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Designs for Reliability and Failure Mode Prevention of Electrical Feedthroughs in Integrated Downhole Logging Tools

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Abstract—**To enable an electrical feedthrough integrated downhole logging tool to maintain high reliability during its logging service in any hostile wellbores, it is critical to apply some guidelines for the electrical feedthrough designs. This paper introduces a safety factor-based design guideline to ensure an integrated electrical feedthrough has sufficient compression or thermo-mechanical stress amplitude in the stress well against potential logging failures. It is preferred to have a safety actor of 1.5-2.0 for an electrical feedthrough at lowest temperature, such as −60°C, and a safety actor of 2.5-5.0 at operating temperature range of 200-260°C. Moreover, the designed ambient pressure capability should be 1.5-2.0 times higher than the maximum downhole pressure, such as 25,000-30,000 PSI. To validate this thermo-mechanical stress model, several electrical feedthrough prototypes have been tested under simulated 200-260°C and 31,000-34,000 PSI downhole conditions. The observed testing data have demonstrated that there is a maximum allowable operating pressure for an electrical feedthrough operating at a specific downhole temperature. It is clearly demonstrated that an electrical feedthrough may operate up to 60,000 PSI at ambient temperature in a real-life application, but it may actually operate up to 30,000-35,000 PSI at 200-260°C downhole temperatures.**

Keywords—**Electrical feedthrough, stress well, safety factor, reliability, failure mode prevention, LWD and MWD**

Introduction

Elevated temperatures and rapidly increasing pressures during wellbore failure events often lead to cascading electrical or mechanical failures from the installed wellhead electrical feedthroughs, downhole connectors, and/or interconnectors [1-4]. These failures mainly cause malfunctions of downhole wireline tools, logging while drilling (LWD), and measurement while drilling (MWD) tools. In additiona, whenever an electronic feedthrough package is no longer hermetically sealed, the moisture, corrosive gases, or aqueous fluids may cause electrically catastrophic failures in the harsh conditions of the downhole environments. The thermal profile in most wellbores normally varies gradually from subsurface to deep well with very small temperature gradient. Similarly, the wellbore pressure also slowly increases with the well depth but the pressure levels may surge because of different failure events, such as vertical/lateral wells crossover, connection, and/or fracking-induced rock collapse.

In general, the downhole pressure in most wellbores could vary from 15,000 PSI to 30,000 PSI (15-30 KSI), but the transient pressure may be a ∼40 KSI spike. A transient pressure wave could load significant mechanical stresses onto electrical feedthroughs. In extreme cases, the extra stresses could exceed the maximum allowed mechanical strength of the sealing material or/and package materials. To ensure survivability and reliability for downhole LWD and MWD logging tools during any potential failure events, it is desirable to have an integrated electrical feedthrough not only sealed with a high-strength sealing material but also designed with a high-operating pressure limit that could enhance reliability and mitigate failure modes.

A downhole electrical feedthrough is normally made from a metal header (Inconel alloys or stainless steel), conductive pins (BeCu, Inconel X750, Alloy 52), and dielectric sealing material (glass, glass-ceramic, and PEEK) [5, 6]. To ensure the electrical feedthroughs survive hostile downhole environments with long-term operating reliability, a thermo-mechanical stress modeling analysis should be developed and implemented during its design phase to determine whether the thermo-mechanical stress has exceeded maximum allowable tensile yield strength or maximum allowed compression strength of the header and sealing materials [7, 8]. Even if the actual thermo-mechanical stress is lower than maximum allowable strength of the metal and sealing package materials, one still needs to understand the preferred thermo-mechanical stresses for an electrical feedthrough that are required to be operated up to a specific temperature and pressure, for example, 200°C and 30 KSI. If the seal is under high compression that could likely cause cracks in the sealing glass body, then the seal surface is under high tension that could likely cause cracks at the sealing glass surface. On the contrary, if the seal is under low compression, an electrical feedthrough package may have its maximum working temperature and pressure lower than true downhole temperature and pressure values. If the metal header is under high tension, that may lead potentially to limited thermal cycles and to material fatigue via environmental temperature variations.

