The Influence of Deep Rolling Process on Fatigue Durability for Vehicle Tie-Rod Component

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Abstract - In the automotive industry, most of the components are consistently subjected to the dynamic loading due to the randomly observed situations from road inputs and periodic vibration from IC engine working during the operation. Such loadings cause the durability problem which may result in failure or cracking at stresses that are well below the yield strength of the material. Therefore, along with the development of new processing techniques, different surface treatment processes are applied to enhance the fatigue behavior of components. Being one of the mechanical surface treatment methods, deep rolling is an efficient way for improvement of fatigue performance by strengthening the critical section and providing compressive type of residual stresses. In this paper, the effect of the deep rolling process on fatigue behavior of steel stud in tie-rod used as steering system component was investigated. Force-Number of cycles curves (F-N graph) for the fatigue test have been obtained from the tests. Evaluation of the fatigue endurance limits of the stud at un-rolled condition and rolled conditions at three different loads were performed. Test data was analyzed with a regression line to account for the scatter using probability density functions. The results indicate a significant enhancement in the endurance limit following the implementation of the rolling process, as compared to the unrolled state. Furthermore, it was observed that the endurance limit proportionally increased in line with the rolling load. These findings underscore the crucial role of the deep rolling process in determining the optimal rolling load for the specific stud design and material conditions.

Keywords: Deep Rolling, Tie-Rod, Steering Components, Fatigue Life, Surface Treatment Process

1. Introduction

Tie-rod is one of the most critical parts of the steering mechanism in a vehicle which has the duty of transmitting the force from the steering system to the knuckle, causing the wheels to turn, which plays a significant role on steering system performance, and noise level as well as driver and passenger's safety. Any defect of tie rod ball joint end may cause acoustics and stability problems in the vehicle during driving. Therefore, it is important that the tie rod operates reliably and under severe working condition being one of the factors to need suitable design and proper conditions during manufacturing.

Tie rod consists of two components, which are outer tie rod (OTR) and inner tie rod (ITR). An adjustable threaded connection is the way to connect these two main parts of the tie rod. OTR should have enough inner or outer thread permitting the length of tie rod to be arrangeable. It is important that this adjustment is used to set a vehicle's alignment toe angle on both steered wheels. The joint type of the OTR is an angular ball stud made by steel alloys. It has perpendicular orientation against to general axis of the tie rod. Figure 1 shows a systematic assembly of the sub-components building the OTR. This component consists of a forged or cold-forged housing with a place for the radial ball joint and inner threads at the shaft end to meet axial ball joint of ITR. Another main component of outer ball joint is sealing boot protecting the joint against the ingress of water and dirt, plastic ball race and endcap. Here, grease is used for lubrication which covers inside and outside of the ball race to contact joint ball. Only the ball surface, neck region of the ball joint, and thread connection in housing are machined which gives ready to go shape to OTR. In order to meet and connect end cap with the bottom of OTR housing joint area, rolling operation is applied to the bottom of housing. By having plastically deformed back, end cap seats and perfectly sealed with the bottom of housing [6].

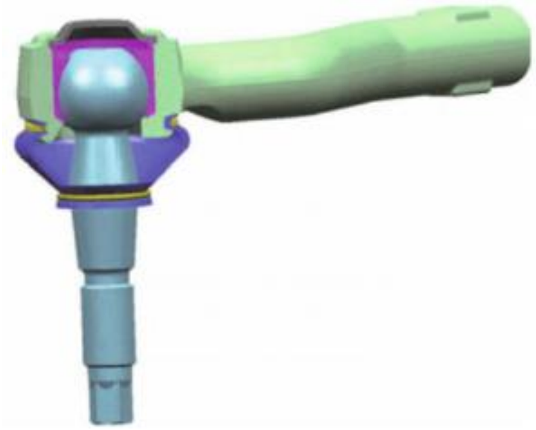


Figure 1. Outer tie rod assembly [6]

