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Research Paper

Study the Effects of the Cryogenic Method Using Liquid Nitrogen on Fittings in Assembly Process

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Abstract
Cryogenics is a field that involves producing, storing, transporting, and using materials at freezing temperatures. One application of this technology is in the shrinkage fitting process, where coolant materials like liquid nitrogen are used to reduce the dimensions of parts so that they can be joined together. This technique is often utilized in sub-assemblies to create a strong fit between the internal and external surfaces of components, which eliminates relative movement between parts, allowing force to be directly transferred from one part to another. In a recent study, we investigated different methods for fitting bush and axle parts with precise dimensions. Cryogenic, pressing, and thermal methods were utilized for assembly fitting. The cryogenic and thermal methods utilized contraction and expansion of parts for assembly fitting, while no dimensional changes occurred in press fitting. Results from the study showed that the cryogenic method required less force for the assembly and disassembly of parts, and the surface quality of the parts after disassembly was better compared to the other methods. Metallographic tests demonstrated that the microstructure of the parts did not change, and impact tests showed that there was no decrease in the toughness of the parts after the cryogenic operation. Based on these findings, the researchers concluded that the cryogenic method is an excellent technique for fitting SAE4140 Steel parts.

Keywords
Cryogenics, Liquid Nitrogen, Assemble and Disassemble, Fitting Process

1. Introduction

Cryogenics, which means "cold," is the field in which materials are produced, stored, transported, and used at freezing temperatures. Extreme cold can cause substances to change from gas to liquid. The temperature at which gases turn into liquids varies from one gas to another. Oxygen liquefies at minus 183°C, while helium requires a temperature of at least minus 269°C. Cryogenic methods are used in various industries and research has focused on its effects on machine tools but no evidence of experimental study on fitting process was found.

In the shrink-fit process, the temperature decreases the dimensions of one part so that the pieces fit together and become fixed. This type of connection method is used in sub-assemblies to create a tight fit between internal and external components so that relative movement does not occur and force can be transferred from one part to another. Relative movements of mated parts can produce fretting fatigue. Typical applications of shrink-fittings include axles in wheels and rotors, liners in engine cylinders, bearings and bushings in housings, valve seats, and guides in engine blocks.

Cryogenically assisted manufacturing processes are emerging as environmentally-being, toxic-free, hazardless operations, producing functionally superior products. The fitting method has significant advantages compared to traditional methods of fastening or pressing connections for assembly because the parts of a set connected with fitting have fewer components and require fewer machining operations. Also, there is no need to rotate the parts to produce threads or key and keyway. Assembly is also simplified because there are no studs to hold the spike, screws to turn the nut, or welds to attach. Unlike pressing, shrink fitting doesn't put too much pressure on the parts. This is particularly important in the case of axles, where stress-induced distortion can lead to deformation. Analysis of process mechanics and material performance covering tribological and thermo-mechanical interactions, followed by surface integrity, product quality, and performance in cryogenic manufacturing are then discussed by Jawahir, et al. [1].

A study on the applications of self-tightening assemblies such as clamps shows that they are often used in machine-building industries due to their high transmission capacity for static and dynamic forces and simple and convenient use but the drawback of this type of connection is the weakness in holding firmly during work, the deterioration of surfaces during disassembly, application in the fields of small tolerance and lack of necessary reliability [2].

The results of measuring and evaluating hole characteristics for the drilling performance of carbon fiber reinforced plastic composites (CFRP) using a locally developed cryogenic machining indicate the suitability of cryogenic drilling in the drilling industry [3].

The effect of cryogenic treatment on the load-bearing capacity of installed interlocking assemblies is the subject of research conducted by Sogalad and Udupa. En8 steel pins and bushings were used for this research, and pins were soaked in liquid nitrogen and ice for different periods for assembly. While the bushings were heated and assembled without external pressure, the assembly was tested for strength. A comparative study has been done on the results of the experimental method and the Lame approach. The results show that sets with pins under cryogenic treatment provide a higher load-bearing capacity than expand-fit joints. The change in load-bearing capacity obtained through experimental investigation is consistent with Lame's approach interference and is controlled by surface roughness and magnitude of interference [4].