To ensure that an electrical feedthrough design can maintain reliable operation under a hostile downhole environment, this paper introduces a safety factor, a ratio of sealing compressive

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strength to the thermo-mechanical stress-based design guideline for specifying the allowable thermo-mechanical stress amplitude in a designed downhole electrical feedthrough. As the seal compression in the electrical feedthrough package is both temperature and pressure dependent, the temperature-related safety factor should be chosen in the range from 1.5 to 2.0 at low temperature and 2.5 to 5.0 at operating temperature ranges. Similarly, a designed electrical feedthrough has to be reliably operated at maximum downhole pressure. The corresponding pressure-related safety factor, a ratio of maximum allowable pressure of a designed electrical feedthrough to the maximum downhole pressure, requires that the designed maximum allowable pressure should be 1.5-2.0 higher than the maximum downhole pressure, for example, 25-30 KSI as nominal downhole pressure range.

To explain such safety factor-based design guidelines, several electrical feedthroughs have been prototyped and tested under 200-260°C and ≥30 KSI simulated water-fluid-based downhole conditions. The testing data have verified that the prototyped electrical feedthroughs can perform under a temperature and pressure of 200°C/30 KSI. However, an electrical feedthrough can fail whenever the external temperature and pressure surpass its designed upper limit. It has been demonstrated that the use of the safety factor-based design guidelines could provide any electrical feedthrough integrated logging tools (LWD and MWD) long-term reliability for signal, data, and electrical power transmission from any hostile downhole or/and wellbores.

Results and Discussion

A. Stress Well and Thermo-Mechanical Stress Amplitude

A downhole electrical feedthrough normally consists of a mating pair (plug and receptacle) each equipped with male (*pin*) or female (*socket*) contacts [6]. Each package basically consists of metal header, pin(s), and sealing material. Polymeric material, such as PEEK, is often used for making conventional electrical feedthroughs for low-temperature and pressure application because of its low mechanical strength and weakly water absorption limits. Dielectric glass or glass-ceramic materials are widely used for making various electrical feedthroughs, connectors, bulkheads, and interconnectors. To ensure reliable operation under downhole conditions, most of these electrical feedthroughs are commonly designed with a compressive seal, enabling high hermeticity under elevated operating temperature.

A thermo-mechanical stress model has been developed for analyzing maximum allowed temperatures and pressures from a designed electrical feedthrough package [9]. For a compressive stress package design, the cylinder-shape sealing material, metal header, and conductive pin normally suffer from tensile and compressive stresses. In the downhole fluid, hydraulic pressure also adds extra stress onto the electrical feedthrough package. As described by eqs. (8)-(14) in [9], the temperature- and pressure-dependent shear stress (σ_g) in the glass seal is a function of design parameters related to pin and sealing material body diameters and sealing length. As each glass sealing material has its maximum compressive strength (σ_{mcs}), the ratio of the maximum compressive strength to the shear stress at a specific temperature and pressure could be defined as safety factor, as shown in eq. (14) in [9], for enabling an electrical feedthrough package reliability controllable. For example, if the maximum compressive strength of the sealing material is about −450 MPa, a safety factor of 3 at 200°C/20 KSI will require the designed shear stress to be about −150 MPa at 200°C/20 KSI. As the metal header of the electrical feedthrough package is normally welded onto a fixed object such as a wireline logging tool ends, the sealing material body not only suffers from compressive stress but also from the downhole hydraulic pressure, a stress difference between the sealing material and metal header along long axis is defined as thermo-mechanical stress amplitude, $\Delta\sigma$.

Fig. 1(a) describes a typical electrical feedthrough that has multiple pins sealed with a dielectric sealing material [7, 8]. Fig. 1(b) indicates that each pin has a diameter range of 0.3 mm $\leq \phi_{pin} < 2.5$ mm, and each metal seal has a diameter range of 1 mm $\leq \phi_{seal} < 10$ mm. The sealing length (ξ) typically ranges from 10 mm to 25 mm. A stress well will form with a thermo-mechanical stress amplitude $\Delta\sigma$ that describes the magnitude of the compressive stress in the seal, which is strongly dependent upon the operating temperature (T) and pressure (P).

