is the number of nodal planes in the hoop direction.

The bending load is the bending moment equivalent to the bending amount that is given at the end of the pin. **Figure 9** shows the results of FEA calculation. **Figure 10** compares the results of calculation using the newly proposed FEA model and the theoretical values. The two sets of values are in good agreement.

5 Performance Evaluation Test of KSBEAR

The method for evaluating threaded connections for oil well use is stipulated in API RP 5C5. However, in recent years, customers are increasingly requesting additional bending tests and higher compression tests.

The performance evaluation test that a certain major oil company requested is introduced below as well as the results of the tests performed on the KSBEAR.

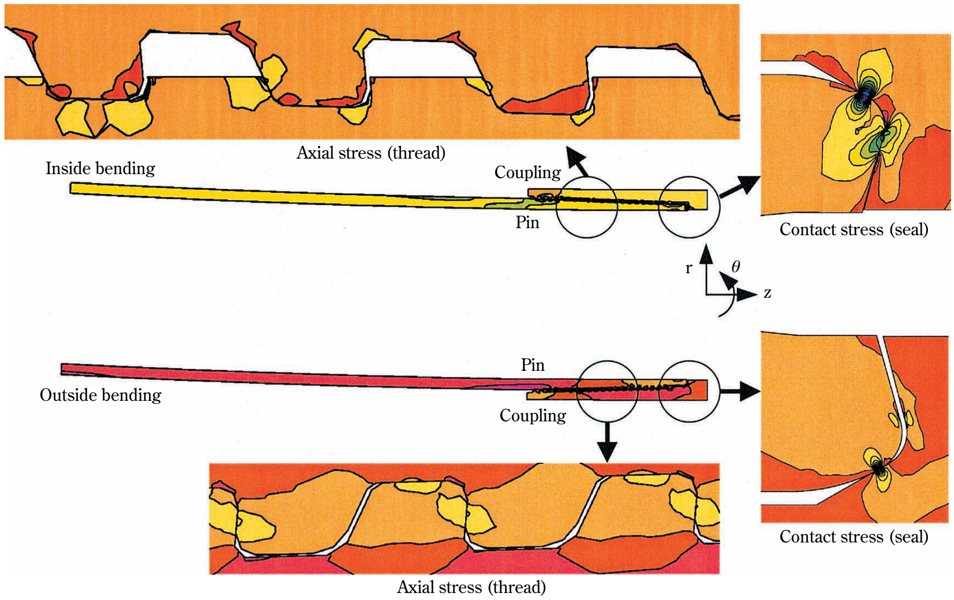


Fig. 9 FEA for 39.4°/30 m bending (80 ksi 5-1/2″ × 17.0 lb/ft)

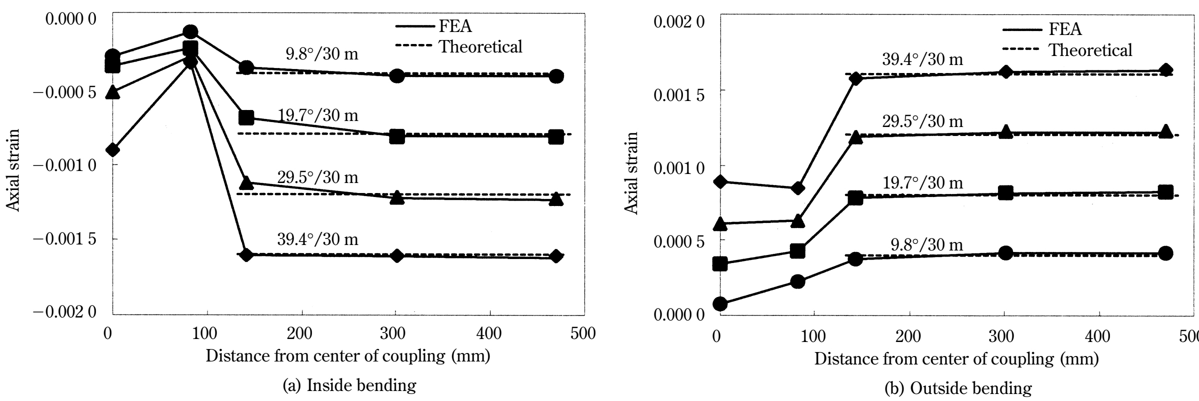


Fig. 10 Axial strain at bending (80 ksi 5-1/2″ × 17.0 lb/ft)

5.1 Test Method

Table 2 shows the grades, sizes, and combinations of interference (thread and seal) of the test specimens. The test procedure is summarized in **Table 3**. The features of this test are as follows.