Today Functionally Graded Materials (FGM) are widely utilized in industry, aerospace, and military fields. Simultaneously, there is a growing interest in using the shrink-fit process to join composite pipes, high-pressure vessels, reactors, and tanks. While extensive research has been conducted on the effect of cryogenic temperatures on tools during various machining processes, limited research has been performed on fitting. Salehi Kolahi et al. presented an analytical formulation for the shrink fit of FGM thick-walled symmetric cylinders based on the linear plane elasticity theory. The findings indicate that changes in material composition influence the shrinkage compliance pressure at the intersection area of two installed pipes. The value of this pressure affects the radial and annular stress distribution in the wall of a functionally graded circular cylinder [5].

Furthermore, several numerical analyses have been carried out on the thermal stress behavior of FGM-graded circular cylinders. The outcomes reveal that thermal stresses invariably arise in the FGM cylinder at any temperature other than zero, which can be minimized by carefully designing the material composition [6].

The possibility of cracking due to large interference stresses and low fracture toughness in the presence of cryogenic temperatures led to an investigation of the effect of staged cooling on compounded cylinders. The study showed that the resistance to failure increased by up to 50 percent when the compounded cylinder was first cooled in a refrigerated air chamber and then immersed in liquid nitrogen [7]. The auto-fretting and shrink-fit processes are known to increase the load-bearing capacity and fatigue life of pressure vessels under thermomechanical loads. The research demonstrated that the combination of shrink-fitting two base layers and subsequent double auto-fretting (exterior auto-fretting before interior auto-fretting) on the entire assembly can provide a higher fatigue lifetime for both inner and outer layers of the cylinder [8]. The use of finite element methods by Bhatnagar et al. on ANSYS13 has validated auto fretting and post-auto fretting machining. They used a combination of analytical and Huang's models to create a compounded tube that achieves a high maximum safe pressure, good fatigue life, and manufacturing economy by reducing auto fretting pressure, resulting in less hydraulic auto fretting plant maintenance [9]. Jahid et al. have carried out an optimal design of a three-layer conduit for maximum fatigue life under the combined process of automatic excitation and contraction adaptation. They used the Simplex search method for numerical optimization and optimized the initial stress distribution for each layer. The proposed method was tested on several samples and results showed that the optimization method significantly increased the life of the duct [10]. In traditional fitting, a cylindrical outer component with an open end or hole is heated to expand the opening to accommodate an inner part with a bigger external diameter, known as induction fitting. This technique relies upon thermal expansion, a fractional increase in a material's size in response to the rise in temperature. However, heat input also can alter the structural, electrical, and magnetic properties of metal parts.

Cryogenic shrink fitting, which uses cooling instead of heating, can hold dimensional changes to tight tolerances with minimal metallurgical changes. This study researched assembling parts using the cryogenic method, where liquid nitrogen was used for cryogenic operations. This study compared the cryogenic method with several existing methods of assembling parts and evaluated their effect on the quality of the surface and ease of assembling. The study also examined and measured the force and surface quality of the assembled parts disassembled in different ways to determine the advantages and disadvantages of each assembly and disassembly method.

2. Materials and methods

This research involved the use of ten samples, consisting of five bush and five-axle samples of the same size made of AISI4140 (42CrMo4) steel. 4140 steel is a type of alloy steel that has high strength, toughness, and resistance to wear and can be made into round or flat & square steel bars, steel plates, and steel tubes and has many uses in the aerospace, oil, and gas and automotive industries, typical uses are thin-walled pressure vessels, forged gears and shafts (Motor shafts, pump shafts, hydraulic shafts, etc.), lathe and milling spindles, collars, clamps, high strength bolts, valve bonnet, screws, and nuts.

The first step involved turning the samples using a lathe machine with a surface quality of 1.6 microns. The samples were then heat treated to attain a hardness of 34±2 Rockwell C, cleaned, and oxides were removed using sandblasting. The axles were manufactured to have an outer diameter of Ø37.5 s6 (+0.04) (+0.06) (Figure 1), while the Bush's internal size was Ø37.5 H7 (0+(+0.03)) (Figure 2). To achieve a surface quality of 0.4 microns, the manufactured axles and Bush's internal sizes underwent a grinding operation. The constituent elements of 42CrMo4 steel and its mechanical properties, both in normalized and annealed conditions, are presented in Tables 1 and 2, respectively. To enhance dimensional accuracy and ease assembly and disassembly of the designed parts, several jigs and fixtures were utilized.