Let's first examine temperature effect on a design electrical feedthrough package reliability. For an Inconel X750 alloy-based electrical feedthrough package with 0.76-mm diameter Inconel X750 pin, 1.83-mm metal seal diameter, and 5.1-mm sealing length, one can calculate the stress well and its stress amplitude profile under different temperatures. Fig. 2 illustrates that the thermo-mechanical stress amplitude ($\Delta\sigma$) can vary from −370 MPa to −100 MPa when the operating temperature changes from −100°C to 300°C, implying that the compressive stress in the seal body decreases with increasing temperatures. In this case, to obtain an electrical feedthrough with high reliability, a safety factor of 2, 3, 4, and 5 has been used to quantify compressive stress in the seal body. At low temperatures, for example, $-50°C < T < 25°C$, a safety factor of 1.5-2.0 is acceptable, but a safety factor of 2.5-5.0 is preferred for an electrical feedthrough operating at downhole temperatures from 200°C to 260°C.

However, the thermo-mechanical stress amplitude ($\Delta\sigma$) is not only dependent upon operating temperature but also upon

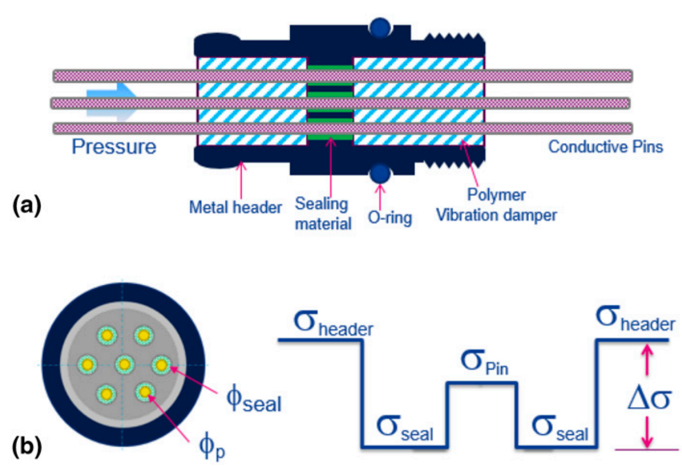

Fig. 1. (a) A simplified multipin electrical feedthrough and (b) stress well and thermo-mechanical stress amplitude.

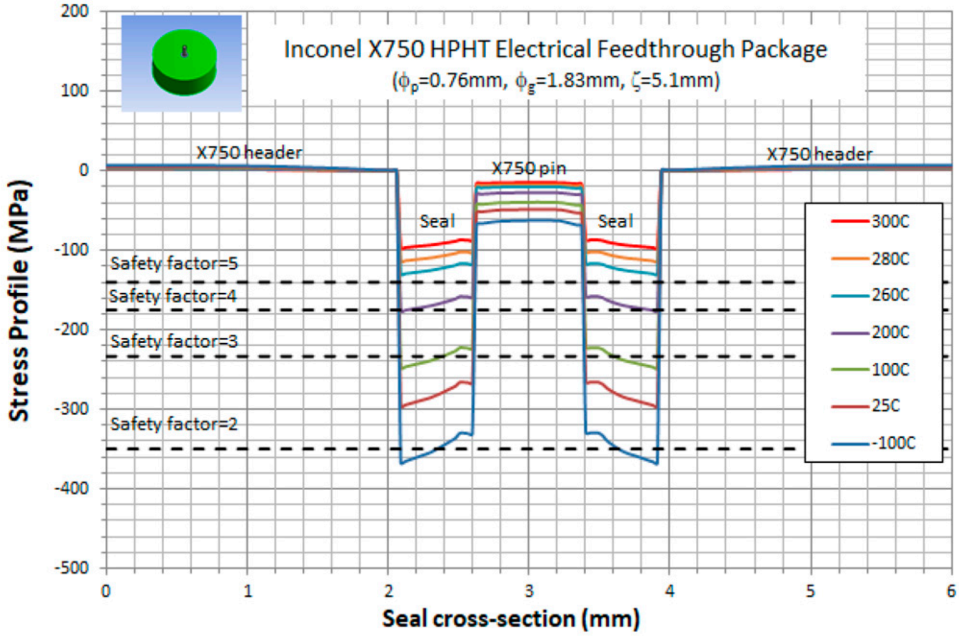

Fig. 2. Seal compression of a specific designed electrical feedthrough under different temperatures and corresponding safety factors from an Inconel X750 metal-based electrical feedthrough package.

the downhole pressure. Fig. 3 shows that the thermo-mechanical stress amplitude ($\Delta\sigma$) can be greatly reduced by both temperature and pressure parameters. For example, the ambient (25°C/0 KSI) thermo-mechanical stress amplitude of 240 MPa can be reduced to 60 MPa under 260°C/30 KSI operation conditions. In fact, an electrical feedthrough may fail if its seal doesn't have sufficient compression because any downhole transient pressure variation could break down the seal and the loss of the hermeticity will lead to a catastrophic electrical insulation failure.

