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Effect of Manufacturing Parameters on Screw Thread Microhardness in Wind Turbine Fasteners

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Abstract

Wind power plants (WPPs) are structures that produce energy by absorbing large-scale loads coming from many different directions with their bodies and blades. The critical fasteners of WPPs resist all these loads. One of the critical fasteners used in the assembly of wind turbines is screw studs. WPP studs are currently mainly produced from 10.9 tempered steel. Threading heat-treated steels allows heat treatment defects to be detected with magnetic testing after threading. All WPP studs are subjected to 100% magnetic particle testing after threading to investigate heat treatment defects. The threaded stud samples without crack defects are then subjected to hardness measurement. In this study, the Vickers hardness of the shaft studs produced from two different raw materials, 32CrB4 and 34CrMo4, was measured and noted before threading. Then, the samples were threaded at two different speeds. The Vickers hardness distribution on the stud threads was determined by measurements. In the rolling process of the studs that were observed to be out of the specified range, firstly, trial studies were carried out on the spindle speed (rolling roller speed), which is one of the most important parameters in the process. The rolling operations at 28 and 40 rpm were carried out for the determined samples. The effect of both the material type and the speed of the roller on the Vickers hardness distribution on the stud teeth after the gear cutting was investigated. As a result of the experiments, it was seen that the 32CrB4 sample and the speed value of 40 rpm were more suitable.

Keywords: *Fasteners, Wind power, Thread rolling, Vickers hardness distribution.*

1. Introduction

Elements that mechanically connect two or more parts to each other, to a body, or to any structural foundation for fixing machine components are called "connectors". Bolts, nuts, washers, anchors, screws and threaded rods are among the basic connecting elements included in this group. Among these elements, bolts stand out in particular due to their widespread use and being the first component that comes to mind when it comes to connecting elements [1]. The main reasons for the widespread preference of connecting elements such as bolts and screws are; high mechanical strength, low production cost, easy assembly and disassembly possibilities. Thanks to these features, they are effectively used in many industrial applications, especially in the machinery and construction sectors [2–4]. In addition, they provide suitable joining solutions in applications requiring maintenance and repair. Optimization of bolted connection systems is of critical importance in terms of safety, structural reliability, and cost effectiveness. However, incorrect tightening of connecting elements or unbalanced load distribution can cause accidents that threaten occupational safety [5-6]. For this reason, numerous studies have been conducted in the literature on the optimization of bolted connections. The most frequently studied parameters include bolt arrangement, applied preload, bolt class, plate material, coefficient of friction, bolt diameter, and length. For example, Khurshid [7] investigated the displacement behavior and stress distributions of bolted connections under shear loads on a four-bolt model. Similarly, in another study, the stress distribution was analyzed using the finite element method [8]. From the perspective of bolt manufacturers, in order to ensure product reliability, it is necessary to maintain steel purity, eliminate surface defects, prevent thread overlaps, control surface decarburization, limit surface phosphate diffusion, and eliminate the risk of hydrogen embrittlement [9]. For example, Shakeri et al. [10] investigated the effects of manufacturing defects originating from the thread rolling process on high-cycle fatigue life of M30 class 10.9 stud bolts. As a result of high-cycle fatigue tests of two different batches of bolts with the same nominal properties, significant differences in fatigue strength were observed.

In WPP turbines, the anchor cages that connect the variable wind forces coming to the blades to the ground, and the anchor connection elements group meet the dynamic and static loads in the anchor cages. In fact, turbine connection elements must be manufactured with mechanical properties that will meet production standards despite the forces they will resist. In order to prevent the negative effects of heat treatment defects on WPP connection elements in later processes, a threading process is performed after heat treatment. Especially during threading, if there are carburization, decarburization, cracks, and defects related to production parameters or the threading mold in the materials threaded, they are detected after this process. 100% crack control and Vickers hardness distribution control on the thread are performed in quality laboratories on the materials threaded. In wind turbine connection elements, it is 320-380 HV for 10.9 quality connection elements according to ISO 898-1 standard. However, in customer specifications of energy giant global companies, it may be requested that this hardness be kept in wider ranges such as 320-390 HV in the distribution of the thread [11].

