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TIGHTENING STRATEGIES FOR BOLTED JOINTS

METHODS FOR CONTROLLING AND ANALYZING TIGHTENING

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Tightening Strategies for Bolted Joints

1. Overview

Fastener engineering and the mechanical testing of threaded fasteners and bolted joints are important specialties within the field of mechanical engineering that require a thorough program of testing and analysis. These efforts must begin with an understanding of the behavior of individual fasteners. A proper overview recognizes the complex interaction of the material properties of the fastener, clamped components, and internally threaded components, as well as the influence of coatings, lubricants, and adhesives on the performance of fasteners in bolted joints. The test methods and procedures that yield the most informative data will test the threaded fastener in the same manner in which it is actually installed.

Test methods have been established and published for mechanical properties such as hardness, tensile strength, and torsional strength as well as corrosion and hydrogen embrittlement. These methods provide the baseline information necessary for proper interpretation of the friction coefficient, torque-tension, and angular ductility testing methods that are used for complete evaluation of bolted joints.

Combining basic material strengths and friction coefficient information has lead to development of a powerful method called *Torque-Angle Signature Analysis*. This method provides valuable information on joint strength and performance when applied to testing fasteners in bolted joints. By careful review of an applied torque vs. angle-of-turn plot, signature analysis can be used to evaluate bolted joints for loss of preload due to settling, creep and relaxation, or vibration and dynamic loading. In addition, joint strength problems such as thread strip and embedment of bearing surfaces and material yield within the bolted joint are easily identified.

There are many factors that must be considered when establishing a threaded fastener bolted joint analysis program. Included here are some methods for modeling the joint, experimental testing of components and assemblies, and procedures for conducting post-assembly audits.

The basic torque-angle signature is used as a starting point for all analysis. As a first example, it can be used to illustrate the influence of underhead and thread friction on the tightening process. An increase in friction, in either the thread or underhead regions, results in a proportional increase in the slope of the torque-angle signature. The study of the slope of the elastic tightening zone is an important element in analyzing the performance of threaded fasteners in bolted joints.

To apply torque-angle signature analysis, a torque-angle transient recorder is used for measurement and curve plotting. The transient recorder can provide curves on-screen for analysis as well as print them out for detailed study. Tightening, audit and release angle signatures for a given fastener can be simultaneously displayed and printed.

2. Classical Design Concepts: Modeling the Tightening Process

When developing a testing program to correlate the design of a bolted joint and the actual assembly, it is necessary to document the relationship between torque and turn in the development of tension. Before you can gain control of a tightening process, you must become familiar with what actually happens when the fastener is tightened. The process of tightening a fastener involves turning, advance of the lead screw, and torque, or turning moment, so that preload, or tension, is produced in the fastener. The desired result is a clamping force that holds the components together. A torque vs. angle signature correlated to the clamp force vs. angle plot offers the best model that can be used to explain this process. The most general model of the torque-turn signature for the fastener tightening process has four distinct zones as illustrated in Figure 1.

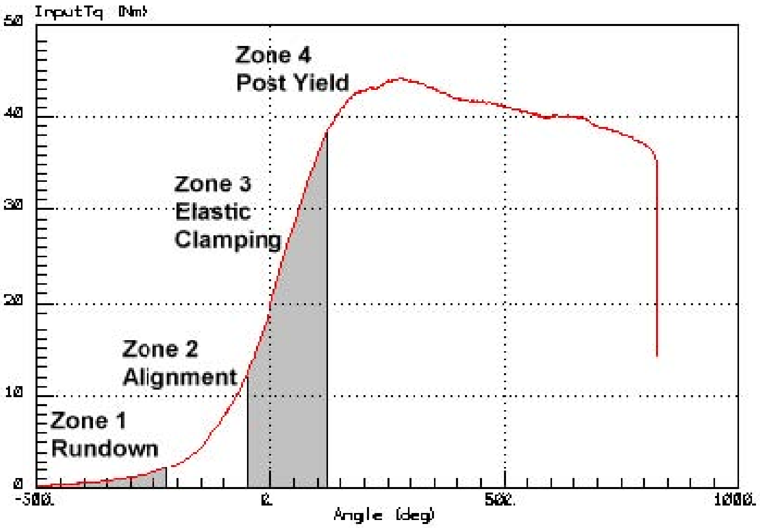

Figure 1. Four Zones of Torque-Angle Tightening

The first zone is the rundown or prevailing torque zone that occurs before the fastener or nut contacts the bearing surface. Prevailing torque, due to thread locking features such as nylon inserts or deformed threads, will show up in the rundown zone. Frictional drag on the shank or threads due to misalignment of parts, chips or foreign material in the threads as well as unintended interference due to out of tolerance threads are additional causes of prevailing torque in the rundown zone.

The second zone is the alignment or snugging zone, wherein the fastener and joint mating surfaces are drawn into alignment, or a stable, clamped condition. The nonlinear alignment zone is a complex function of the process of drawing together the mating parts, and bending of the fastener as a result of non-parallelism of the bearing surface to the fastener underhead surface. In addition to the macro effects related to alignment of parts, there are micro effects within the alignment zone. The micro effects include contact stress-induced deformations of plating and coatings as well as local surface roughness and thread deformations. These macro and micro effects are illustrated in Figure 2.

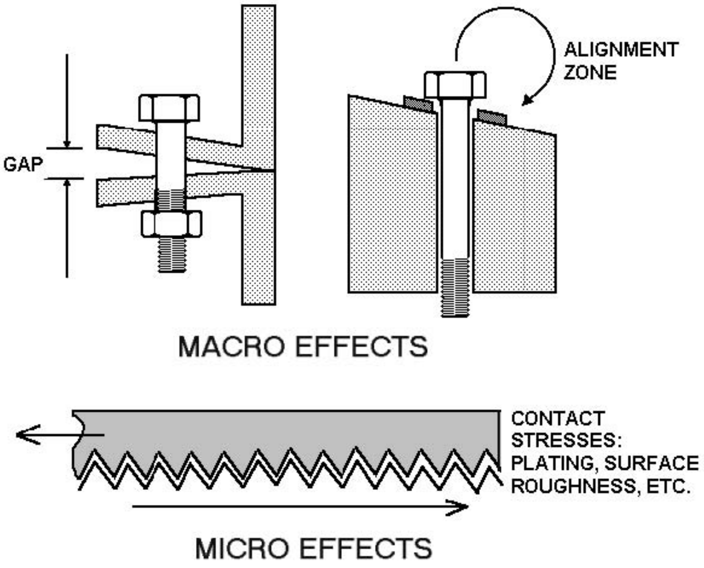

Figure 2. Macro and Micro Effects in the Alignment Zone

The third zone is the elastic clamping range, wherein the slope of the torque-angle curve is essentially constant. The elastic clamping zone torque-angle slope is a very important characteristic of each bolted joint. This slope can be projected backward to zero torque to locate the elastic origin. For joints with prevailing torque in the rundown zone, the elastic origin is located at the intersection of the prevailing torque level and the backward projection of the tangent to the elastic clamping zone. If the angle-of-turn is measured from the elastic origin to the point where torquing was stopped in the elastic clamping zone, the tension in the fastener is directly proportional to that angle-of-turn. In this elastic zone the compression of the parts and the stretching of the fastener are occurring in a linear fashion from the projected elastic origin. Even if friction between threads or in the underhead region of the fastener is varied, it still will be found that within the elastic zone, the tension generated is always proportional to the angle-of-turn from the elastic origin. The angle-of-turn from the elastic origin to the point where the torque is removed can be multiplied by the angle-tension coefficient to estimate the tension that has been created by the tightening process.

To further illustrate the concept of the elastic origin, the torque-angle signatures in Figure 3 show the increased slope, induced by increased friction, in the elastic-tightening zone. Note that as friction increases, the torque required to bring the bolt to yield is also increased. The curves in Figure 4 show that, as friction increases, the clamp force at the yield point is reduced, while the torque that is required to reach the yield point increases. This illustrates the fact that for a given fastener size, the torque required to yield the bolt is a function of the material yield strength and the thread friction coefficient.