B. Maximum Allowed Pressure

Maximum allowed operating pressure from a designed electrical feedthrough is temperature dependent. For example, an electrical feedthrough may operate under 25 KSI pressure and

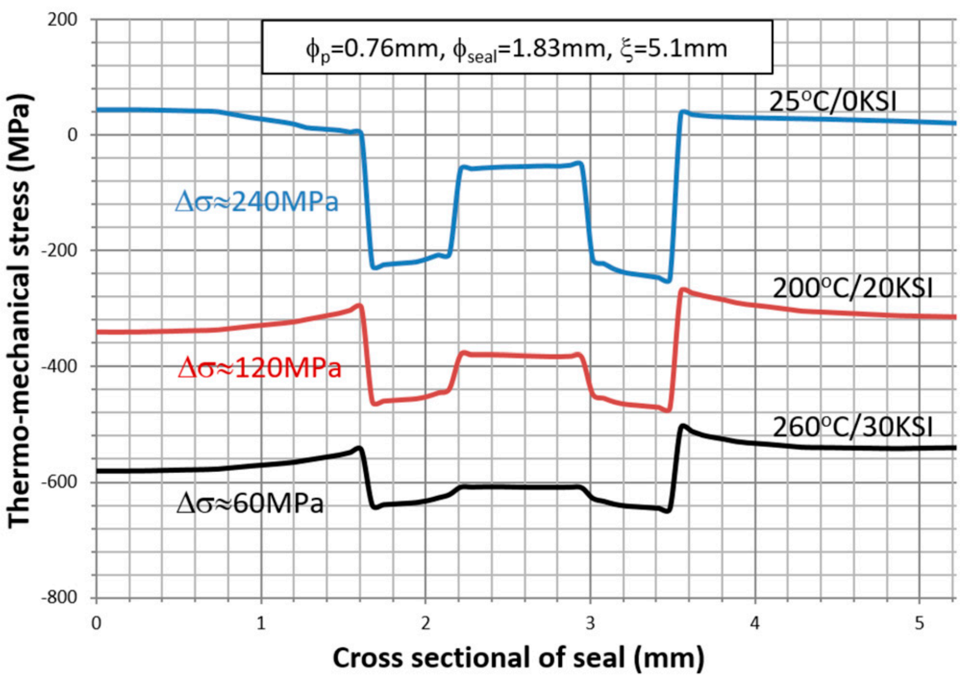

Fig. 3. Seal compression of electrical feedthrough under different temperatures and pressures from Inconel 718 metal-based electrical feedthrough package designs.