2. Materials and Methods

2.1. Threading process of fasteners

In fasteners, threads are critical points of structural strength due to their load-bearing and transmission functions. Since the weakest section is usually found in the diameter of the thread root, thread strength is the determining factor of overall connection strength. Two basic methods are used in the production of thread: the rolling method, where the material is shaped by pressure force, and the cutting method, which is performed by removing chips. The production process of both methods shows significant differences in terms of requirements and the quality of the thread obtained. The plastic shaping method of crushing the part to be threaded between the threading dies, usually with hydraulic pressure, and crushing the material on the material is called rolling. This method is also a cold forming method. Rolling machines are used in the rolling method. The machines used are named and classified according to their hydraulic pressure capacities. In addition, these machines are classified according to whether the shafts to which the threading dies are attached can be angled. In the rolling method, the material with the rolling diameter to be threaded between two threading dies is placed on the lower support. By applying hydraulic pressure at a specified speed, the profile in the threading dies is cold deformed to the material to be threaded. Shaping a round steel bar by removing chips and creating a thread profile is called cutting. Thread form is given by removing chips on various machines, such as universal lathes, CNC lathes, etc. Here, instead of crushing with thread opening molds, the thread profile is created by cutting with cutting inserts and tools. Many parameters come into play in thread quality and tool life. Parameters such as cutting tool tip angles, clamping angle, wear control, etc., affect thread quality in the thread method by removing chips. Screw cutting is a difficult process that requires high operator skill and low machine tolerance. In contrast, the thread rolling method offers higher fatigue (50–75%) and tensile (10%) strength. While larger diameter raw materials are required in the cutting method due to chip removal, smaller diameter materials can be used in the rolling method thanks to cold deformation. In addition to preventing material loss, rolling provides shorter production times and lower unit costs. Therefore, the rolling method is more advantageous than the cutting method in terms of mechanical performance and production efficiency [11].

2.2. Rolling Method

Rolling machines are systems that give profiles such as threads, serrations, and shafts to round-section materials by cold forming. These machines crush the material between rolling rollers with hydraulic pressure, allowing high-strength and quality products to be obtained. With the developing technology, production flexibility and infinite length thread cutting capability have increased thanks to PLC-controlled systems and angled roller connection possibilities. Factors determining the effectiveness of cold deformation include material properties, roller angle, pressing tonnage, and lubrication systems, and these parameters have a direct effect on the geometry, surface quality, and strength of the thread. In particular, appropriate lubrication both reduces wear resistance and contributes to the improvement in the thread profile [12]. Figure 2.1 shows an image of a sample during thread cutting in the rolling process. Thread cutting dies, the lower support on which the thread is turned, the raw material shaft, and the thread cutting sides are shown.

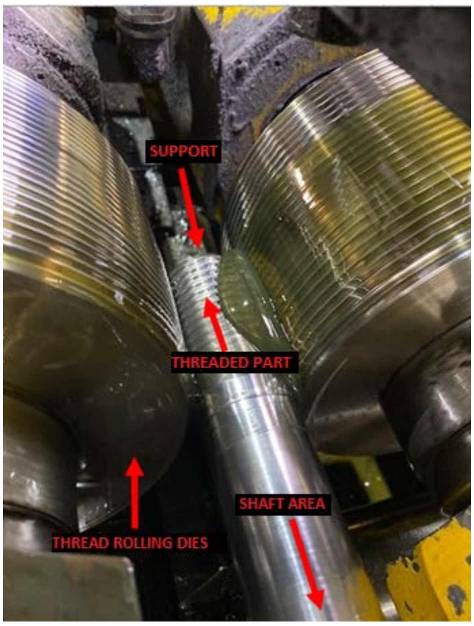


Figure 2.1 The sample image in the rolling process [11]