In chassis of components, the design of a tie rod is classified as simplest if the centerline of ball joints are in the same axis with ITR and OTR axes. External clamping parts such as steering rack from ITR side and knuckle from OTR side must be in same axis with the ball studs to prevent bending type of loadings in tie rod. This enables a rigid connection by reducing required cross-sectional area. This simplest design cannot be used in every situation because of space restriction of vehicle which requires more complex designs. In order to have fit tie rod to available volume, a calculated offset is given to OTR by moving its center in required axis directions and/or re-design its housing shaft such as presenting initial bend in design (Figure 2). During service life, tie-rods are subjected to static, bearing and dynamic loads under numerous cyclic loadings, similar to those experienced in the random excitations from road inputs, namely the curb steer force which occurs when the vehicle is steered while parked against a curb. The most percentage of forces acting on tie rod is generally compressive type of forces during service [6].

Figure 2. Outer tie rod housing variations [6]

In the automotive industry, mechanical failure is frequently encountered, with fatigue being one of the primary failure modes in various components. In this regard, the durability analysis is the most important step for components subjected to cyclic loading while in design phase. The improvement of time and cost, failure analysis and also optimization of the parts are severe targets in the event of durability analysis through development cycle. It can be said that determination of component and vehicle life is one of the most significant tasks during development. In this regard, numerous research has investigated fatigue failures of outer tie rod. In OTRs, taper region of radial ball studs are the most susceptible areas against fatigue type of failures. Because this region is the interface between OTR and knuckle which has the location of concentrated stress due to excessive dynamic and static loadings. Other critical region for crack initiation is the neck diameter on ball stud. In the literature, it can be found a significant number of examples explaining the fatigue failure on ball stud.

A study about failed SUV tie rod has been published [1]. According to the measurements based on spectrum and hardness results, failed region was on AISI 8620 steel. Failure analysis showed that required composition and hardness were not respected according to the reference standard. Later on, the fatigue type of failure has been found as the main reason after fractographic features inspection. The crack initiation point as well as beach marks have been clearly identified at thread part of the rod. As a conclusion, study observed the main failure reason due to material deficiency which crack initiation and propagation with rupture end supported this outcome. The accident which was taken place was the result of incompatible mechanical part.

Shinde et al. [4] detailed the analysis and investigation of the factors leading to the abrupt failure of an outer ball joint. Without showing any crack initiation, ball stud neck was identified as fracture region. In their study, the finite element analysis is performed to predict the structural responses. The design of ball stud is modified in terms of fatigue and static behavior within safety limit. Sener [3] determined the steering tie-rod fatigue life by collecting the force from roads in Turkey. After processing different signals fatigue characteristics of Turkey’s roads, finite element analysis is executed with the collecting force. This analysis has led to the determination of critical load and stress ranges in the ball stud neck region of the tie-rod. Ozsoy and Pehlivan [8] investigated the maximum stress on the outer tie rod by using finite element method. Different articulation angles were considered as parameters in the analysis. Based on the static analysis results, maximum stress for outer tie rod occurs on ball stud during articulation.

It is well known that the fatigue strength as well as fatigue life strongly depend on the surface integrity. The fatigue behavior of the ball stud can be enhanced through various surface treatment processes, such as deep rolling, nitriding, and induction hardening. In automotive industry, deep rolling process is one of the most common methods to achieve improved fatigue behavior for components especially if there is a critical region to be rolled over. The process is highly effective method to generate compressive type of residual stresses in aimed region of the component. Thus, hardness measurements generally increase thanks to this localized compressive type of loading. Large amount of plastic deformation with low strain rates elevates the dislocation densities in material’s surface having suitable cell structures.