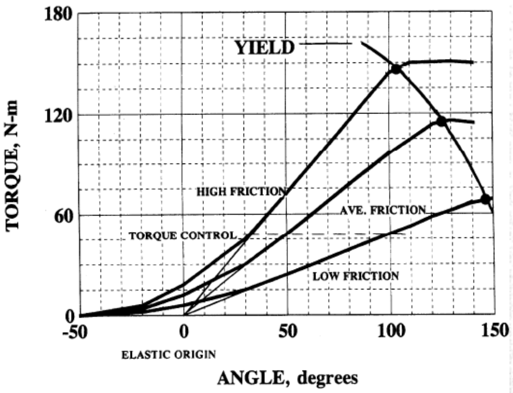

Figure 3. Friction Effects on Yield Point

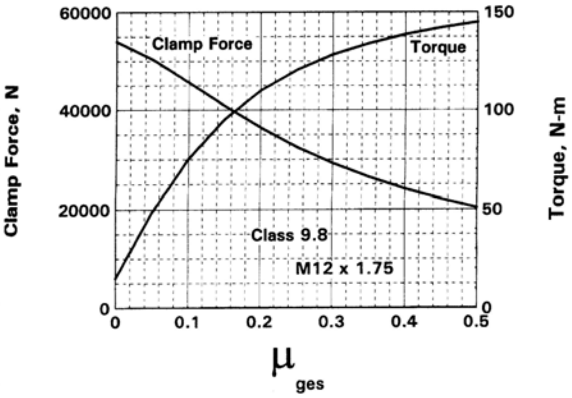

Figure 4. Friction Effects on Applied Torque and Clamping Force at Yield

The fourth zone is the post-yield zone, which begins with an inflection point at the end of the elastic clamping range. Yielding can occur in the bolt or in the joint assembly as a result of underhead embedment or as thread strip in the bolt or mating threads. This fourth zone can be due to yielding in the joint or gasket, or due to yield of the threads in the nut or clamped components or nut rather than to yield of the fastener. The yield point of the bolt can be used to approximate the angle-tension coefficient for the tightening process.

Note the yield clamp load of a torqued fastener is less than the tensile yield due to the combined tension and thread torque. Since the thread friction coefficient is unknown an initial assumption could be that the clamp load at yield torque is about 90 percent of the tensile yield load. This would be approximately correct for an average friction coefficient, *µges*, of 0.1.

3. M-Alpha Diagram Introduction

The M-Alpha (torque-angle) Diagram is a powerful tool for use in joint analysis. As shown in Figure 5, it is a straight-line projection of the tangent to the torque-angle assembly curve projected backwards from the predicted yield point through the elastic tightening point to zero torque. This tangent projection is used to locate the elastic origin. Since the M-Alpha diagrams in this discussion are taken from SR1, a bolted joint stress calculation software program based on the well known German design standard VDI 2230, we will use the terminology native to VDI in this discussion, such as M for torque from the German word Drehmoment.

In addition to the applied torque, MA, the M-Alpha Diagram has projections from the elastic origin for both the thread torque, MG, and the pitch torque, MG0 (where μ= 0). A very useful feature of the M-Alpha Diagram is the manner in which the diagram clearly illustrates the distribution of the torque in a tightening process. With MA showing the total input torque, MG represents the thread torque that is the thread friction plus the pitch torque that creates the clamp-force. The difference between the MA and MG curves represents the underhead friction torque. The difference between the pitch torque curve, MG0, and the MG curve represents the thread friction torque.

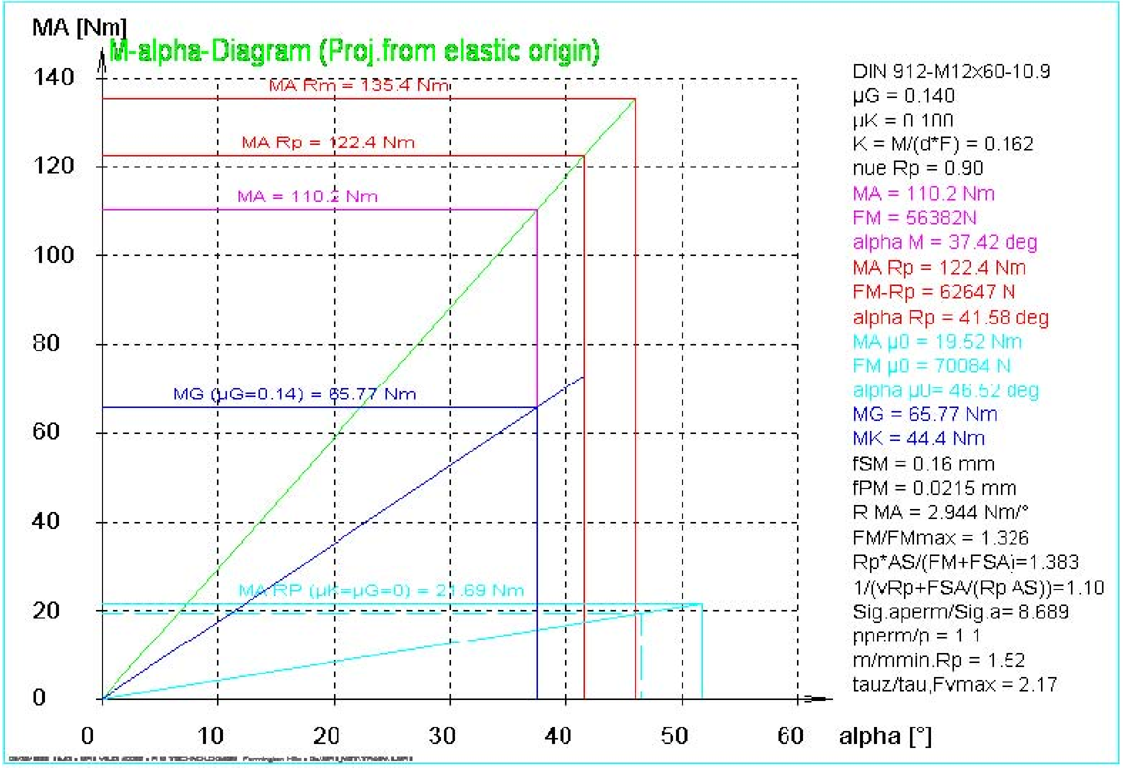

Figure 5. M-Alpha Diagram from SR1

The M-Alpha Diagram is a straight line projected from the elastic origin to the yield point. By changing the coefficients for thread friction, μG, and underhead friction, μK, assumed for the VDI 2230 analysis, the effect of friction on the tightening process can be clearly seen. In the M-Alpha Diagram shown in Figure 6, the torque values required to reach the assembly preload and the yield point are lower because the assumed friction coefficients are lower.

4. Strength Considerations

The clamp force and preload requirements for a bolted joint are determined by the static and dynamic loads that the assembly is expected to see in service. The bolted joint design must be completely engineered with regard to the axial (concentric), eccentric, and shear loads to which the assembly will be subjected. This is the first step in any fastener engineering project.

After the external working loads have been defined, the necessary bolt preload can be calculated. Next, the safety factors against embedment and thread strip must be checked to insure that yielding in the bearing areas or threads will not limit the preload to less than the required amount. Safety factors for shear slip, fatigue, loss of preload, and over-elongation due to combined loads must also be evaluated.