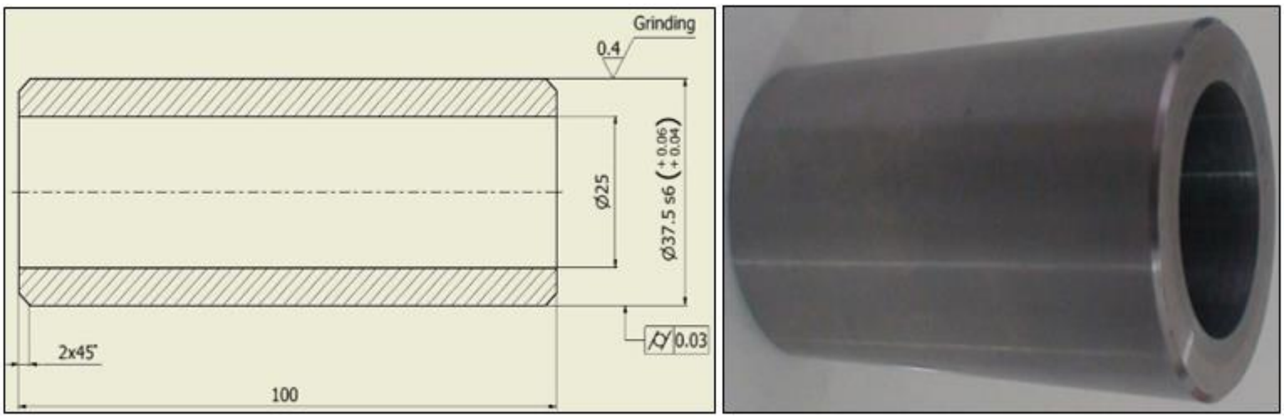

Figure 1. Geometric dimensions and image of the hollow axle

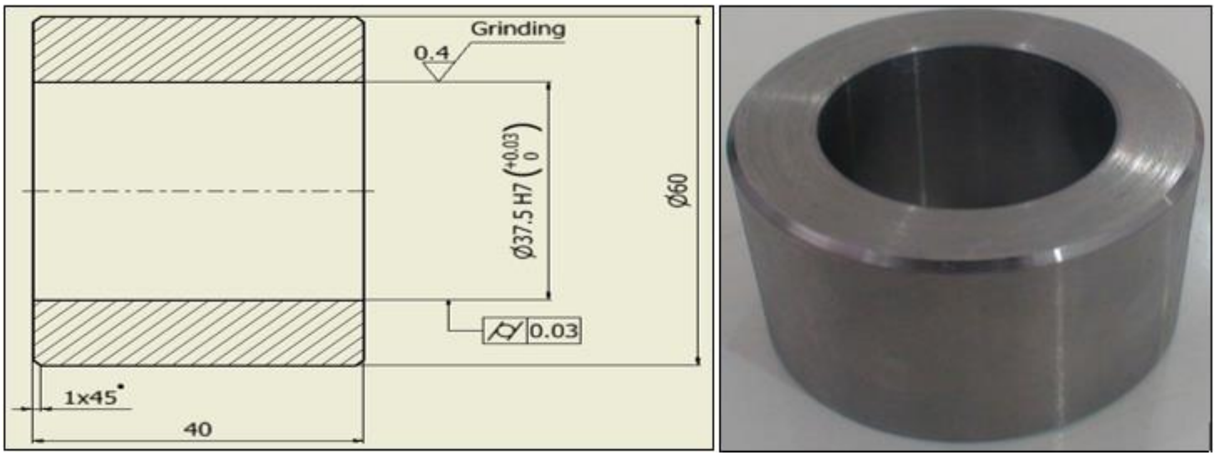

Figure 2. Geometric dimensions and the image of the bush

Table 1. The chemical composition of the 42CrMo4 steel

Elements	Mo	Cr	Mn	P	S	Si	C
Weight%	0-2.3	0.1 – 8.2	0.1 - 6	0 -0.02	0-0.15	0-0.06	0-38.45

Table 2. Mechanical properties of 42CrMo4 steel

AISI	Operation Temp. F (C)	Yield strength (Psi)	Tensile strength (Psi)	Elongation%	Surface Reduction%	Hardness (BHN)	Impact strength
4140	Normalized at 1600F(871C)	95000	148000	17.7	46.8	302	16.7
	Annealed at 1500F(815C)	60500	95000	25.7	56.9	197	40.2

Liquid nitrogen is obtained from the distillation of liquid air and is a cryogenic fluid that can cause freezing and frostbite in contact with living tissue. It has a temperature close to -196 degrees Celsius in a liquid state and is available as LIN, LN2, and LN. Nitrogen is inert and does not contribute to the combustion process.