In service, ball studs encounter mostly tensile type of loadings. The incorporation of deep rolling during the manufacturing process of the ball stud results in the introduction of compressive residual stress, effectively counteracting the tensile stress induced by service conditions. This interplay leads to a notable extension in the fatigue life of the component. In addition, improved surface hardness also contributes to fatigue behavior. Deep rolling is also efficient way to create smooth and clean surface finish. During the process, ball or roller type of skater is pushed against surface with a certain number of longitudinal and rotational passes in order to create plastic deformation. Materials having high modulus of elasticity and wear resistance are generally preferred such as hardened steels but also tungsten carbide and ceramics for better mechanical properties to perform deep rolling. Deep rolling process has variety of parameters such as ball rolling speed, feed, number of passes, pressure, lubrication, tool dimension and material which directly affect the finished product’s surface finish [2]. Illustration for deep rolling can be seen in Figure 3.

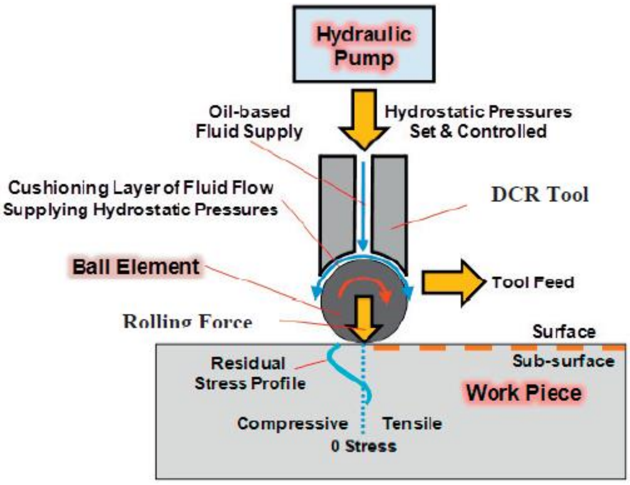


Figure 3. Working principles of deep rolling process

The present study aims to examine the impact of the deep rolling process on the fatigue behavior of a steel stud utilized in a tie-rod for steering system components. To achieve this target, fatigue tests are conducted as part of an experimental investigation to generate S-N curves. These tests aim to assess the fatigue endurance limits of the stud under two distinct conditions: the unrolled state and the rolled state at three different loads.

By analyzing load amplitude versus the number of cycles to failure curves at these three loading conditions, the study calculates the endurance limits by employing regression lines to account for any scatter using probability density functions. Furthermore, the research endeavors to compare these endurance limits with those of the unrolled condition. Additionally, the study assesses the improvement in the endurance limit in relation to the different rolling loads applied.

2. Materials and Methods

The ball stud, composed of 41CrS4 grade steel, is initially formed via the forging process, known for its applicability in producing essential automotive components like transmission shafts, gear shafts, and crankshafts. After the forging phase, the ball stud is subjected to a quenching and tempering treatment, a pivotal procedure for enhancing the strength and hardness of steel and iron-based alloys.

Quenching, a thermal process, involves elevating the material's temperature followed by rapid cooling using diverse mediums such as water, oil, forced air, or inert gases like nitrogen. This controlled process demands rigor regulation by the operator, who precisely manipulates critical parameters, including heating temperature, cooling technique, and speed. These parameters are meticulously tailored in accordance with the material's specific properties, ensuring the achievement of designated material characteristics such as hardness and strength. At room temperature, the initial sample exhibits a tensile strength of 950 MPa and a yield strength of 660 MPa. Subsequently, spectrometric analysis is conducted on the steel ball stud specimens, with the resulting chemical composition presented in Table 1.

Table 1. Chemical composition of 41CrS4 forged steel [11]

Chemical Composition, wt %						
Material	**C**	**Si**	**Mn**	**Cr**	**S**	**P**
41CrS4	0.42	0.25	0.70	1.05	0.020 - 0.035	0.025

In this study, the focus is placed on investigating ball studs subjected to three distinct fillet rolling conditions to establish a relationship between fatigue strength and the applied rolling load. Specifically, the examination encompasses ball studs exhibiting the un-rolled condition, as well as those subject to fillet rolling at 70%, 100%, and 170% of the standard rolling load (%70 F, %100 F, and %170 F, respectively) in the taper region. Figure 4 presents the critical region of the ball stud, as identified from the literature, along with the assembly conditions connecting the ball stud to the knuckle.