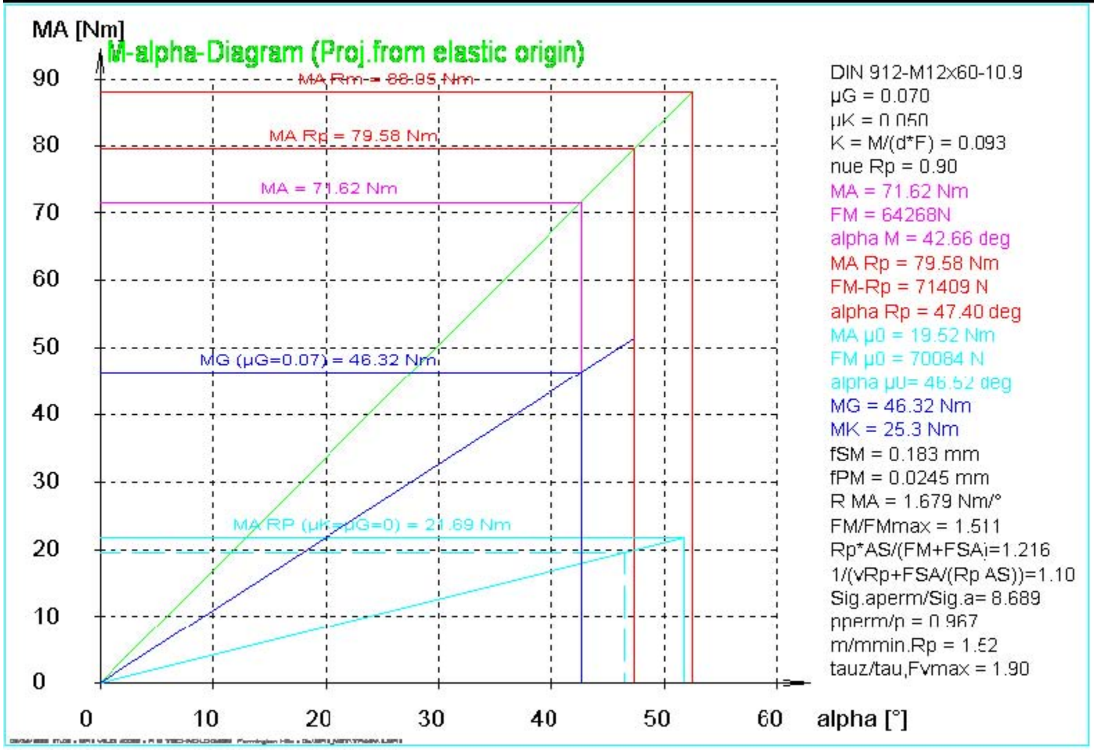

Figure 6. M-Alpha with Low Friction Coefficients

The safety factors for embedment and thread-strip are important both for the initial installation of the fastener and for long term reliability with regard to both loosening and fatigue resistance. The illustration in Figure 7 shows some of the strength factors that should be evaluated with regard to expected service loads and preload requirements.

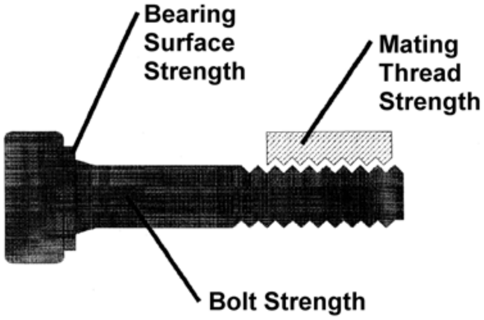

Figure 7. Clamping Force and Material Strength Considerations

5. Bolt Yield

Tightening a fastener beyond the yield point is a means of achieving the maximum preload possible for a given size and strength. This tightening method is commonly used in automotive engine assembly for connecting rod bolts, crankshaft bearing cap bolts, and engine head bolts. When bolts first replaced rivets in the construction of bridges and buildings, tightening beyond the yield point quickly proved to be a reliable method of assembly. The preload obtained by tightening beyond the yield point is proportional to the material yield strength and inversely proportional to the thread friction coefficient, μG. The thread friction coefficient is important since the yield point during tightening results from combined tensile loads plus the torsional load due to the thread friction and pitch torque.

After the yield load is reached, the clamping force will continue to increase in proportion to the increase in torque. In the elastic tightening zone, tension is proportional to the angle-of-turn from the elastic origin located on the torque-angle signature. When tightening beyond the yield point, the clamp force can be estimated by the procedure illustrated in Figure 8.

The tangent line to the elastic straight-line tightening section of the signature is projected beyond the yield point and the final torque value is projected to the tangent line. The angle-of-turn from the elastic origin to the intercept of the backward projection from the final torque can be used to estimate the tension. This procedure can be seen as related to the strain-hardening phenomena observed when working materials beyond the yield point.

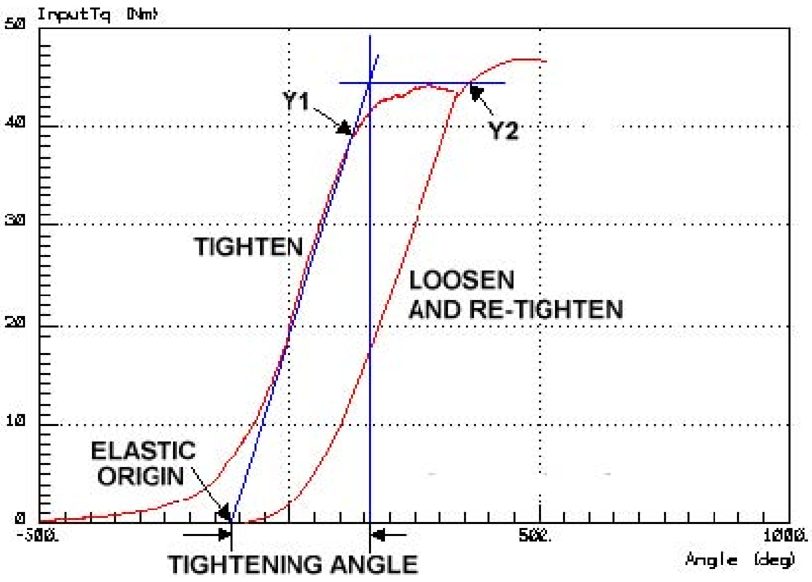

Figure 8. Bolt Yield

After the material is first loaded beyond yield, Y1, the yield point is found to be at a higher level, Y2, on the next tightening cycle. After yielding, when the load is released, the release curve is offset and parallel to the elastic tightening curve.

6. Thread Strip

In general, a properly designed bolted joint will not fail by stripping of the threads either during installation or if the assembly is overloaded in tension. As a matter of good design practice, failure should always be due to fracture of the bolt.

The thread stripping areas for internal and external threads can be approximately calculated using the formulas expressed in Equations 1 and 2. The geometric configurations that define the formulas are shown in Figure 9.

$$AS_B = \pi\left(\frac{d_3}{P}\right)L_e\left[0.5P + 0.577(d_2 - d_3)\right] \tag{1}$$

where:

AS_B = Stress area of the bolt
L_e = Effective grip length of the fastener
d_2 = Pitch diameter
d_3 = Root diameter

$$AS_N = \pi\left(\frac{D_3}{P}\right)L_e\left[0.5P + 0.577\left(D_3 - D_2\right)\right] \tag{2}$$

where:

AS_N = Stress area of the nut
L_e = Effective grip length of the fastener
D_2 = Pitch diameter
D_3 = Root diameter

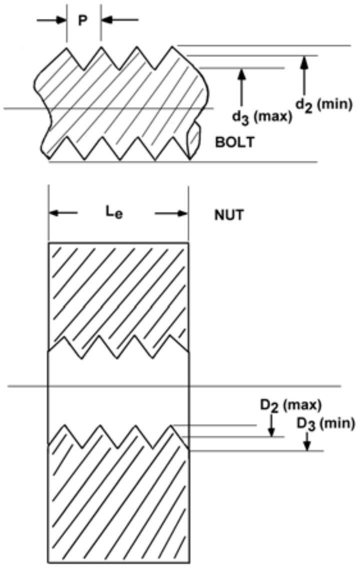

Figure 9. Thread Stripping Areas

Assuming that the maximum shear strength of the bolt material equals half of the tensile strength (ductile material, maximum shear stress failure mode), the bolt load to strip the threads can be estimated by multiplying the calculated shear area times the shear strength of the bolt or nut. This is a simplified calculation that assumes that the loading is uniformly distributed on all engaged threads. In actual practice, due to the elastic coupling between threads, the first engaged thread carries a higher than average load while remaining threads carry progressively lower loads as the load is transferred between the bolt and nut, or internally threaded hole.