To accurately measure the size of the bushes and axles, digital calipers with an accuracy of 0.01 mm and micrometers with an accuracy of 0.05 mm were used. An inner diameter measuring tool, a three-jaw micrometer with an accuracy of 0.01 mm was used to measure the inner diameters. A non-contact infrared thermometer was utilized to measure the temperature of the workpieces during heating. Mechanical data on the assembly and disassembly process was extracted using a universal tensile testing machine, which performs tension and compression tests.

2.1 Assembly methods

This research aims to compare various assembly and disassembly methods for fitting connections, specifically interference, clearance, and transition fits. To accomplish this, 10 samples of axles and bushes were assembled using three different methods: press, thermal, and cryogenic assembly.

In all these three methods, the axle was secured in a built jig and fixture to prevent movement during the assembly process. During the press assembly method, the bush was placed onto the axle, and the assembly was subjected to a constant speed of 5 mm/m by the compression testing machine. No lubricants or cooling materials were used and this process was conducted at ambient temperature, and the results are shown in Figure 4.

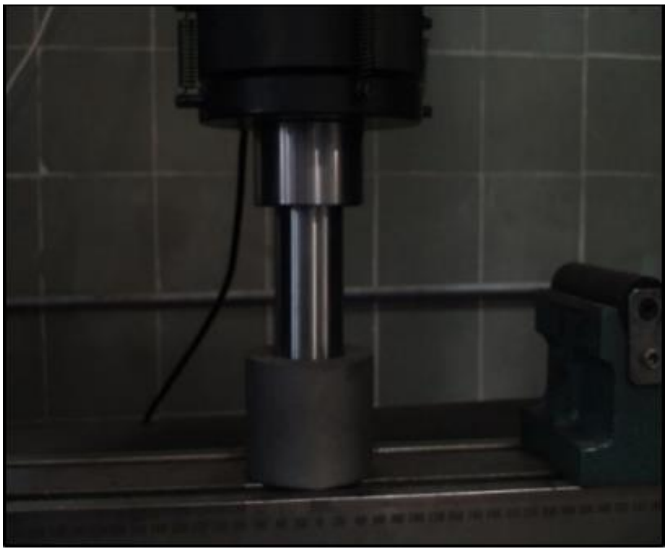

Figure 3. Fixture used for assembling the bush and axle

Figure 4. Assembled parts by press method

The thermal assembly method involved two bush and axle samples. Two heating methods were used: heating with a thermal electric furnace and direct heating with a torch flame. In the first method, the bush was heated for 15 minutes at 200°C, then immediately assembled onto the axle using the compression test machine (as shown in Figure 5). This method was safer and cleaner but took longer time. The direct flame method involved heating the bush to 459°C before assembly (as shown in Figure 6).

Overall, this research aimed to compare the effects and efficiency of different assembly and disassembly methods for fitting connections, using axles and bushes as sample parts. The results of the press, thermal, and cryogenic assembly methods are discussed and compared.

Figure 5. Thermally assembled bush and axle

Figure 6. Bush heating up to 459 °C by direct flame

It is important to note that assembly should be completed quickly to prevent a drop in the temperature of the bush. During the assembly process, the bush is heated to a high temperature, resulting in expansion. Due to the close tolerance range between the bush and axle, the parts were smoothly assembled without the need for external forces (as shown in Figure 7).

For the cryogenic assembly test, the axle must be immersed in liquid nitrogen for approximately 5 minutes until it reaches a temperature of -196°C, causing the axle to shrink and reducing its outer diameter to 37.49 mm. After removing the axle from the liquid nitrogen, the parts must be quickly assembled to prevent the temperature from rising. As with the previous method, the parts were smoothly assembled without the need for external forces (as shown in Figure 8). Table 3 presents the maximum force required for the assembly of parts using all three methods, including press, thermal, and cryogenic assembly methods.