It's important to note that the deep rolling process, as an integral part of this investigation, is solely implemented within the taper area of the ball stud.

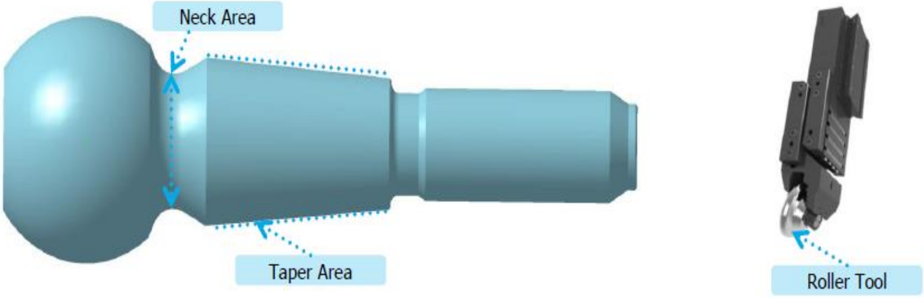


Figure 4. Schematic representation of the ball stud and roller tool

The application of deep rolling on the taper area of the outer tie rod ball stud is performed using a hydraulic rolling apparatus. This rolling apparatus incorporates a primary roller that induces deformation in the taper region of the ball stud simultaneously during the rolling operation. The rollers exert force on the ball stud's taper area at a specific angle to the radial axis, as illustrated in Figure 4.

The deep rolling tool is compatible with both conventional and CNC-controlled machines, seamlessly integrating into the existing process chain. To ensure efficiency, a ball stud undergoes the deep rolling process in a single setting immediately following the neck and ball surface machining process. The deep rolling process is performed at room temperature. Figure 5 demonstrates the rolling operation of the ball stud taper area.

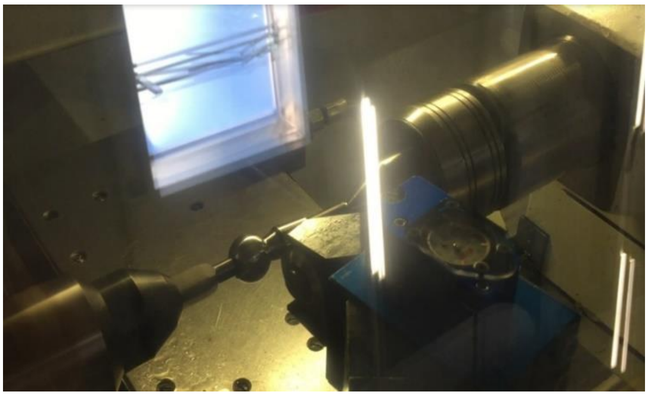


Figure 5. Application of deep rolling process

2.1. Experimental Procedure

In order to comprehensively understand the implications of the deep rolling process on the ball stud of the tie rod component across varying loading parameters, an experimental approach has been devised. Fatigue testing is employed as the primary methodology for evaluating the load versus cycles to failure curve data of the ball stud under three distinct rolled conditions, facilitated by a servo-hydraulic testing machine.

The specimen is precisely secured from the taper area using an adaptor designed to replicate the dimensions of the original knuckle. Subsequently, it is mounted onto the fatigue test rig, where a nut is fastened to the original torque value. A cyclic radial force is then systematically applied to the taper region of the ball stud, identified as the critical point within the outer tie rod under operational conditions. Notably, the tests were conducted under completely reversed constant amplitude cyclic loads. For visual reference, Figure 6 provides tangible insights into the configuration of the test specimen and the experimental setup.