When evaluating a bolted joint torque-angle assembly signature, the onset of thread stripping appears as a "yield point," or change of slope in the elastic portion of the tightening curve. Refer to Figure 10 that illustrates this phenomenon. The thread strip signature is similar to the signature for embedment of the fastener into the bearing surface. Both embedment (refer to Section 7) and thread strip lead to creep of materials within the loaded surface areas of the assembly. Over a period of time, embedment and excessive thread stripping loads cause loss of preload as the high stress regions relax and redistribute the loads.

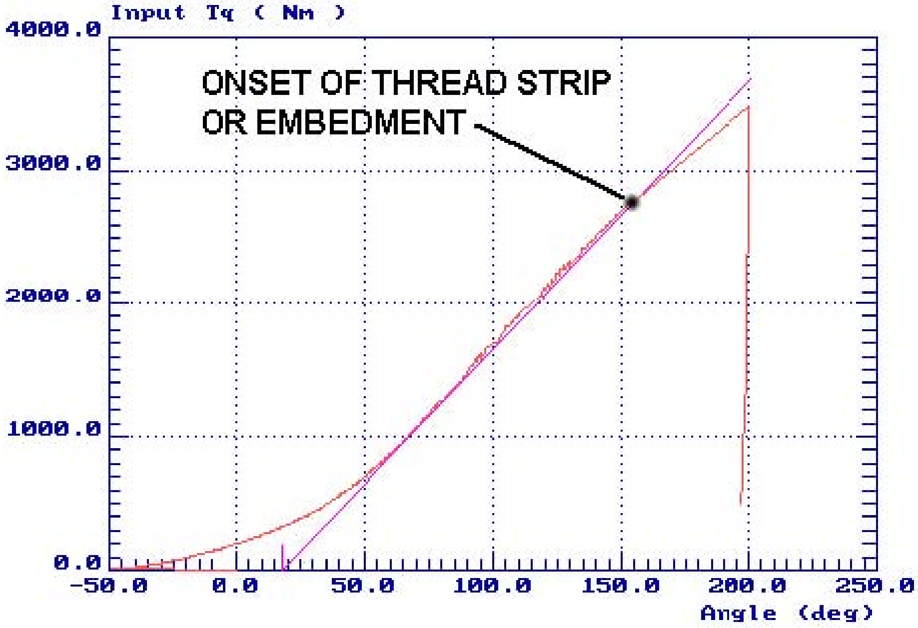

Figure 10. Test Plot of Fastener with Stripped Threads

In service, thread strip failure can be progressive in nature, gradually transferring the load from thread to thread. Loss of preload due to thread strip can occur over many hours or days and is cause of fastener loosening that is often difficult to diagnose.

7. Embedment or Loss of Preload

The release angle method has been successfully used to study fastener-loosening problems. The basic procedure involves recording and analysis of the torque-angle signatures for tightening and then loosening the fasteners that are to be tested.

First the torque-angle-tightening curve is plotted, the elastic origin is located, and the amount of angle of turn from the elastic origin is determined. After the assembly has been allowed to relax, for example, to sit overnight or run on a dynamic field test, the fastener is loosened and the loosening curve is analyzed. The release angle is determined, compared to the tightening angle, and if not equal, evaluated to see how much tension was lost by relaxation or loosening.

In one release angle study, a fastener had a tightening angle of 120 degrees. After 10-12 hours, the release angle was 20 degrees. The manufacturer was already aware there was a major problem because the parts were literally falling apart somewhere between the assembly factory and the auto plant where they were delivered for final assembly in vehicles. The signature analysis study showed that creep or relaxation in the threads was causing an approximately 80 percent loss in clamp force over a 12-hour period. The release angle method provided a quantitative answer as to the amount of clamp force lost, and clearly showed that the parts needed to be redesigned.

The release angle method is particularly valuable for studying short grip length fasteners holding composite or plastic parts. These parts are generally too small to allow for use of strain gages or ultrasonic stretch measurements to confirm fastener preload.

For these applications, a torque-angle signature curve for tightening is recorded, then the parts are put in an environmental chamber and load/ temperature cycled.

Following the test load cycle the release angle signature is recorded. Analysis of the release-angle signature in comparison to the tightening signature is used to directly estimate the percentage of initial of clamp load lost due to embedment or creep of the plastic part in response to applied loads or temperature cycles. By changing geometric shapes and washer size, the effects can be quantitatively measured and compared. Refer to Section 10 for details on the M-Alpha audit method that can be used along with the release angle method to help audit relative fastener tension values.

8. Estimating the Angle-Tension Coefficient

A number of different methods can be used to determining the angle-tension coefficient for the bolted joint. A basic assumption is that as the fastener is turned to develop preload in the joint, the fastener stretches and the clamped parts compress elastically according to the effective spring rates of the fastener and the clamped parts. After the angle-tension coefficient is determined for elastic clamping through analysis of the torque-angle signature, it is relatively easy to estimate the tension achieved when tightening beyond the bolt yield point.

The angle-tension coefficient for each bolted joint must be determined in order to establish the control parameters for torque-angle-tension control. By shutting off the assembly tool at a specified angle-of-turn after the threshold torque is attained, the scatter in achieved tension will be much less than the scatter observed for the same fasteners tightened with torque-only control. For this process to work reliably, it is necessary that the threshold torque level for starting angle counting be set at a level which is above the alignment zone of the tightening process. The curves in Figure 11 show how the process control limits are determined to achieve torque-turn-tension control for an application.

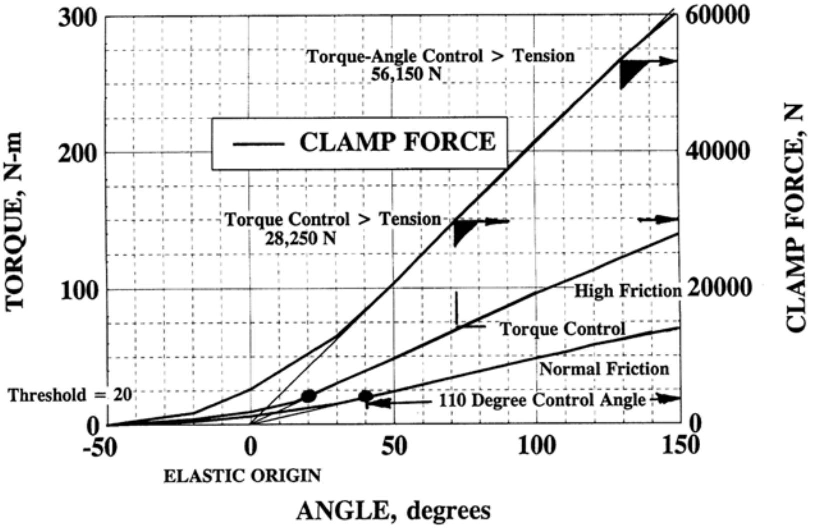

Figure 11. Torque-Turn-Tension Control Principles

After the installation process has been defined and implemented, methods must be specified to audit the results in order to verify that the process has achieved the desired fastener preload. Process audit procedures including the Release Angle measurement method and hand torque breakaway audits are presented later.

9. Release Angle Analysis

The complete analysis of a fastener involves looking at both the tightening and the loosening torque angle curves as the fastener is first installed and then loosened. These curves are studied initially in the elastic tightening region where the fastener has not gone beyond yield, such as the assembly torque-angle signature shown in Figure 12. When the fastener is loosened, a torque-angle-loosening signature, as shown in Figure 13, can be recorded. The release signature shows the release of the fastener stretch and also the release of the compression in the clamped parts. Analysis of this signature provides a direct method for verification of preload or tightness. First, the line tangent to the elastic release portion of the curve is projected to zero torque to locate the elastic origin. The release angle, measured from the point where loosening starts to the projected elastic origin, is a direct measure of the tension released from the bolted joint.