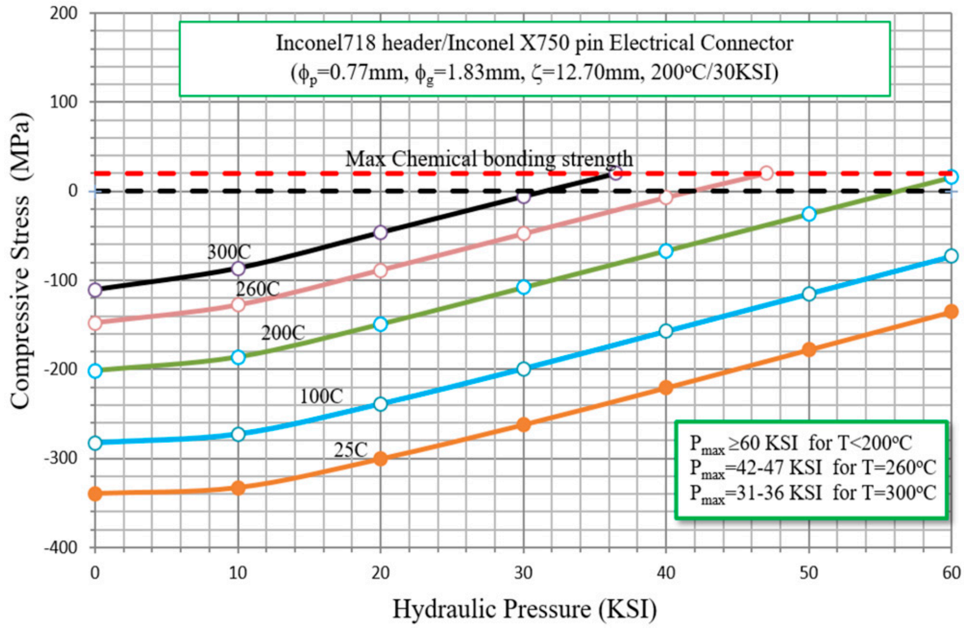

Fig. 4. Thermo-mechanical modeling predicted maximum pressure limits at several temperatures from an Inconel 718 metal- and X750 pin-based electrical feedthrough package.

200°C downhole environment, but it can operate up to 35-40 KSI at ambient. Actually, the elevated temperature can significantly reduce seal compression of an electrical feedthrough and thereby decrease the shear strength between metal and sealing material, which effectively reduce maximum operating pressure.

Fig. 4 shows the maximum allowed operating pressures at several typical temperatures from an electrical feedthrough, made from Inconel 718 alloy with Inconel X750 alloy as pin material. For $T < 200°C$, the designed electrical feedthrough package may allow to be operated up to $60 +$ KSI, which has a safety factor of 2.0 by comparing with the presumed downhole 30 KSI pressure requirement. It is true that the maximum allowable pressure will be reduced by the elevated temperatures. For example, such an electrical feedthrough may operate up to 42-47 KSI at 260°C, and 31-36 KSI at 300°C, respectively. Here, the low limit of pressure corresponds to nearly zero seal compression, whereas up limit reflects the maximum chemical bonding strength for maintaining seal integrity with the metal header, similar to a "CTE-matched electrical feedthrough design." If a designed electrical feedthrough is required to operate at 260°C/30 KSI, the maximum pressure of $42 - 47$ KSI could provide a safety factor of ~1.5. Moreover, this electrical feedthrough could operate up to 300°C with the maximum pressure of 30-35 KSI. In general, it is recommended that the designed ambient maximum pressure capability is 1.5-2.0 higher than the specified downhole pressure limit. The modeling of maximum allowed pressure at different temperatures, as shown in Fig. 4, also indicates that an electrical feedthrough may operate under 60 KSI at ambient (~25°C) without failure, but this doesn't mean that this electrical feedthrough package can operate under 40 KSI at 300°C. A further modeling analysis also discloses that the geometrical parameters, such as sealing length, seal diameter, pin diameter, sealing glass transition temperature, and coefficients of thermal expansion of both metal header and sealing materials, are critical factors for modulating maximum allowed pressures from a specific feedthrough package design.

C. *Validation of Designed Electrical Feedthrough*

To validate whether the thermo-mechanical stress model can provide practical solutions for electrical feedthrough failure mode prediction and prevention, several electrical feedthroughs, made from Inconel 718 and X750 alloys, have been prototyped and tested under simulated downhole conditions. For assisting the feedthrough package reliability test, an electrical feedthrough package was welded into an Inconel alloy flange, which was subsequently sandwiched in the middle of a testing fixture. The hydraulic pressure is transmitted into the testing fixture via a water-filled stainless steel tube. There are thermocouples for monitoring the temperatures inside the testing fixture and the oven operating temperature.

Initial tests from the prototyped Inconel 718 alloy-based electrical feedthrough packages were conducted under simulated downhole conditions with pressure up to 35 KSI and temperature up to 204°C. Fig. 5 has shown an Inconel 718 electrical feedthrough with a designed maximum capabilities of 200°C and 25 KSI. Validation tests had been routinely at both ambient and 204°C (400°F) with pressure from 30 KSI (A point) to 35 KSI (B point). As shown in Fig. 5 that this Inconel 718-based electrical feedthrough should work well at the testing points of ambient and "A" (204°C/30 KSI), but it is not clear the feedthrough could survive at 204°C/35 KSI testing point "B."