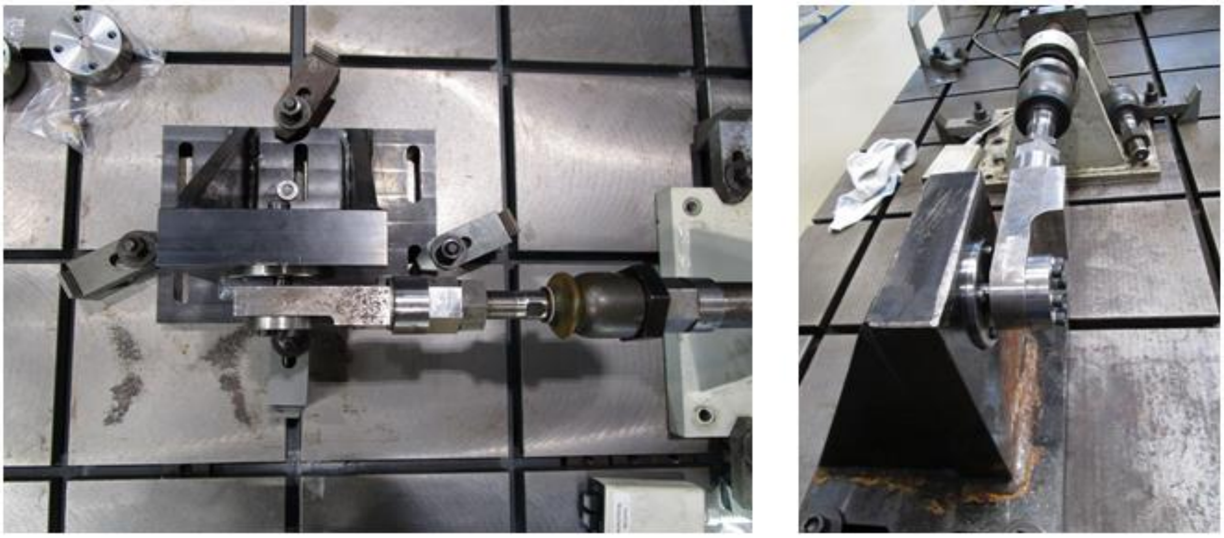


Figure 6. Experimental set-up of ball stud fatigue test

Throughout the testing process, the operating frequency was consistently noted to be in the range of approximately 8-10 Hertz. To adequately encompass both the crack initiation and propagation stages on the test specimens, a relatively substantial frequency limit of ±1 Hertz, equivalent to 10% of the operating frequency, was employed. The number of cycles to failure is recorded for the applied radial loads to establish the load amplitude versus the number of cycles to failure (F-N) curves for the ball stud under three distinct rolling conditions. The rolling force is adjusted by regulating the depth of penetration. Moreover, a test run-out criterion is implemented, set at 10 million cycles. Consequently, the fatigue strength values incorporated in this study represent the fatigue strengths observed at the 10 million cycle mark.

A staircase test methodology is adopted for the selection of the load amplitude in the fatigue tests. With this approach, the first specimen is subjected to testing at a pre-established load amplitude level, guided by prior experience. Should the specimen fail, the subsequent test utilizes a reduced load amplitude level. Conversely, if the specimen endures without failure, the subsequent test incorporates an increased load amplitude level. This sequential process is reiterated until a substantial dataset is acquired, enabling the construction of the F-N curve and facilitating the calculation of the endurance limit.

3. Results and Discussion

In order to compare the deep rolling process effect, un-rolled ball stud specimen testing is firstly carried out on tension – compression fatigue test machine. During test, the number of cycles until failures is recorded against applied radial load amplitude throughout the tests. Fatigue test results of ball stud in un-rolled condition are presented in Table 2. It can be seen that the fatigue results of the ball stud without rolling process have a high spread of the reached load cycle when the fracture location is changing from neck to the taper area within load level. At the loads higher ±8 kN, results showed that there is an acceptable spread. The fracture location is found as always in ball stud neck area.

Table 2. Fatigue results of ball stud in un-rolled condition.