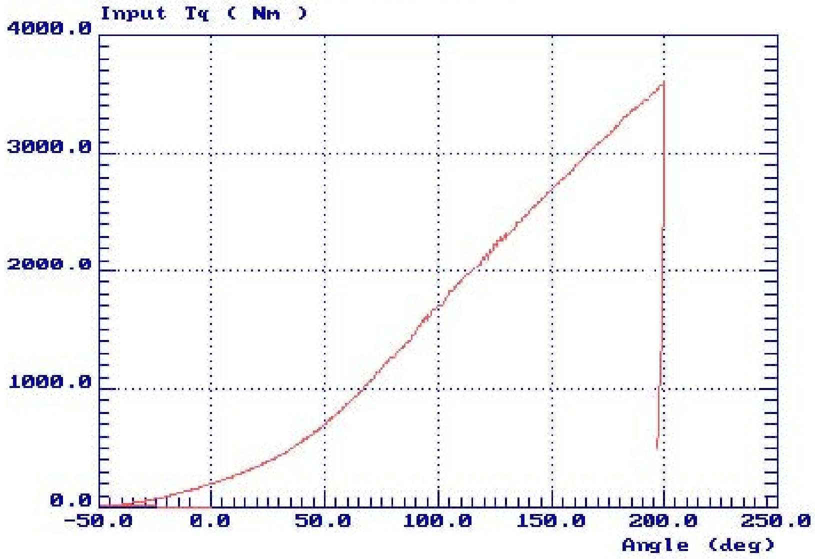

Figure 12. Torque Angle Signature

The tangent line must be drawn on the straight-line portion of the curve after the initial peak release torque due to static friction or thread-locking adhesive has been broken free. The starting point is the angle where initial loosening motion begins. The total release angle is measured from the initial loosening point to the projected elastic origin. Note that if a significant prevailing torque is present after loosening the fastener, the elastic origin must be located at the prevailing level, not zero torque.

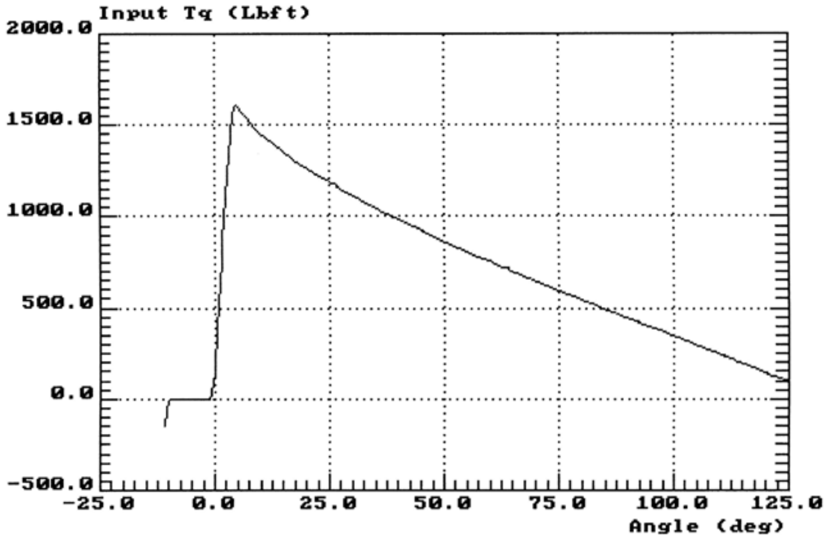

Figure 13. Loosening Torque-Angle Signature

The torque-angle signature shown in Figure 14 has been plotted as a M-Alpha Diagram with the tangent line, locating the elastic origin, drawn at 50 percent of the maximum torque to set the elastic tightening slope below the onset of embedment of the nut. The bolt is a M30 x 3.5 with strength Class 11.9. The corresponding clamp force signature, plotted as an F-Alpha (tension-angle) Diagram, confirms that the clamp force increases linearly with the angle of turn from the projected elastic origin. In the example shown in Figure 15, the elastic-tightening angle is approximately 125 degrees.

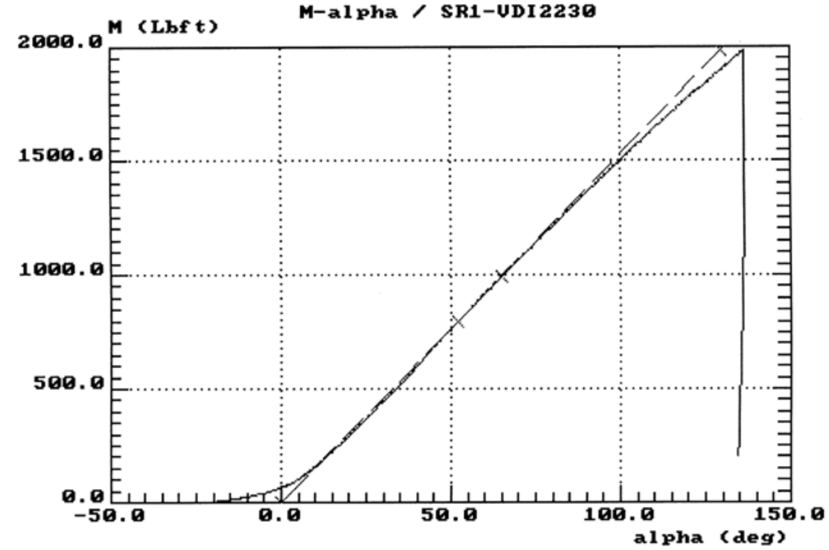

Figure 14. Torque-Angle Signature with Embedment

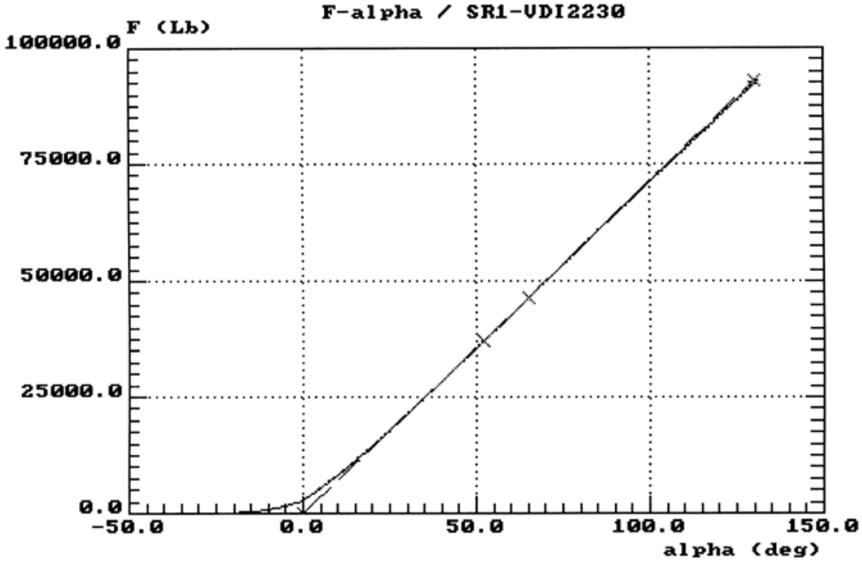

Figure 15. Clamp Force vs. Angle of Turn from Elastic Origin

The loosening torque-angle signature (refer back to Figure 13) also has a projected release angle of approximately 125 degrees. The F-Alpha Diagram (refer to Figure 15) confirms the fact that, even after embedment occurs, the clamp force increases directly in proportion to the angle of turn from the elastic origin. Similar to the analysis of added tension achieved after yield of the bolt, for embedment or thread strip, the backward projection to the extended tangent to the curve before thread strip or embedment is used to locate the effective tightening angle. Experiments with strain gage bolts or force washers, where the clamp force is measured along with the torque and angle during tightening, verify that this theory is correct for a given fastener.