2.3. Rolling Rollers

The molds used to give the material a new form on rolling machines are called rolling rollers. The concept of Screw Rolling Roller was first developed by Profiroll in Germany [13]. The material taken between the rolling rollers is crushed in the screw profile with hydro-mechanical crushing force and subjected to cold deformation. In order for this crushing process to continue along the circumference of the workpiece, the rolling rollers are rotated with a large torque, and the molds are brought closer to each other until the thread profile depth is formed, thus rotating the workpiece and creating the thread profile. The energy used in this process is less than the energy of turning and machining that will perform the same process. There are types of rollers used in the rolling process, such as push-pull and ring rolling relays [14]. If the thread length of the material to be rolled is approximately equal to the mold length and is short, the thread opening process is performed with relays called push-pull. The exterior of the push-pull rollers is the same as the desired thread form of the material to be rolled. In the use of push-pull rollers, the material takes the form of a thread by rotating without moving back and forth. The materials with steps in front and behind the rolling section are connected flat without angle adjustment, and these rollers produce a product with each press. In Figure 2.2, the axial positioning and working method during the rolling process are shown with arrows.

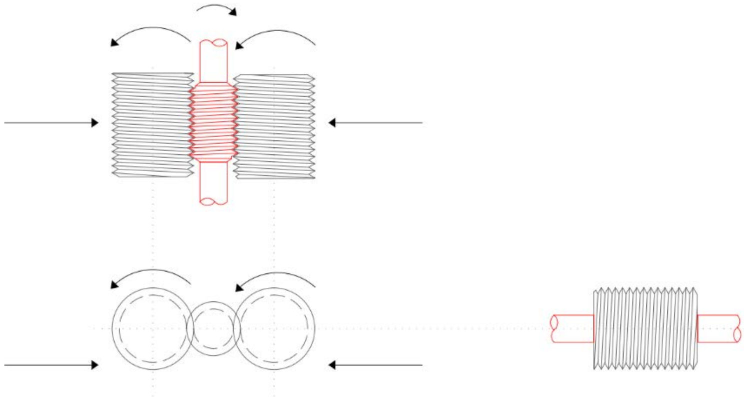


Figure 2.2 Push-pull rollers [11]

Ring rollers are connected to the machine at a certain machine angle. This angle is given to the machine spindle and therefore to the relay, allowing the thread to be opened on materials with a longer thread length than the roller length. The difference from the push-pull roller is that there is no helix angle in the thread on the ring roller, and the thread channels are not connected to each other. On the outside of these rollers, there are section channels of the desired screw thread instead of the screw form. In Figure 2.3, the axial positioning and working method of the ring thread die and the part being threaded are shown with arrows.

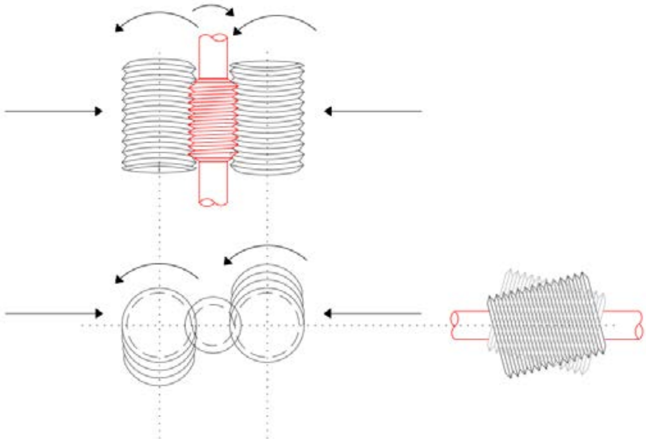
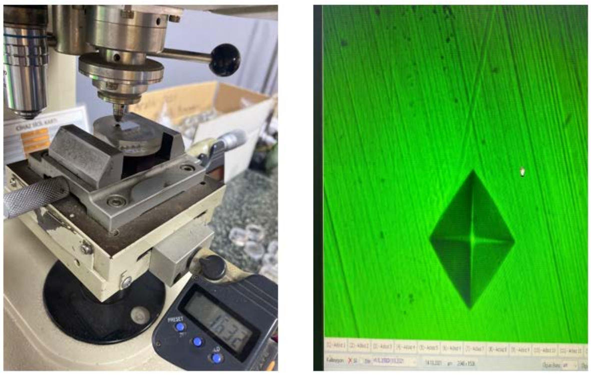