Figure 7. Assembled parts using a direct flame

Figure 8. Assembled parts by the cryogenic method

Table 3. Maximum force required to assemble parts

Assembling method	Force (KN)
Cryogenic assembly	0
Press fitting	18.31
Thermal assembly with direct heat at 459°C	0
Thermal assembly with heating in an oven at 200°C	8

2.2 Dismantling the assembled parts

The pressure testing machine was utilized to disassemble all assembled parts using three different methods, and the required forces for each method were determined. Additionally, the surface of all parts was examined, and surface roughness measurements were taken. To disassemble the parts using the pressure machine, two auxiliary parts were utilized; one for holding the assembled set, and the other for pulling out the bush (Figure 9). Disassembly of the bush and shaft was accomplished by applying pressure with the movable jaw of the machine, at a constant speed of 5 mm/m on the auxiliary part (Figure 10).

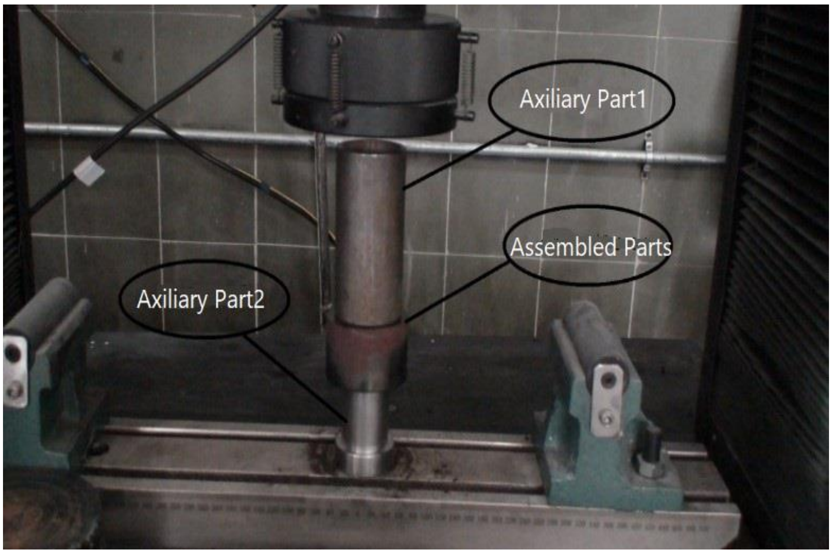

Fig. 9: Disassembly of the assembled set using auxiliary parts

Figure 10. Disassembly of Press assembled set

For disassembling two sets of assembled parts of the bush and axle by the cryogenic method, the axle side of one set was soaked in nitrogen for 20 minutes. Before the start of the cryogenic disassembly test, liquid nitrogen was poured into a specially made wooden container, and the assembled set was placed inside, such that the axle was submerged in the liquid nitrogen, as depicted in Figure 11. It's important to note that liquid nitrogen should not come into contact with the bush. Placing the axle in liquid nitrogen leads to a decrease in temperature and reduces the diameter of the assembled axle. Assembled parts were quickly removed from the nitrogen container to the compression test machine to prevent rising temperature. These two sets were disassembled like the other three sets by using a pressure machine (Figure 12). The surface quality of parts disassembled by a thermal method is shown in Figure 13.

Table 4 depicts the maximum force required for disassembling parts utilizing the press, thermal, and cryogenic assembly methods. Following the disassembly of the assembled sets, the Taly-Surf instrument was utilized to evaluate the quality of the surface roughness of the bush and axle parts. The results of the surface roughness of the mentioned parts are presented in Table 4.

Figure 11. Placement of the axle side of the set inside the LN

Figure 12. Disassembly of the cryogenic assembled set

Figure 13. Surface quality of parts disassembled by thermal method

Table 3. Surface roughness and required forces during assembly and disassembly of bushes and axles

Assembly and disassembly method	The maximum force required		Surface smoothness of parts in microns	
	assembly	disassembly	before assembly	after disassembly
Cryogenic assembly and disassembly with liquid nitrogen and press disassembly	0	27.12 KN	0.4	0.8
Cryogenic assembly and press disassembly	0	25.7 KN	0.4	1.6
Press assembly at room temperature and press disassembly	18.31 KN	27.82 KN	0.4	3.2
Thermal assembly with a torch and press disassembly	0	37.9 KN	0.4	Very poor quality
Thermal assembly with oven and press disassembly	8 KN	32.11 KN	0.4	6.3

2.4 Charpy impact test

The impact test was conducted on samples based on the ASTM A370 standard to determine their fracture energy. Four pieces of 42CrMo4 steel, each with the same dimensions, were machined and subjected to heat treatment. The first sample underwent an impact test without any external treatment. For the second sample, a direct flame was used to heat it to 459°C before cooling and then subjecting it to an impact test. The third and fourth samples were submerged in liquid nitrogen, with one being retrieved after 20 minutes and the other after 15 hours. The impact test was performed on all four samples. The results of the fracture energy for all parts are presented in Table 4.