First test was to gradually ramp hydraulic pressure from zero, at ambient temperature, to the maximum system hydraulic pressure of 45 KSI and maintain the test within hours. Next test was set at "A" point, namely, 204°C/30 KSI. The tested feedthrough prototype has shown stable pressure within a few

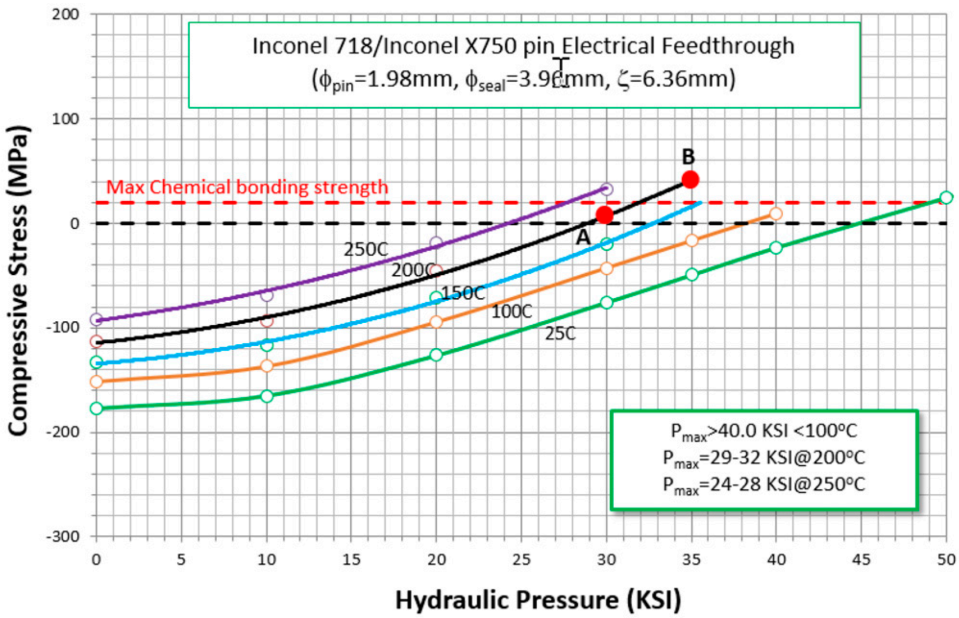

Fig. 5. Validation tests from an Inconel 718 alloy-based electrical feedthrough package, where two testing points have been chosen for modeling validation, plus ambient test up to 45KSI hydraulic pressure.

hundred hours. To find maximum pressure limit at 204°C, the test was conducted by gradually ramping system hydraulic pressure from 30 KSI to maximum system pressure capability of 45 KSI. A hermeticity failure was seen by sharply drop of the hydraulic pressure around 32-36 KSI range. The observed failure is consistent with the thermo-mechanical modeling analysis, where the 32-36 KSI at 204°C is out of the designed pressure reliability limit of 29-32 KSI.

To further demonstrate low-reliability scenario cases from a designed electrical feedthrough package, Fig. 6 presents another electrical feedthrough package, made from Inconel X750 header, ϕ_p = 0.77-mm Inconel X750 pin, ϕ_{seal} = 1.83-mm metal seal diameter, and ξ = 12.70-mm sealing length, with a designed temperature-related safety factor of 4.0 around 200°C operating condition. The dielectric sealing material has an average 6.3 ppm/°C coefficient