Figure 2.3 Ring rollers [11]

2.4. Vickers Hardness

The Vickers hardness test is measured by the method of creating an indentation by dipping a diamond tip in the shape of a square pyramid with a top angle of 136° into the sample under variable loads. Normally, the indentation load varies between 1 kp and 30 kp, but both higher and lower loads can be used [15]. The Vickers hardness value HV is measured as the load divided by the pyramidal area of the indentation (kp/mm^2). The Vickers test, which has a wide range of use, is used in thin layers rather than very soft and very hard materials. The numerical hardness value in Vickers hardness measurements varies between 3 HV and 1500 HV. In order to measure the hardness as a result of the test, it is necessary to measure the diagonals of the square-shaped indentation precisely. This measurement is made with a metallurgical microscope. The indentation image formed on the sample is transferred to the measurement screen with the microscope, the lengths between the diagonals are measured on the measurement screen, and the average is taken. In the measurement, the hardness value is used as kg and the test load area as mm^2.



(a) (b)

Figure 2.4 Vickers hardness, (a) placement on the device, (b) sunset projection image [11]

3. Results and Discussion

In this study, stud screws produced from two different 32CrB4 (C1) and 34CrMo4 (C2) tempered steels were used. The wind turbine studs in the study are fasteners with M36-M64 nominal diameters, varying in length between 3-6 meters and having thread lengths between 200-800 mm at both ends. Research and experimental studies were carried out to control the Vickers hardness distribution in the studs' threads and to ensure that it is in the range of 320-380 HV according to the standard and 320-390 HV according to the specifications. In the experimental studies, ring rollers were used to open the threads of these studs by rolling method. The reason for using ring rollers is that the thread length is longer than the roll length. The screw profile was shaped on the ring roller, which is the threading mold of the material to be threaded. First, the hardness distribution of the materials in the rolling diameter was examined without opening the thread, and then experimental studies were carried out. Experimental studies were designed by taking into account the effects of the amount and speed of cold deformation on the Vickers hardness distribution as a result of literature reviews and research [16-17].

3.1 Microhardness control before threading

Before the experimental studies in which Vickers hardness was aimed to remain within a certain range by making threading experiments, microhardness measurements were made from the shaft part of the steel. In Table 3.1, these measurements are shown by defining the experiment sequence numbers, the blank casting number of the raw material (according to the records of Berdan Civata A.Ş.), raw material diameter, type, and quality of steel, Vickers hardnesses taken from the shaft as HV_1, HV_2, and HV_3. Hardness measurements were made from the shaft as determined by the standard ISO 6057-1 2002 [18]. All materials used in the experimental studies are 10.9 quality tempered steels.

Table 3.1 Shaft microhardnesses taken from pre-threading samples [11]

Experiment Sequence No.	Raw Material Casting No.	Raw Material Diameter (mm)	Raw Material	Shaft Hardness HV_1	Shaft Hardness HV_2	Shaft Hardness HV_3
1	18H00895	Ø 38.90	C1	340	352	353
2	18H00895	Ø 38.90	C1	344	351	348
3	18H00895	Ø 38.90	C1	327	334	357
4	18H01210	Ø 38.90	C1	317	319	325
5	18H00895	Ø 38.90	C1	329	334	338
6	18H00895	Ø 38.90	C1	349	336	328
7	18H00895	Ø 38.90	C1	330	336	343
8	18H00895	Ø 38.90	C1	322	316	328
9	18H01210	Ø 35.85	C1	343	342	309
10	18H01210	Ø 35.85	C1	335	333	331
11	17H01167	Ø 35.85	C2	363	371	376
12	17H01167	Ø 35.85	C2	368	375	374
13	17H01167	Ø 35.85	C2	360	360	368
14	17H01167	Ø 35.85	C2	354	374	378
15	17H01167	Ø 35.85	C2	343	347	365