Table 4. Impact test results for 42CrMo4 Steel

Impact Energy(J)	Test Condition	Specimen
91	Ambient Temperature	1
94	20 Minutes Soaking in Liquid Nitrogen	2
96	15 Hours Soaking in Liquid Nitrogen	3
103	Heating to 459-degree centigrade	4

3. Results and Discussion

According to data in Table 3, it has been determined that cryogenic and thermal methods using direct flame require less force for assembly compared to other methods. By altering the external dimensions of the axle or the internal dimensions of the bush through heating or cooling, it is possible to eliminate friction and wear between mating surfaces, thereby changing the fit type from interference to transition or clearance fit. In some cases, the force required for assembly can be reduced to zero. The higher magnitude of required force in thermal assembly with oven for flame heating is related to a lower temperature and less expansion of bush.

Disassembly tests have shown that cryogenic methods require less force than any other method, and lead to high-quality surfaces after disassembly. Using less assembly force results in more uniform force transition and less susceptibility to relative movement of parts and fretting fatigue.

The surface quality of parts treated with the cryogenic method can be the same or better than that before a final grinding operation. However, results from the thermal method using a torch were unfavorable, with parts being almost unusable due to the strong oxidation of internal bush surfaces, which led to the destruction of other contact surfaces during assembly and disassembly. Moreover, Taly-Surf Surface roughness measurement showed that the surface quality of parts after disassembly when using press fit decreased from 0.4μm to 3.2μm, with scratches of oxide particles and reduced quality in the contact surface due to disassembly friction and pressure from interference fit condition. The highest disassembly force was observed with the thermal method through direct heating, which overheated the bush, leading to cold surface welding by radial forces during cooling through shrinkage and thus increasing disassembly force, causing damage at welded points of parts. Additionally, electrical heating in a furnace at lower temperatures decreased disassembly forces but also led to oxidation and deterioration of part surfaces, rendering them unusable after disassembly. The part heated in the electric furnace (oven) also oxidized during heating, and its surface quality deteriorates from initially 0.4μm to 3.6μm after the disassembly operation. It can be seen that thermal methods generally caused oxidation and destruction of the surface quality. Damages to the parts that occurred in thermal methods minimized the possibility of re-using parts after disassembly.

Table 4 shows that liquid nitrogen had no negative impact on part properties based on impact test results. Furthermore, Figure 13 highlights that an initial force of about 4 KN is required at the beginning of the assembly test to perform the assembly process of the bush and axle through the pressing method.

As the axle gradually enters the bush, the contact surface between the two parts and friction force increases, resulting in a higher total force required for assembling. Due to the increased friction, it takes approximately 6 minutes for the machine to apply enough force for assembly. Figure 14 displays the diagram of the disassembly force of the press fit method in terms of time, while figures 15 and 16 depict the disassembly forces of bush and axle parts by thermal and cryogenic methods.