Load [kN]	**Frequency [Hz]**	**Load Cycles [-]**	**Fracture Region**
±3.5	8	2.000.000	-
±5	8	382.600	-
±5	10	508.600	Taper
±5	10	438.800	Taper
±5	10	490.400	Neck
±6.5	10	175.600	Neck
±6.5	10	134.400	Neck
±6.5	10	104.500	Neck
±6.5	10	149.700	Neck
±8	10	56.000	Neck
±8	10	64.700	Neck
±8	10	63.200	Neck
±8	10	63.700	Neck
±12	10	6.400	Neck
±12	10	8.500	Neck
±12	10	7.100	Neck
±12	10	9.100	Neck
±14	10	5.300	Neck
±14	10	5.600	Neck
±16	10	2.000	Neck

The ball stud is subjected to extremely high cycle fatigue load in service conditions, requiring the stresses to be elastic. In cases where stresses are primarily elastic and high cycle fatigue is predominant, F-N approach is frequently employed. This approach utilizes the nominal stress rather than the localized stress at the root of the notch. In this regard, F-N curve in Figure 7 shows the fatigue life determined by using experimental method with the scatter probability density for un-rolled ball stud. The staircase test data are demonstrated as the applied load in N versus number of cycles to failure curves on a semi-logarithmic scale. Results are analyzed with a regression line to account for the scatter using probability density functions. It is observed from graph that the tension-compression endurance limit for the un- rolled ball stud is around 3.5 kN.

As explained in material and methods section, 3 different rolling force levels are considered during ball stud sample production and fatigue test has been performed on those samples to investigate the effect of different rolling forces. Due to a small amount of rolled ball studs including different rolling parameter, the test with rolled ball studs is performed only on load level ±10 kN and ±12 kN to compare the reached load levels with the former basic wöhler test that is created for un-rolled ball studs (Figure.7).

The achieved load cycles for ball stud produced with different rolling forces can be seen in Table 3 as follows.

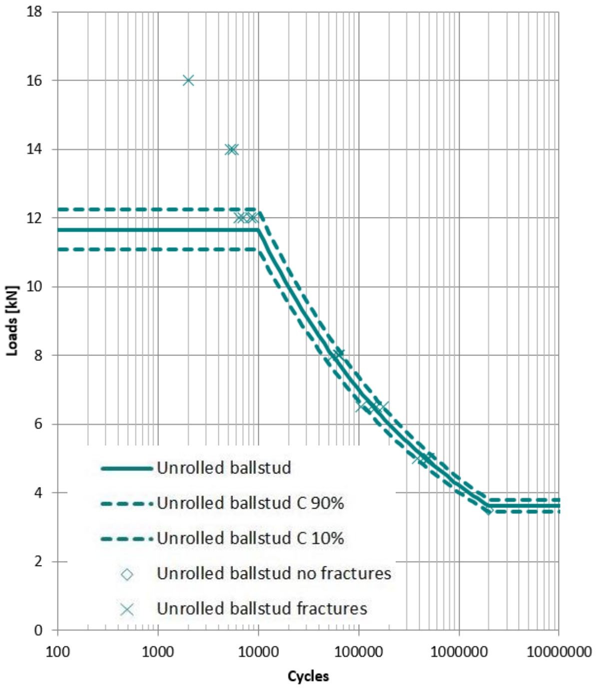
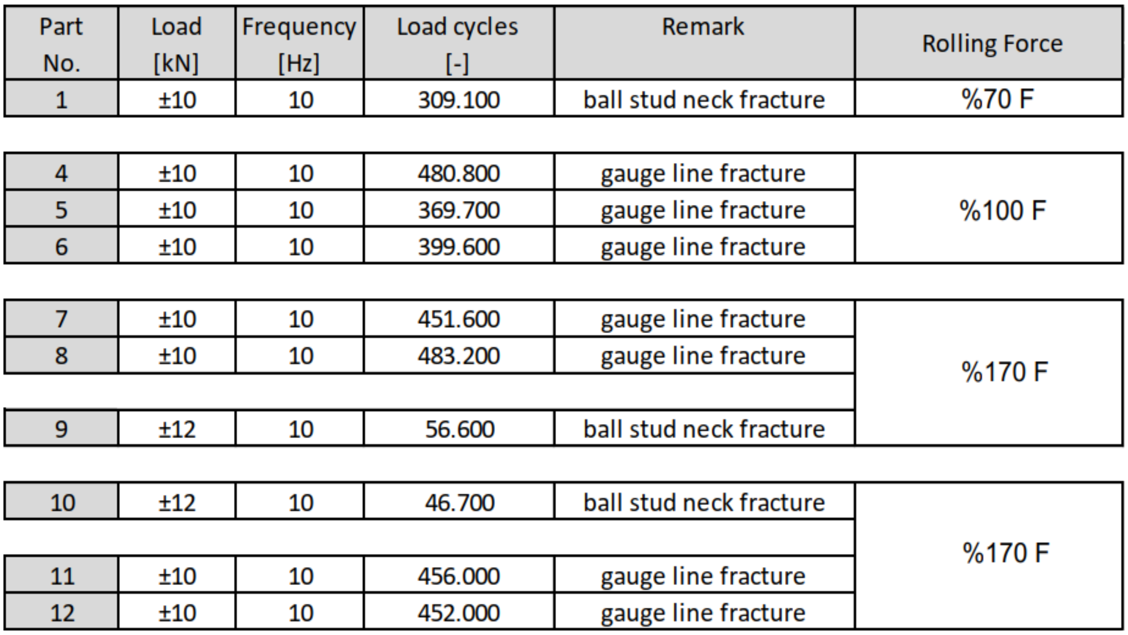