Figure 16 shows a release angle study performed on an automotive wheel nut. A tool with a torque and angle sensor connected to a transient recorder is used to loosen the nut, record the torque and angle values, and plot the data. The resulting printed curve shows an extremely high release torque. The high initial breakaway loosening peak torque region is disregarded, as this is simply an indication of the static torque required to start loosening motion. The high value of release torque is significant from the point of view that it illustrates the high thread friction due to thread pitch distortion on the wheel nut, a factor that helps prevent vibratory loosening on typical wheel nuts.

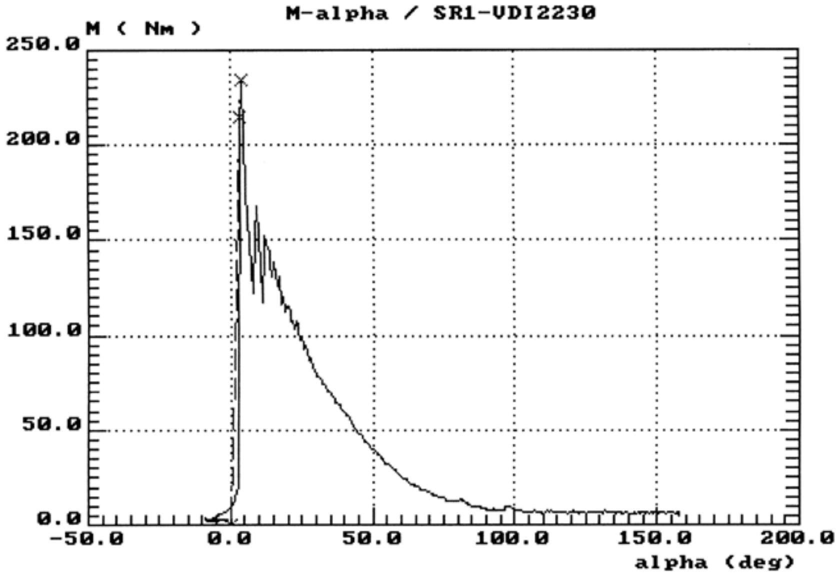

Figure 16. Wheel nut Loosening Signature

The elastic release angle for the wheel nut shown in Figure 16 is approximately 40 degrees. The nut had been tightened to a peak torque of 206 Nm (152 lb-ft), which is 75 Nm (52 lb-ft) greater than the vehicle manufacturer specification. The wheel nut was originally tightened to a torque of 160 Nm (118 lb-ft), which did not appear to get past the tightening alignment zone as shown by the signature shown in Figure 17. In this example, high underhead friction limited the tension on the stud, which for normal friction conditions would have resulted in stud yield or fracture due to over-elongation.

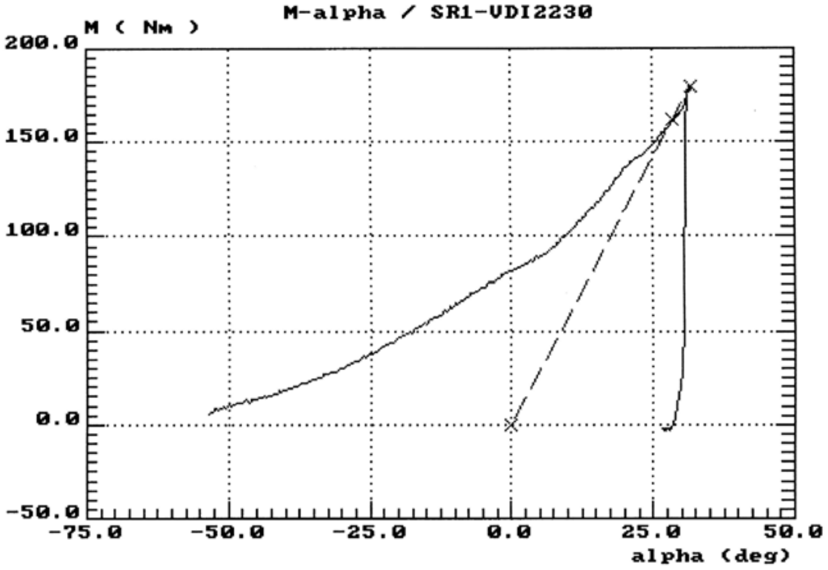

Figure 17. Wheel Nut Installation Signature

The installation was followed by a hand torque breakaway audit where the nut was advanced about 78 degrees in the tightening direction, as shown in Figure 18. The M-Alpha Diagram for the audit shows that the final torque was about 206 Nm (152 lb-ft), with a projected elastic-tightening angle of 40 degrees.

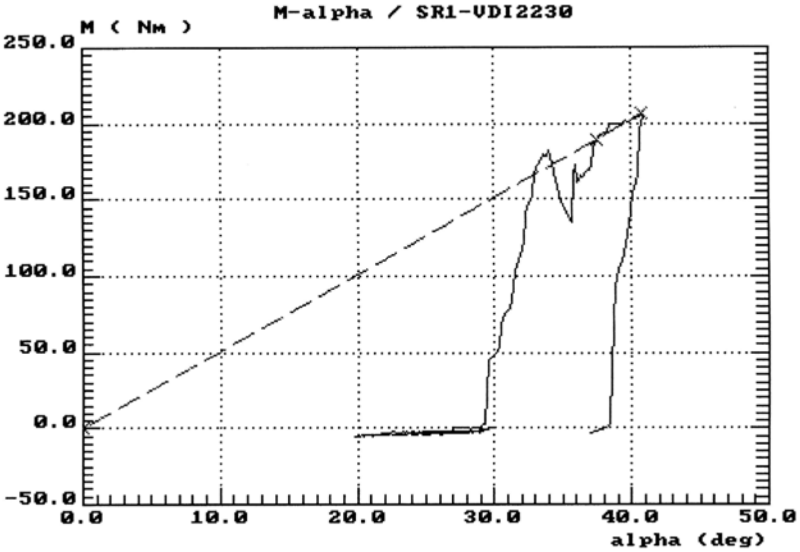

Figure 18. Wheel Nut Audit Signature

Applying the release angle method, a line is projected tangent to the elastic release portion of the curve to zero torque. This release angle, measured from the release torque point to the point where the tangent line crosses the zero torque or prevailing torque level, is directly proportional to the tension or clamp force released. Comparing Figure 18 with Figure 16 a significant correlation is seen to exist between the release angle determined by loosening the fastener and the M-Alpha Diagram as applied to the Torque-angle signature for the breakaway audit. The loosening signature in Figure 16 was recorded after the audit plotted in Figure 18.

10. M-Alpha Tension Audits

Torque-angle signature analysis is particularly useful for studying all critical fastener assemblies where, in terms of safety or reliability, it is important that proper preload is initially obtained and maintained throughout the operating life of an assembly. In addition to analyzing fastener problems such as loosening and embedment, torque-angle signature analysis can also be used to evaluate the performance of tightening tools in applying the desired clamp force on fasteners. This technique is particularly applicable for evaluating processes that employ pulse tools and impact tools.

Due primarily to ergonomic considerations, pulse tools have recently been widely specified for use in high volume assembly operations. Unfortunately, the limitations of these tools related to their energy transfer characteristics are not generally well understood. Pulse and impact tools are particularly sensitive to joint rate and friction variations. Since friction coefficients are a function of velocity as well as surface pressure, tightening results with pulse and high RPM tools must be carefully evaluated to ensure suitable tightening process capability.

For example, pulse and impact tools move fasteners at high speeds with a great deal of stick-slip, chatter, and unique frictional characteristics that are not seen with steady, continuous tightening processes. These factors can lead to a deceptively high torque reading but with minimal clamp force created. By checking the assembled joint with an audit method that can correlate angle of turn and clamp load, the user can ensure that the assembly is securely tightened.

The following series of tightening, breakaway torque audits, and release signatures illustrate the basic concepts of torque and tension audit using torque-angle signatures. Understanding of the engineering mechanics of threaded fasteners is greatly enhanced through use of the concept of the elastic origin and the application of M-Alpha and F-Alpha diagrams to the audit process.