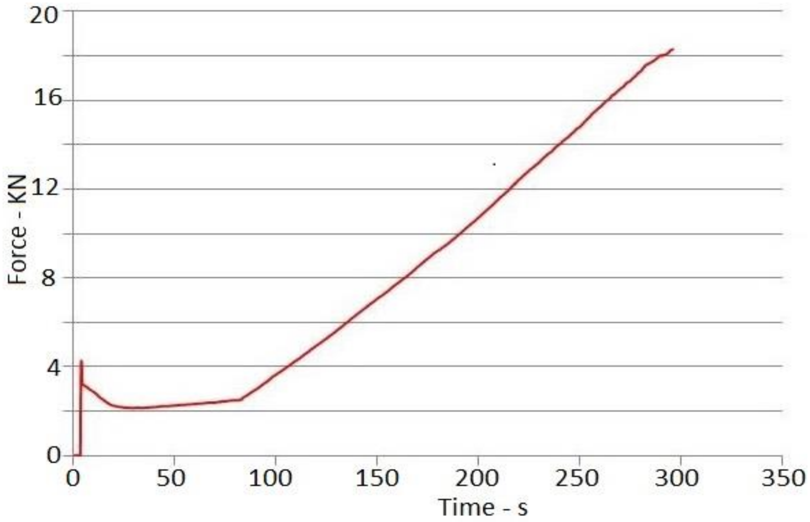

Figure 13. Assembly by press method

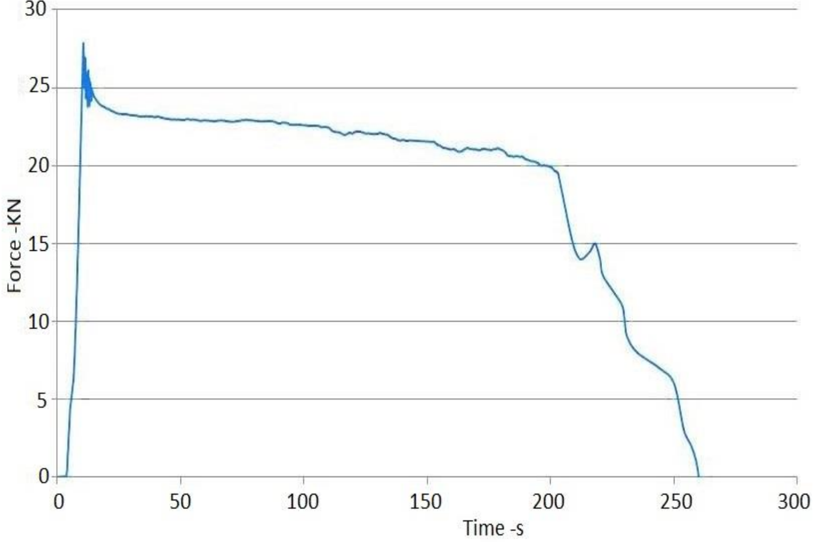

Figure 14. Disassembling by press method

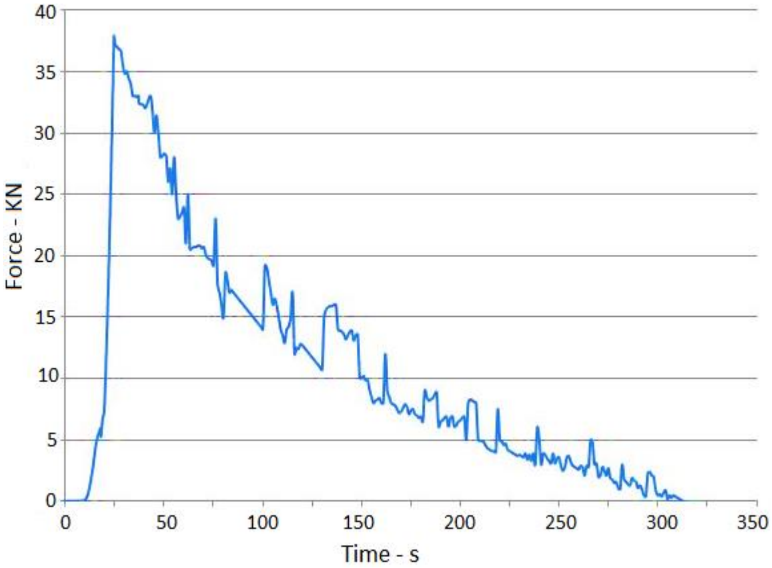

Figure 15. Thermally heated by torch disassembly force

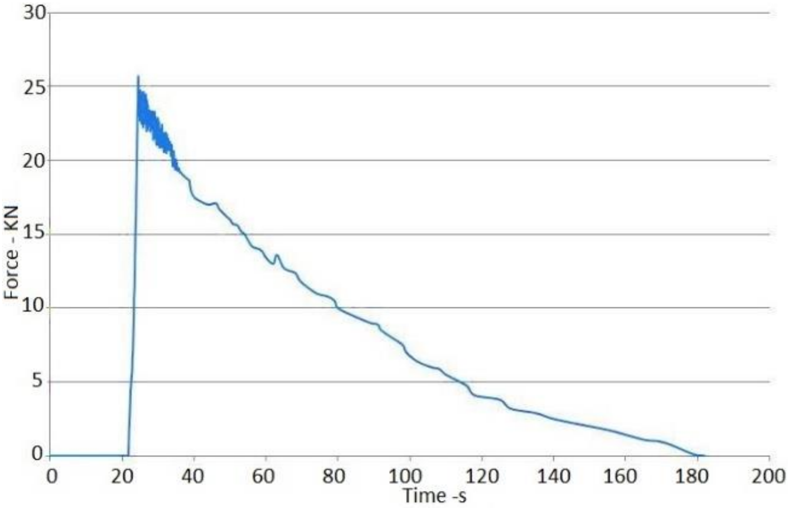

Figure 16. Cryogenically disassembly

According to the disassembly diagram, when the test begins, there is a substantial amount of friction due to the large contact surface between the two parts, requiring maximum force for disassembling. With decreasing surface contact, the force decreases until it reaches zero, and the two pieces are completely separated. The mechanism of the induced forces in the contact surfaces of the assembled samples with heating or cooling is the same and related to compressive forces produced during the temperature reaching the ambient level. However, it's important to note that the bush's surface in its thermal state is full of oxide particles, increasing the likelihood of cold welding. At the beginning of the assembly, there's no real connection between surfaces, and only after assembly, as a result of temperature changes, the parts expand or contract to create a tight connection between the surfaces.

Therefore, the curves showing the force required to separate the two surfaces (Figures 15 and 16) have similar shapes, but the maximum force required in the thermal state is higher due to cold welding between points in the thermal state and the presence of hard oxide particles. The oxide particles present in the thermal state increase the force necessary during disassembly at any moment, creating local scratches that reduce the surface quality. As a result of the oxide particles' presence in the thermal method, the curve in Figure 15 contains many distortions. However, since there are no oxide particles in the pressing method, this distortion is not visible in the curve of Figure 14. Although the surface roughness in the pressing method was not ideal, it is preferable to the surface quality in thermal methods.

Figure 16 illustrates the force required for dismantling the assembly using the cryogenic method. This disassembly process involves less force by placing the assembled set into a liquid nitrogen container from the axle side. However, the surface quality of the parts is slightly reduced, from 0.4 to 0.8 microns, but the contact surface of the two components still maintains favorable quality.

Notably, cooling the axle in liquid nitrogen only minimally reduces the total disassembly force, because the cooling effect is partially transferred to the bush. Nonetheless, the effect on the surface's smoothness is clear. Laboratory tests have demonstrated that the cryogenic assembly method is a cleaner process than thermal assembly, as it does not create environmental pollution. In other words, compared with assembling using heat, the cryogenic assembly method is cleaner and safer.