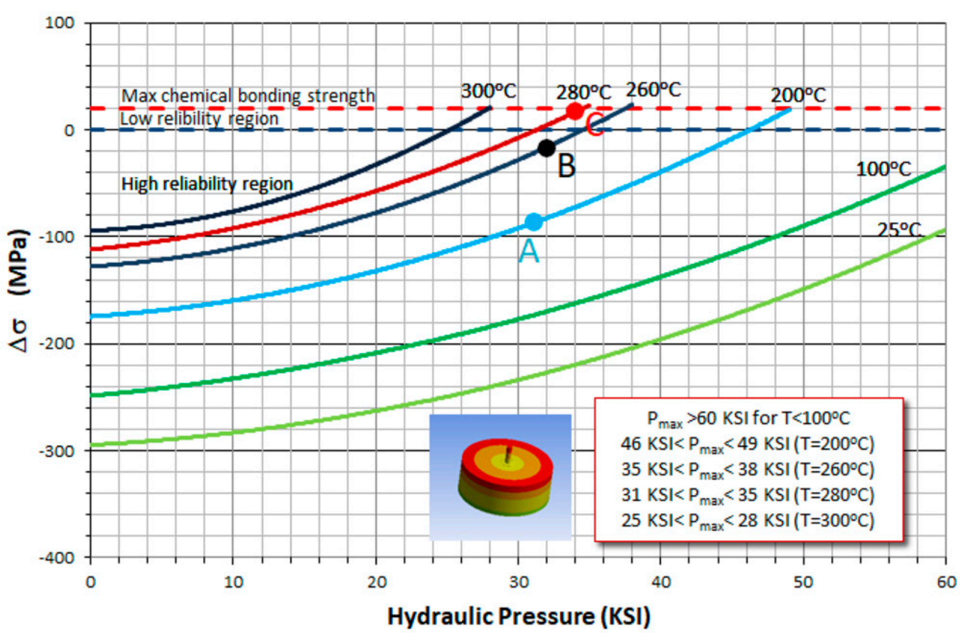

Fig. 6. Temperature-dependent maximum allowed pressures from an Inconel X750 metal-based HPHT electrical feedthrough package, where A, B, and C are selected testing points for modeling validation.

of thermal expansion, 5.7 g/cm^3 density, and 100 KSI compression strength [7, 8].

In comparing with Fig. 5, this electrical feedthrough is made from Inconel X750 metal and its maximum pressure at 200°C is between 46 KSI and 49 KSI, which is ~50% higher than the feedthrough designed with Inconel 718 metal header because of different design parameters related to pin material and diameter, seal diameter, and sealing length selections. As a testing platform, it is theoretically predicted that this Inconel X750-based electrical feedthrough should work well at the testing point "A" (200°C/31 KSI) and testing point "B" (260°C/32 KSI), but it is not clear if the feedthrough could survive at 280°C/34 KSI testing point "C" because the maximum pressure is between 31 KSI and 35 KSI at 280°C.

Fig. 7 has plotted the temperature and pressure testing data of 630 h after the prototype is exposed to elevated temperature and pressure from a water-based testing fluid. During the first 310-h test, the testing system was operated under 200°C and 31 KSI (testing point "A"), the measured 31 KSI pressure is stable, which indicates good reliability at least during first 310 h under 200°C/31 KSI conditions. During continuous second 310-h test, the testing system was operated under 260°C/32 KSI (testing point "B") conditions, the measured 32 KSI pressure is kept stable that also indicates good reliability at least during second 310 h under 260°C/32 KSI conditions.

Final test is to validate model predicted electrical feedthrough package failure under 280°C/34 KSI (testing point "C") conditions. After 620-h test on this feedthrough package, the testing system temperature was ramped to 280°C, and corresponding pressure was also slowly ramped from 32 KSI to 34 KSI. It is interesting that the feedthrough has survived for nearly 10-h operation after the testing system operation at 34 KSI/280°C working point. However, a sudden loss of the pressure in the testing chamber occurred after 10-h operation, which corresponds to the loss of the seal hermeticity in the seal. This observed pressure loss is consistent with the model predicted low reliability at maximum pressure of 34 KSI when the operating temperature is at 280°C.

For a multipin electrical feedthrough package, the failed hermeticity may be from one of the seals that has nearly no compression in the seal, and the bonding strength between the sealing material and metal header was no longer sufficient to hold the pin in the seal cavity position. The observed measurement data have demonstrated that the prototyped electrical feedthrough package can sustain its operating reliability at 30-32 KSI hydraulic pressures and 200-260°C downhole temperatures. In addition, the testing data of 620 h under 30-32 KSI and 200-260°C without failures are consistent with the thermo-mechanical stress model-predicted performances.