16	17H01321	Ø 35.85	C2	319	311	324
17	17H01167	Ø 35.85	C2	321	333	342
18	17H01167	Ø 35.85	C2	356	361	345
19	17H01167	Ø 35.85	C2	314	334	325
20	17H01167	Ø 35.85	C2	332	347	338

Laboratory tests revealed that the HV3 hardness, the highest expected value in the table above, was measured at a maximum of 378 HV in samples taken from 20 different bar raw materials. This hardness distribution complies with standards and specifications.

3.2 Microhardness after threading

The threading by rolling process was carried out at 14 rpm for a total of 20 samples, both C1 and C2, whose shaft microhardnesses were previously measured. Table 3.2 shows the experiment sequence number, blank casting number of the raw material, raw material diameter, type and quality of steel, hardnesses taken from the shaft as HV_1, HV_2, HV_3, and Vickers hardnesses taken from the thread as $HV_{1.2}$, $HV_{2.2}$, $HV_{3.2}$. As seen in Table 3.2, the Vickers hardness distribution reached values between 320-430 HV. HV_1, HV_2, HV_3 hardness values represent the shaft hardness values. While the average values of HV_1, HV_2, and HV_3 were 333.6, 335.3, and 336 HV in sample C1, these values were 343, 351.3, and 353.5 HV in sample C2, respectively. The hardness values of $HV_{1.2}$, $HV_{2.2}$, and $HV_{3.2}$ represent the hardness values obtained from the thread. In the C1 sample, the average values of $HV_{1.2}$, $HV_{2.2}$, and $HV_{3.2}$ were 334.7, 366.2, and 390.8 HV, respectively, while in the C2 sample these values were 347, 379.7, and 397.3 HV, respectively. The target microhardness value obtained from the samples was outside the range of 320-390 HV. This situation occurred more in the C2 samples in particular. It was observed that the C1 samples were more suitable for the rolling process.

Table 3.2 Hardness of the samples with measured shaft hardness after threading at 28 rpm [11]

Experiment Sequence No.	Raw Material Casting No.	Raw Material Diameter (mm)	Raw Material	Shaft Hardness (HV_1- HV_2- HV_3)			Thread Hardness ($HV_{1,2}$- $HV_{2,2}$- $HV_{3,2}$)		
1	18H00895	Ø 38.90	C1	340	352	353	375	344	395
2	18H00895	Ø 38.90	C1	344	351	348	328	384	389
3	18H00895	Ø 38.90	C1	327	334	357	342	394	399
4	18H01210	Ø 35.85	C1	317	319	325	325	374	383
5	18H00895	Ø 38.90	C1	329	334	338	339	351	406
6	18H00895	Ø 38.90	C1	349	336	328	323	364	374
7	18H00895	Ø 38.90	C1	330	336	343	331	392	397
8	18H00895	Ø 38.90	C1	322	316	328	327	344	369
9	18H01210	Ø35.85	C1	343	342	309	330	374	406
10	18H01210	Ø35.85	C1	335	333	331	327	341	390
1	17H01167	Ø35.85	C2	363	371	376	349	412	431
2	17H01167	Ø35.85	C2	368	375	374	368	407	420
3	17H01167	Ø35.85	C2	360	360	368	352	393	420
4	17H01167	Ø35.85	C2	354	374	378	374	392	421
5	17H01167	Ø35.85	C2	343	347	365	354	379	393
6	17H01321	Ø35.85	C2	319	311	324	321	349	380
7	17H01167	Ø35.85	C2	321	333	342	336	348	375
8	17H01167	Ø35.85	C2	356	361	345	332	360	367
9	17H01167	Ø35.85	C2	314	334	325	327	359	380
10	17H01167	Ø35.85	C2	332	347	338	357	398	386