10.1 Tightening Curve Analysis

In the example illustrated in Figure 19, a M12 x 1.75 fastener was tightened to 80 Nm (60 lb-ft). The signature was recorded with a recording threshold of 27 Nm (20 lb-ft). The plot shows both torque and tension vs. angle of turn, with zero angle located at the threshold.

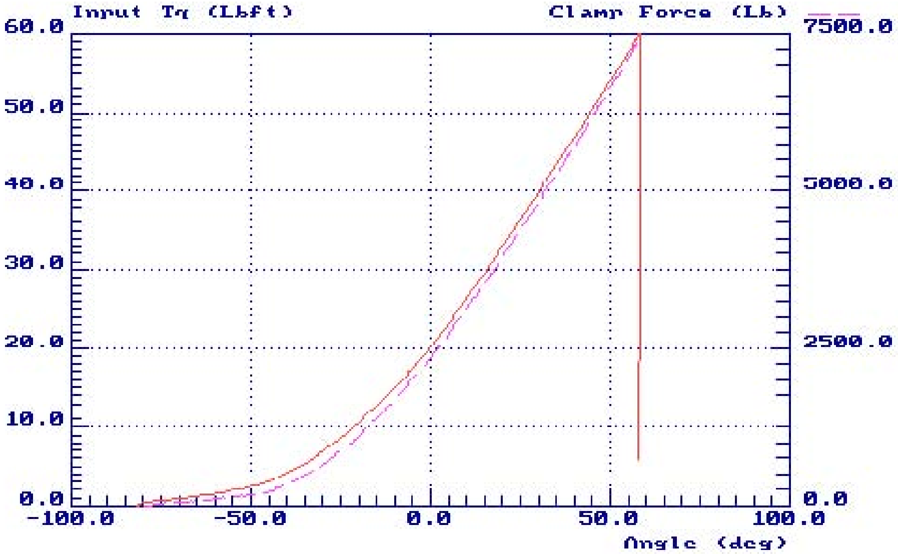

Figure 19. Torque and Clamp Load vs. Angle

The signature analysis software used in this analysis can automatically locate the elastic origin on the M-Alpha Diagram by projecting a tangent line from the final point on the torque-angle curve to the zero torque level. The M-Alpha Diagram for the installation tightening signature, shown in Figure 20, illustrates that the torque resulted in a projected elastic tightening angle of approximately 85 degrees. The corresponding F-Alpha curve, shown in Figure 21, confirms the relationship between torque and angle with the concept of the elastic origin. Note that the 85-degree elastic tightening angle for the bolt results in a clamp force of approximately 33,360 N (7,500 lb.).

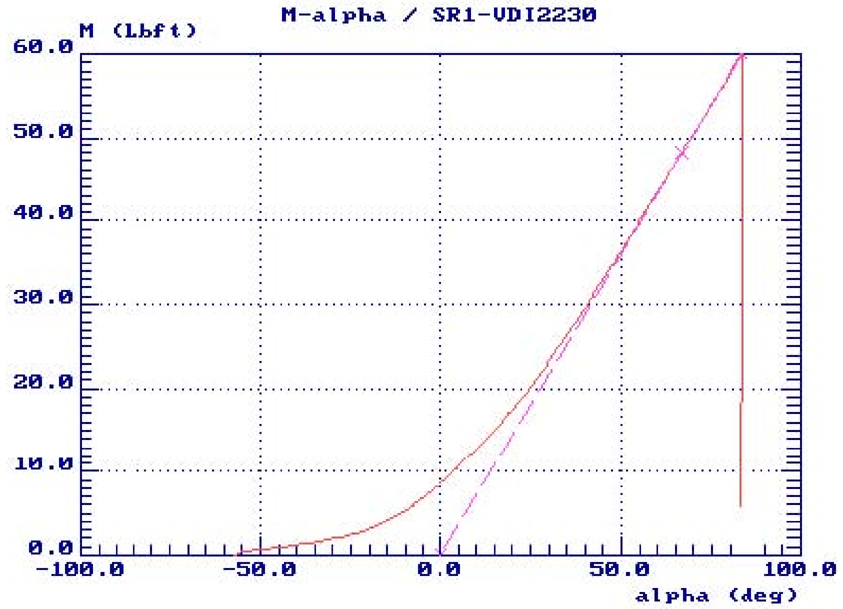

Figure 20. M-Alpha Diagram

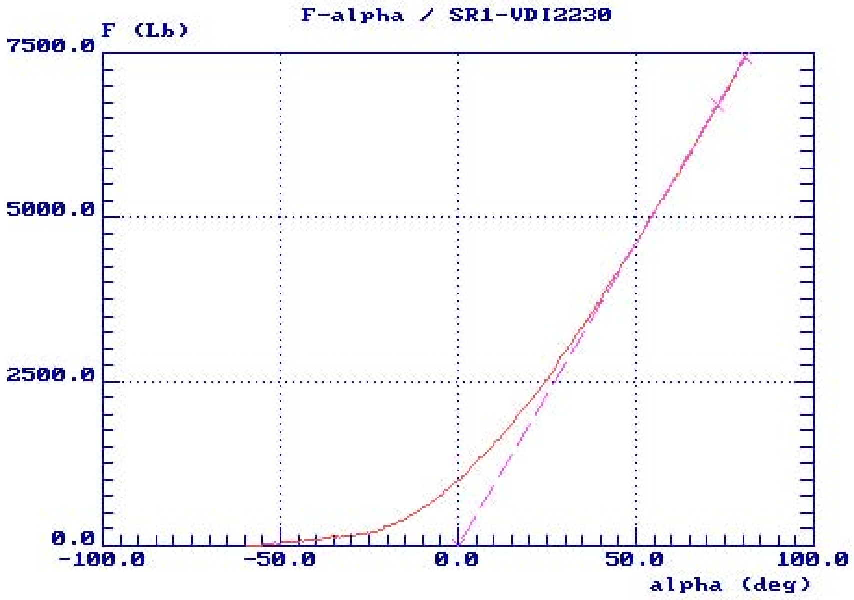

Figure 21. F-Alpha Diagram

10.2 Breakaway Analysis

The next signature is the breakaway torque audit, shown in Figure 22, on the bolted joint tightened for the example shown in Figures 43 through 45. Breakaway hand torque audits are often used in an attempt to correlate the dynamic installation torque with the measured breakaway point. In this example, the fastener is torqued in the tightening direction until an additional angle of turn of about 1213 degrees was attained. Note that the head of the fastener started to move at about 74.5 Nm (55 lbft). The actual breakaway point and continuation of the tightening process occurred at about 88 Nm (65 lb-ft) of applied torque. These observations confirm the installation torque of 81 Nm (60 lb-ft) as is normally done for a breakaway torque audit.

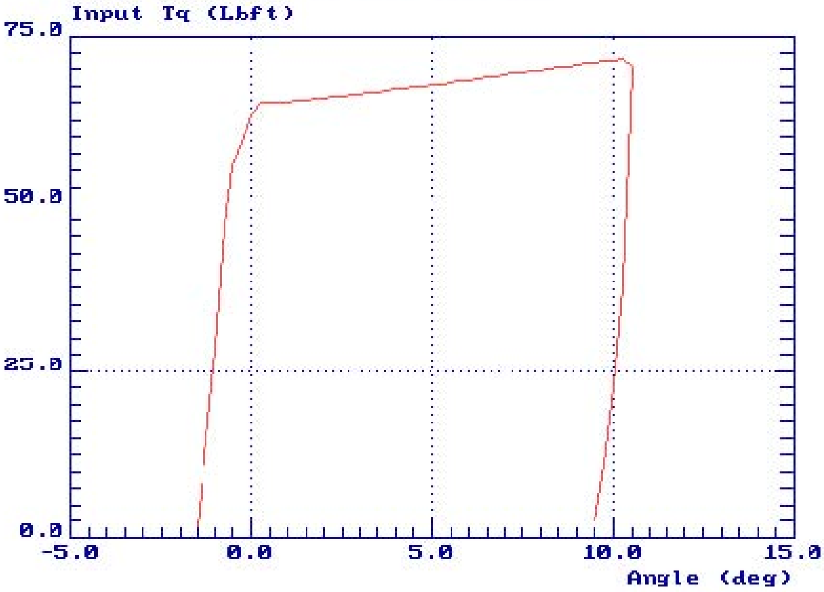

Figure 22. Breakaway Torque Audit

The signature analysis diagram shown in Figure 23 is one of the most significant analysis tools developed in the past 10 years. This diagram shows how it is possible to audit both the installation torque and correlate the signature of the audit curve directly with fastener tension. The projection of the tangent to the torque-angle signature curve that locates the elastic origin is the key to significant improvement of the hand torque audit process. The M-Alpha Diagram for this audit signature clearly shows the torque breakaway point related to the installation torque, and also shows the 85 degree initial tightening angle which correlates with a pre-load of 33,360 N (7,500 lb.) clamp force. Note that the breakaway audit increased the tightening angle to approximately 95-100 degrees projected from the elastic origin, with an expected proportionate increase in preload.