Meanwhile, the Inconel 718 and X750 alloys as header could be used for making highly reliable electrical feedthrough packages with optimum geometrical parameters, such as pin material and diameter, seal diameter and length, and so on, despite the small difference in thermal expansion. Under the same geometrical parameters, the thermo-mechanical stress modeling has predicted that the electrical feedthrough with Inconel 718 metal-based header material could provide about 10% higher seal compression amplitude than that of the Inconel X750 metal-based header material. By comparing with two designs from Figs. 5 and 6, a longer sealing length of greater than 10 mm could greatly enhance pressure safety factor. It is clear that if our initial design goal for making a 200°C/25 KSI downhole electrical feedthrough with Inconel 718 and X750 alloys, the performance and reliability of an electrical feedthrough could be tailored by optimum design parameters to meet different downhole LWD and MWD logging tool integration requirements.

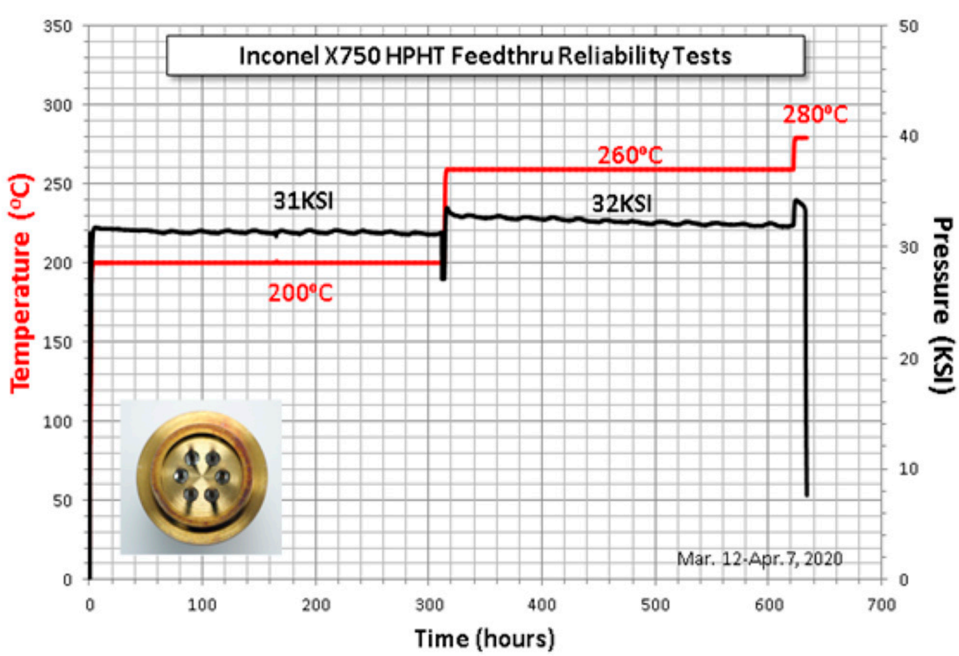

Fig. 7. Validation tests from an electrical feedthrough prototype at "A" testing point of 200°C/31KSI, at "B" testing point of 260°C/32KSI, and at "C" testing point of 280°C/34KSI high-temperature and high-pressure testing conditions.

Conclusions

This paper has demonstrated that there is a maximum allowable operating pressure for an electrical feedthrough operating at a specific downhole temperature and pressure. The ambient maximum pressure capability of an electrical feedthrough could operate at more than 60 + KSI pressure environment but it may actually operate up to 30-35 KSI at 200-260°C downhole temperatures. As a downhole logging tool is an expensive measurement system that needs reliable data, signal, and power transmission via electrical feedthroughs, bulkheads, and interconnectors for long-term downhole deployment or short-term service, this paper has introduced safety factor-based design criteria to ensure an integrated electrical feedthrough having sufficient compression or thermo-mechanical stress amplitude against potential logging deployment or service failures.

It is preferred to have a low-temperature safety actor of 1.5-2.0 for an electrical feedthrough either at lowest temperature, such as −60°C, or low temperature range of −60 to 25°C; and prefer to have a high-temperature safety factor of 2.5-5.0 at the elevated operating temperature range of 200-260°C. On the other hand, the designed ambient pressure capability or safety factor should be 1.5-2.0 times higher than the maximum downhole pressure (e.g., 25-30 KSI). To ensure downhole logging tool long-term operation reliability and failure mode prevention, these guidelines could be used for wellhead electrical feedthrough, downhole electrical connector, and interconnector designs and validation [10].

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