After determining that C1 samples were more suitable for the rolling process, the threading process was carried out at 40 rpm for 12 C1 samples whose shaft microhardnesses were previously measured. Table 3.3 shows the experiment sequence number, blank casting number of the raw material, raw material diameter, type and quality of steel, hardnesses obtained from the shaft as HV_1, HV_2, HV_3, and Vickers hardnesses obtained from the thread as $HV_{1.2}$, $HV_{2.2}$, $HV_{3.2}$. As seen in Table 4.2, the Vickers hardness distribution reached values between 300-392 HV. HV_1, HV_2, and HV_3 hardness values represent the shaft hardness values. In the C1 sample, the average HV_1, HV_2, and HV_3 values were 321.3, 329.4, and 334.1 HV, respectively. The hardness values of $HV_{1.2}$, $HV_{2.2}$, and $HV_{3.2}$ represent the hardness values taken from the thread. In the C1 sample, the average values of $HV_{1.2}$, $HV_{2.2}$, and $HV_{3.2}$ were 331.4, 367.8, and 380.5 HV, respectively. When the average microhardness values were examined, it was determined that 40 rpm was more suitable in the rolling process.

Table 3.3 Hardness of the samples with measured shaft hardness after threading at 40 rpm [11]

Experiment Sequence No.	Raw Material Casting No.	Raw Material Diameter (mm)	Raw Material	Shaft Hardness (HV_1- HV_2- HV_3)			Thread Hardness ($HV_{1,2}$- $HV_{2,2}$- $HV_{3,2}$)		
1	18H01210	Ø35.85	C1	339	340	341	318	352	379
2	18H01210	Ø35.85	C1	343	348	364	329	373	390
3	18H01210	Ø35.85	C1	303	326	336	343	372	389
4	19H00287	Ø35.85	C1	302	336	337	331	366	386
5	19H00287	Ø35.85	C1	322	329	331	334	385	388
6	19H00287	Ø35.85	C1	306	324	342	334	382	382
7	19H00287	Ø35.85	C1	339	334	322	321	364	365
8	19H00287	Ø35.85	C1	319	320	331	331	344	367
9	19H00266	Ø38.90	C1	329	322	312	346	392	389
10	19H00266	Ø38.90	C1	300	305	326	322	354	377
11	19H00266	Ø38.90	C1	328	348	331	339	365	380
12	19H00266	Ø38.90	C1	326	321	336	329	365	374

4. Conclusions

In this study, the Vickers hardness distributions in the shaft and thread regions of studs produced from 32CrB4 (C1) and 34CrMo4 (C2) tempered steels to be used in Wind Power Plant (WPP) were investigated. First, hardness values were obtained from two different tempered steel samples. Then, threading operations were carried out at 28 and 40 rpm shaft speeds by the rolling method. Both the effect of alloy elements in tempered steel on hardness and the effect of speed on hardness were analyzed. When the hardness values of the shaft were examined before the threading process, it was seen that the values obtained from both tempered steel samples were in accordance with the standards and specifications. However, after the threading process, it was seen that the hardness values of especially C2 sample increased to values higher than the required limits. It was determined that the C1 sample was more suitable for the rolling process. When the effect of speed on hardness was examined, it was seen that a 40-rpm value was more suitable. It has been obtained that some hardness values obtained from samples exceed the required limits for 28 rpm.

Ethics committee approval and conflict of interest statement

This article does not require ethics committee approval.

This article has no conflicts of interest with any individual or institution.

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Author Contribution Statement

Memduh KARA: Conceptualization; Investigation; Supervision; Validation; Writing; Critical review.

Dergah UYSAL: Investigation; Methodology; Experimental design; Data collection; Literature review; Writing.

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