Figure 7. F-N curve of ball stud in un-rolled condition.



Part No.	Load [kN]	Frequency [Hz]	Load cycles [-]	Remark	Rolling Force
1	±10	10	309.100	ball stud neck fracture	%70 F
4	±10	10	480.800	gauge line fracture	%100 F
5	±10	10	369.700	gauge line fracture	
6	±10	10	399.600	gauge line fracture	
7	±10	10	451.600	gauge line fracture	%170 F
8	±10	10	483.200	gauge line fracture	
9	±12	10	56.600	ball stud neck fracture	
10	±12	10	46.700	ball stud neck fracture	%170 F
11	±10	10	456.000	gauge line fracture	
12	±10	10	452.000	gauge line fracture	

Figure 8. Fatigue results of rolled ball studs in different rolling force.

On load level ±10 kN the fracture is in ball stud gauge line and even including the part no. 1 with lowest rolling parameter, the spread of the reached load cycles is ok. Nevertheless, part no. 1 with lowest rolling parameter reaches lowest load cycles of all rolled hardened ball studs. The reached load cycles exceed the results of non-rolled ball studs by about 3 times.

On load level ±12 kN fracture is located in ball stud neck and the reached load cycles exceed the results of non-rolled ball studs just about 1,5 times. Since rolling force increase the achieved cycles and failure locations become more stable, fatigue test is performed on ball stud specimen that is deeply rolled under %170 F loading conditions to compare the effect of rolling process. Test results of ball stud in rolled condition are presented in Table 4. It is understood from results that the fatigue limit for the deep rolled ball stud is around 23.000 cycles at ±12 kN whereas the fatigue limit for the unrolled ball stud is around 7.000 cycles. Hence, the deep rolled ball stud’s fatigue limit is enhanced by three times as compared to that of the un- rolled ball stud. It can be also observed from graph that the tension-compression endurance limit is increased to approximately 6 kN for the rolled ball stud.

Table 4. Fatigue results of ball stud in %170 F rolled condition.