Compared with other methods, the cryogenic assembly method requires less force and time due to the compatibility of the components. Unlike thermal assembly, assembling with cryogenic processes does not affect the paired pieces' surface and physical properties, resulting in lesser quality loss in terms of the appearance and surface finishing of the workpiece.

Moreover, the critical factor of the cryogenic method is the replicability of the components after disassembly, as the cryogenic assembly method produces minimal surface damage. In contrast, other assembly methods severely damage the involved components.

Overall, the cryogenic assembly method significantly minimizes the percentage of material loss compared with other methods and is undoubtedly the most economically viable option.

4. Conclusion

The laboratory tests conducted yielded the following general results:

- As compared to other methods, the force required for assembling parts in cryogenic and thermal assembly (using a torch) methods was minimal, almost zero, making the assembly easy.
- The cryogenic assembly method was found to be cleaner, with no environmental pollution, than other methods.
- Disassembly force was also found to be lower in the cryogenic method, at 25.7 kN, as compared to other methods.
- After disassembling using the cryogenic method, the parts had a high surface quality, with a surface roughness of 0.8 microns. Therefore, these parts can be reused as new material, with uniform stress distribution in contact surfaces sufficient to prevent relative movement and fretting fatigue.
- For subsequent assembly, the pressing method with interference fit was recommended over thermal methods due to less force required for disassembly and better surface quality, although the uniform distribution of radial forces between mated surfaces was not expected.
- The cryogenic assembly method did not alter the parts' energy-absorbing ability or hardness, indicating that it did not change the microstructure and properties of the parts.

- Although expansion fit of parts at high temperatures resulted in easy assembly, uniform radial forces, and high disassembly force, non-uniform heating, and oxidation had side effects. Therefore, uniform heating at a furnace with controlled atmosphere is recommended in this method.
- Compared to thermal assembly, the cryogenic assembly method has the added advantage of being a cleaner and safer process, resulting in cost savings.

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