(1) The environment-friendly green dope was applied in making up the threads.
(2) The bending test was performed at 19.7°/30 m.
(3) The compression test was performed at 80%PBYS (40% for API RP 5C5 Class 1 test).
(4) The thermal-cycling test was performed up to 100 cycles.
(5) Simultaneous compressive and bending loads were applied as well as simultaneous tensile and bending loads.
(6) Make-up tests were performed after leakage tests.

5.2 Results of Tests

No leakage was detected in any of the above tests. The thread and sealing sections were visually surveyed after completing the tests, and no galling was observed. As shown in **Fig. 11**, the KSBEAR caused no leakage even in tests of 80%PBYS compression, that is extremely severe condition never applied to tubing connections in the past, and demonstrated stable performance. The FEA result shown in **Fig. 12** confirmed that the contact pressure indicated its peak value at the sealing section, effectively preventing leakage.

The external-pressure burst test was performed at 80 ksi 2-7/8″ × 6.4 lb/ft. An example of collapsed connections is shown in **Photo 1**. In conventional modified buttress threaded connections, no restraining force acts in the radial direction, and the threads of the pin and coupling tend to disengage. In contrast, the threads of the pin and coupling of the KSBEAR are not easily disengaged even if the tubes collapse and are deformed, and sufficient sealing integrity is maintained, causing no leakage. Thus, the high leakage resistance of the KSBEAR under high external pressure was verified.

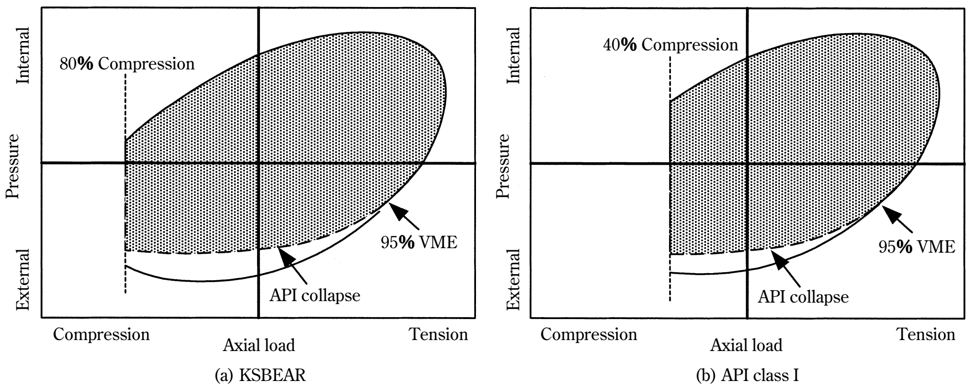


Fig. 11 Performance of KSBEAR

Table 2 Grade, size and interference of specimen

Grade	Size (lb/ft)	Interference*			
13CR-80	5-1/2″ × 23.0	H/H	H/L	L/H	L/L
13CR-80	7″ × 29.0	H/H	H/L	L/H	L/L
13CR-80	7″ × 35.0	H/H	H/L	L/H	L/L

*Thread/Seal
H: High, L: Low

Table 3 Test procedure

	Step	Condition
1	Initial make-up and breaks	1st to 3rd make-up at maximum tubing torque 4th make-up (half of specimens at minimum tubing torque, half of specimens at maximum torque)
2	Bake-out	24 h at 180°C
3	Thermal cycling under tension and internal pressure	Based on 95%VME 40 to 180°C 50 cycles
4	Combined load and internal pressure	Based on 95%VME Tension: 95%PBYS Compression: 80%PBYS Tension and compression with 19.7°/30 m bending
5	Combined load and external pressure	Based on 95%VME Tension: 95%PBYS Compression: 80%PBYS
6	Thermal cycling under tension and internal pressure	Based on 95%VME 40 to 180°C 50 cycles
7	Final make-up and breaks	5th to 10th make-up at maximum tubing torque