Load [kN]	Rolling Load [N]	Frequency [Hz]	Load Cycles [-]	Fracture Region
±6.5	%170 F	10	2.000.000	-
±6.5	%170 F	10	2.000.000	-
±8	%170 F	10	284.500	Neck
±10	%170 F	10	64.000	Neck
±10	%170 F	10	63.700	Neck
±10	%170 F	10	57.000	Neck
±12	%170 F	10	24.700	Neck
±12	%170 F	10	21.500	Neck
±12	%170 F	10	23.500	Neck
±14	%170 F	10	7.300	Neck
±14	%170 F	10	7.400	Neck
±14	%170 F	10	9.700	Neck

The difference in results between deep rolled and un-rolled ball stud is shown in Figure 8 below.

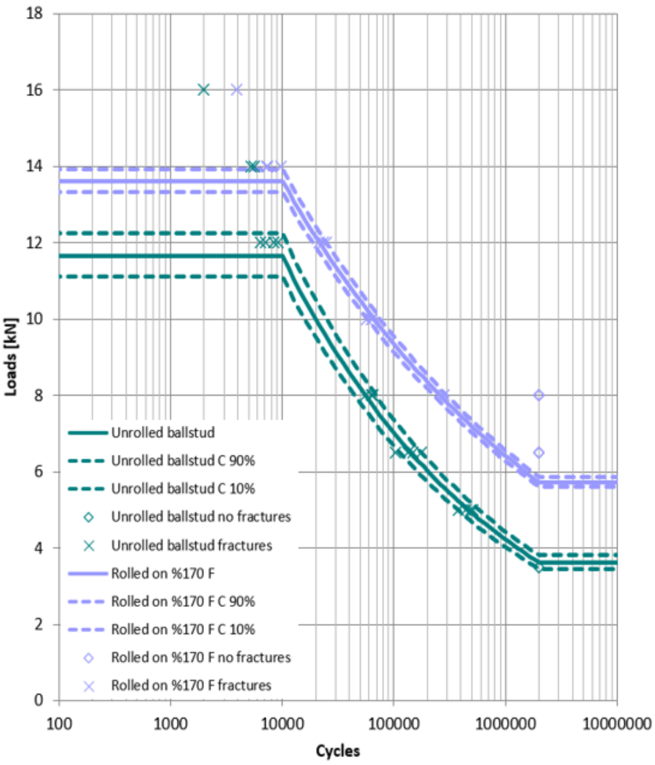


Figure 8. F-N curve comparison of ball stud in rolled at %170 F and un-rolled condition.

4. Conclusions

In this study, the effect of the deep rolling process on fatigue behavior of ball stud made of steel 41CrS4+QT material is investigated. For this purpose, fatigue life predictions by using the F-N approaches are carried out on un-rolled and rolled ball stud at three different loads, which are %70 F, %100 F and %170 F, and then fatigue endurance limits are compared with each other. Regression line to account for the scatter using probability density functions is used for test results. Based on the comprehensive analysis of the experimental results, the following conclusions can be drawn:

The fatigue limit for the un-rolled ball stud is 7.000 cycles whereas the fatigue limit for the rolled ball stud is 23.000 cycle at the same load. The fatigue test of the deep rolled parts proved that the application is successful. Results have shown that the endurance limit of steel are enhanced by four times as compared to those of the un-rolled. This fact describes that the deep rolling is an effective process to improve the fatigue strength of ball stud significantly by a convenient local deformation and hardening process.

With regards to gaining a better understanding on deep cold rolling process variables, rolling load is chosen as the parameter. It can be understood from results that as the rolling loads of ball stud increase, fatigue values for deep rolling indicate the improvement. As expected, the deep rolling results in a residual stress state strongly depend on the rolling force.

Similarly, as the rolling loads of ball stud increase, mechanical surface treatments regarding the maximum residual stresses and the penetration depth increase. Surface strengthening is a major portion of the fatigue limit for ball stud and measuring the residual stress in the near-surface zone showed that certain amount of the surface zone is subjected to high compressive residual stresses. Compressive residual stresses compensate the tensile components of the service loads and local hardness increase can retard the crack initiation which both improves the fatigue strength.

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