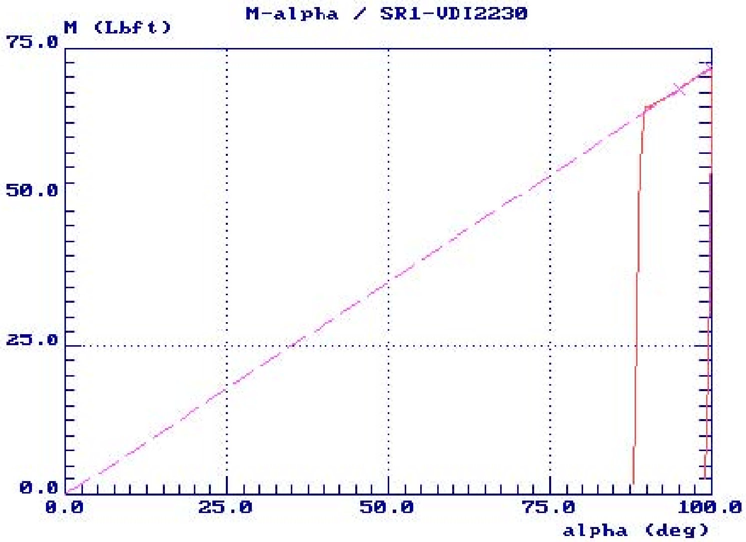

Figure 23. M-Alpha of Breakaway Torque Audit

10.3 Release Angle Audit

If the torque-angle signature is recorded when a fastener is loosened, as shown in Figure 24, the resulting release angle graph can be used to determine the elastic tightening angle, and thus directly estimate the approximate fastener tension that was released, provided that the F-Alpha slope for the joint has been established.

Figure 24. Release Angle Signature

M-Alpha plots and release-angle plots can be used to directly estimate bolt tension, or preload, which is the ultimate goal of the fastener tightening process. The release angle of approximately 95 degrees in the example shown in Figure 24 that confirms the tightening angle measured on the M-Alpha Diagram for the hand torque audit. Clearly the release angle method of audit provides a direct measure of the capability of a given tool to develop tension in the tightened fastener.

10.4 Frictional Analysis Audits

To provide and example of how audit techniques can be used to the effect of differences in frictional characteristics, the fastener type used in the previous examples (Figures 17 through 22) was stripped of all thread and underhead lubricants to create higher friction coefficients in the thread and underhead regions. The M-Alpha diagram for tightening to 81 Nm (60 lb-ft), shown in Figure 25, indicates a tightening angle of only 25 degrees projected from the elastic origin. Compared to the lubricated fastener, where the tightening angle was 85 degrees, the predicted preload of 9786 N (2,200 lb.) was confirmed by the clamp force measurement. The breakaway audit for the dry tightened fastener, shown in Figure 26, confirms that the installation torque was approximately 81 Nm (60 lb-ft), and also reveals the expected very low angle of turn from the elastic origin.

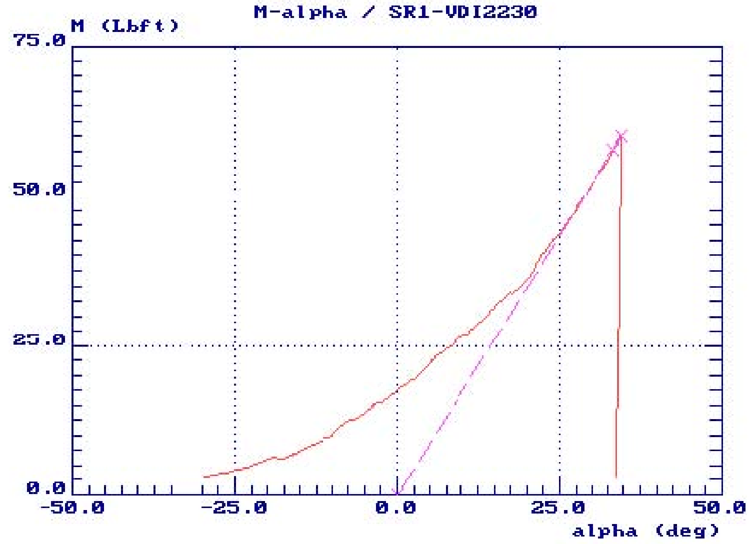

Figure 25. M-Alpha Diagram, Tightened Dry

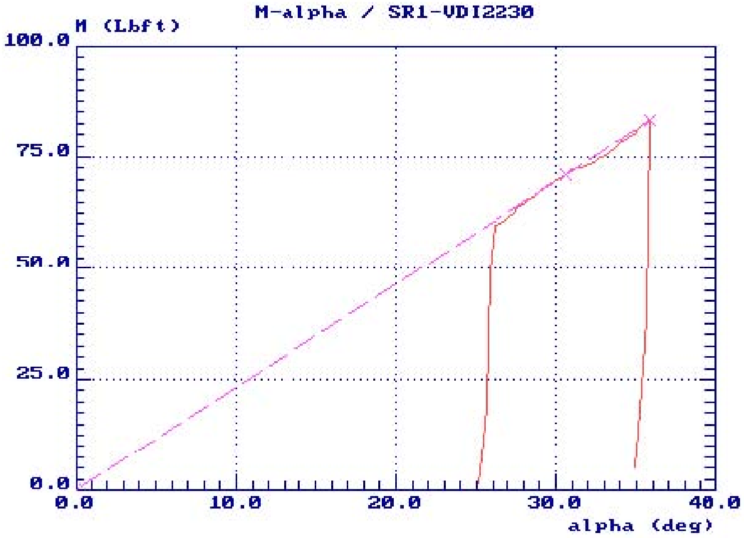

Figure 26. Breakaway M-Alpha, Dry Fastener

11. Summary

The torque-angle signature method of analysis applied to tightening and loosening curves is plain, simple, and straightforward. It is a basic engineering analysis technique using fundamental stress, deflection, and material strength properties to model and measure the bolted joint tightening process. Torque angle signatures can be analyzed to determine installation torque, thread strip, underhead embedment, bolt yield, and most important, fastener tension. While there are many factors that can alter the tightness of a given bolted joint, the torque-angle signature analysis method provides a practical method for direct verification of clamp force to assure a quality fastener assembly. The technique can be applied to fasteners of all sizes and all grip lengths.

The release-angle signature, when compared to the installation torque-angle, can be used to evaluate the clamp load retained after a dynamic test. Material creep and embedment phenomena, which lead to loss of pre-load, are readily analyzed and quantitatively evaluated through use of the release-angle analysis methods. The results of release angle audits, being directly related to the achieved tension, are significantly more meaningful than the torque magnitudes obtained from breakaway torque audits. An improved version of the breakaway torque audit, which uses the torque-angle signature of the audit, can be used to directly estimate fastener tension. This analysis process correlates precisely with the release-angle-signature method. The only limitation is that the breakaway audit must be conducted in the elastic tightening region for the bolted joint where bolt yield or thread strip are not present.

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