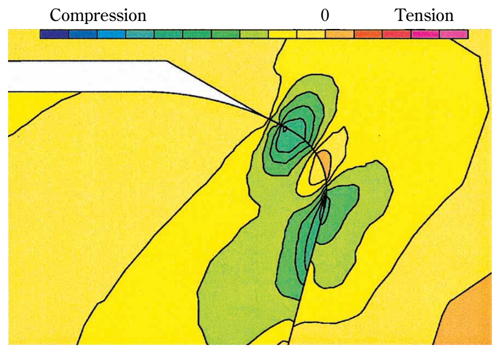


Fig. 12 Seal contact stress under 80%PBYS compression and collapse pressure

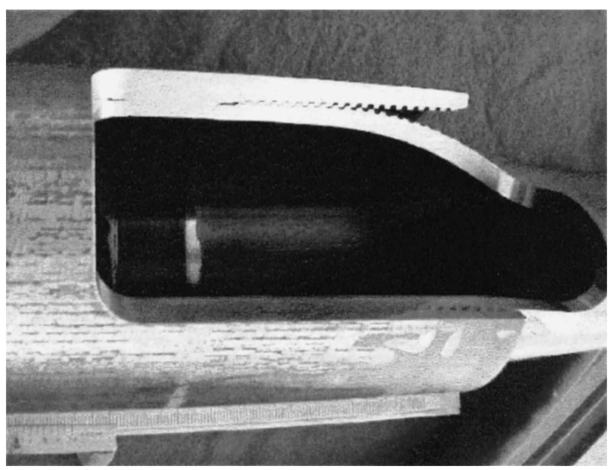


Photo 1 An example of collapsed connection (80 ksi 2-7/8″ × 6.4 lb/ft)

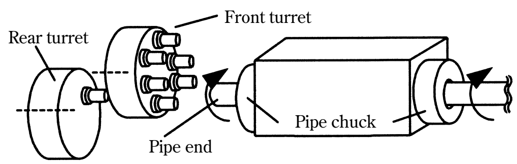
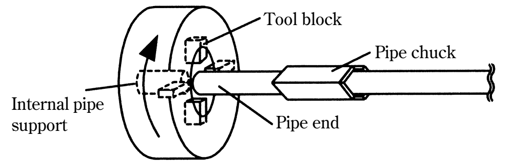
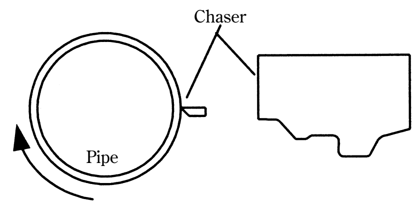
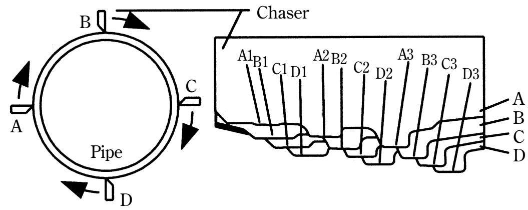
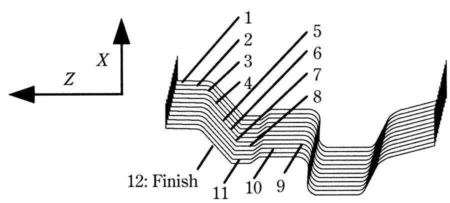
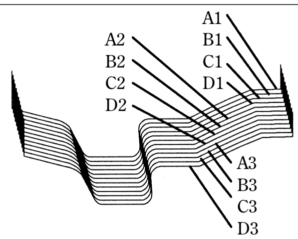
6 Examples of Applications

In November 1999, 249 tubes of HP1-13CR-110 3-1/2″ × 9.2 lb/ft were run. The total length of the tube string was 3 099 m. The running work was completed in just 15.7 h, and no troubles were encountered either in make-up nor in the taking down the tube. It was demonstrated that the KSBEAR has excellent stabbing performance and causes no galling or other troubles.

7 Production Technology

The KSBEAR are produced at Chita Works using the 9-5/8″ NC threading line.[3] This is an integrated production line that performs all the work from pin threading, coupling make-up to length measuring, weighing, marking, and bundling. The features of the technology employed for producing the KSBEAR at this line are as follows.

Table 4 Comparison in threading machine between pipe-rotating type and tool-rotating type

	Pipe-rotating type threading machine	Tool-rotating type threading machine
Schematic illustration		
Chaser arrangement and chaser form		
Cutting order		

7.1 Threading by Tool-rotating NC Machine

There are two types of threading machines: pipe-rotating type and tool-rotating type. The two types are compared in **Table 4**. The pipe-rotating type commonly used has one chaser, and has a large space around the pipe being cut, which leads to excellent tip disposability. However, it performs a designated amount of cutting at a time, and takes longer to complete the threading work, which results in lower productivity. It also has a disadvantage in cutting a hooked thread of KSBEAR, because, for each cutting operation, the cutting trajectory needs to be shifted to the pipe's axial direction (*z*-axis direction) as well as to the radial direction (*x*-axis direction).

On the other hand, the tool-rotating type employed in this threading line uses four chasers positioned around the pipe for cutting threads. Three crests in each chaser have a phase delayed by one-quarter of a cycle from the corresponding crest in the preceding chaser, and the corresponding crests become higher and wider in the order of cutting. The last crest finishes the cutting work. The tool block moves in the pipe's axial direction while the chasers rotate around the pipe. The tool-rotating type can quickly cut a thread that requires a complex cutting method such as a hooked thread. However, its tip disposability is inferior because multiple chasers simultaneously perform cutting work, and the crests of the chasers tend to be broken off. Kawasaki Steel has overcome these shortcomings by improving the configuration of the tool block and so on.

7.2 Seal Portion Cutting by Formed Tool

The seal portion is generally cut by the single-point cutting method. The threading machine in this line employs the formed tool for cutting the seal portion. **Figure 13** compares the cutting methods of the seal portion by single-point cutting and formed tool cutting. In the single-point cutting, the cutting speed needs to be reduced for cutting the seal portion because a high-quality surface finish is required, which prolongs the required cutting time. In the formed tool cutting, a highly accurate seal shape can be obtained in a much shorter time.

7.3 Fully Automatic Thread Inspection by Optical Gauging System

A fully automatic optical gauging system is employed in this threading line, as shown in **Fig. 14**. The feature of this system is that the thread form is recognized by an optical, non-contact method. In order to establish consistency of measured values with conventional contact-type gauging systems, a virtual probe system was adopted, which simulates the contact between the thread form obtained by the optical system and the probe in the con-

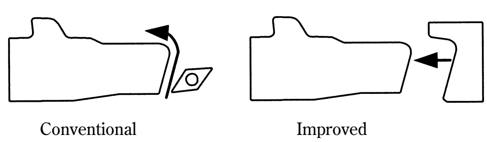


Fig. 13 Cutting method of seal portion

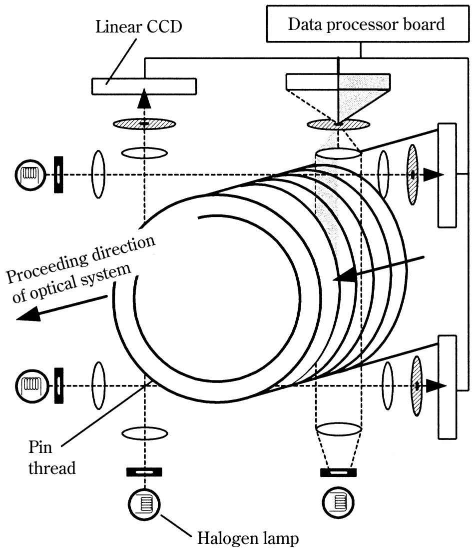


Fig. 14 Schematic illustration of optical gauging system

ventional gauging system. This system can quickly perform the measurement, and makes 100% inspection possible without lowering the productivity of the line.

8 Conclusion

The KSBEAR is a premium threaded connection for oil well tubes used in severe environments and was developed based on a new concept different from that for conventional connections. The following results were achieved.

(1) Plastic deformation at the seal portion under the high compressive load was suppressed by optimizing the gap between the stabbing flanks.
(2) The hooked thread's tendency to cause galling was overcome by changing the corner radius of the load flank.
(3) The galling resistance was further improved by optimizing the load flank angles of both the pin and coupling.
(4) FEA models were developed for analyzing the effects of multiple cycles of successive make-up and break-out the connections.
(5) Also, FEA models were proposed for analyzing the effects of bending.
(6) Performance evaluation tests confirmed that the KSBEAR causes no leakage even under the compression of 80%PBYS and bending of 19.7°/30 m, and markedly outperforms the API Class 1 performance requirements.
(7) A new technology was developed for quickly cutting a thread that requires a complicated cutting method such as a hooked thread using a tool-rotating type threading machine.

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