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Simulation, Prototyping and Testing of a New Gripper Design to Automate Double Chlorination of Rubber Gloves

H.J. Chua[1*], D.W. Tan[1], J.E. Lim[1], M.W. Yip[1] and A.A.D. Sarhan[2]

[1]Centre for Systematic Innovation Research, Faculty of Engineering and Technology, Tunku Abdul Rahman University College, Jalan Genting Kelang, Setapak, 53300 Kuala Lumpur, Malaysia
[2]Dept. of Mech. Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

ABSTRACT

Chlorination improves rubber gloves donnability. Production of single-chlorinated gloves is fully automated. Double-chlorinated gloves are needed for medical applications. These gloves are chlorinated on both internal and external surfaces. Double-chlorinated gloves are produced with second chlorination. Gloves after the earlier chlorination were manually immersed into another chlorine tank. This manual process endangers the workers and is time-consuming. A gripper was designed to integrate double chlorination to be fully online. The gripper grasps the glove after first chlorination to proceed to second chlorine tank. The gripper has a solid stainless steel body and flexible rubber seal. It is applicable to different glove sizes, chlorine resistant, leakage proof, and heat resistant. Engineering analysis was conducted through simulation and experimental testing. Simulation results showed the solid body does not yield under load. Simulation results also showed the gripper does not experience fatigue damage after multiple working cycles. A prototype was built for experimental testing. Experimental results proved that gripper is heat resistant, grasps all glove sizes, and no seepage indication under water for all glove samples. It was concluded that the gripper justifies for a full trial production run. The project contributes to improved worker safety and productivity, leading to lower production cost.

Keywords: *rubber glove, chlorination, gripper, automation, simulation*

1. INTRODUCTION

Current automated rubber glove manufacturing process generally follows a standard sequence [1]. Hand-shaped ceramic formers are coated with coagulant and immersed in a latex solution so that a layer of latex is deposited onto the surface of thes former. This layer of latex is solidified into rubber gloves [1]. However, the rubber gloves in this state cannot be worn because they stick easily to the users' hands.

The gloves are subjected to chlorination to improve donnability [2]. While still on the formers, the gloves are immersed in chlorine water. The chlorine stiffens the rubber slightly to reduce surface tackiness [1]. The chlorinated gloves are leached in water to remove excessive coagulants on the product [3]. The gloves are dried in an oven and cooled to 60ºC [3]. The gloves are then transferred to the strsipping unit operation [3]. The stripping unit draws out the gloves from the former [3]. Robotic arms invert the gloves on the former, turning the chlorinated surface into the inner surface for donning. Because only the inner surface is chlorinated, these gloves are called single-chlorinated gloves. The production of single-chlorinated gloves is fully automated and completely online.

Aside from chlorination, polymer coating and hydrogel coatings are alternative post-treatment processes to reduce tackiness [4]. However, chlorination is the preferred process because it also

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*chuahj-wt17@student.tarc.edu.my

removes residual protein from the gloves [4]. The proteins in natural rubber latex must be removed to avoid inducting contact allergies [5]. Therefore, chlorinated gloves are recommended for use in health care applications [6].

Single-chlorinated gloves have a weakness. The outer surface of single-chlorinated glove is not treated with chlorine, thus such gloves tend to stick to each other [1]. This characteristic prohibits double donning, which is the practice of wearing two layers of glove, one on top of the other. This practice provides an additional barrier and further reduce the risk of contamination [7]. By double donning, if the top layer of glove is torn, the bottom layer still protects the user's hand [7]. Furthermore, indicator double-donning systems have a coloured inner glove and an outer glove in neutral colour [7]. If the glove is breached during surgery, the colour of the inner glove is visible and alerts the user [7]. Therefore, the risk of transmission of bloodborne pathogens is minimized [7].

Double-chlorinated gloves are produced to allow the users to double don gloves. Current industry practice for double chlorination is manual and offline. To produce double-chlorinated gloves, single-chlorinated gloves are installed on a rig. The workers manually immerse the gloves on the rig in chlorine water again, but this time treating the outer surface of the glove. The treated gloves are manually transported to be dried in the drying oven.

During the manual double chlorination process, the workers are exposed to chlorine fume, which can lead to lung-related medical conditions such as irritant-induced asthma and airways hyperresponsiveness [8]. Specialized protective equipment, exhaust facilities, and training must be provided to safeguard the workers from excessive chlorine exposure, increasing the production cost of double-chlorinated gloves. The manual double chlorination process is slow and production rate is low. Current glove production system can be extended to include and automate the second chlorination process. A gripper must be developed to extend the current production system.

The objective of this work is to design a gripper to continue and extend the current single-chlorinated glove production process to include the double chlorination process. The online-double-chlorination (ODC) gripper replaces the human workers in transporting the gloves for the second chlorination and drying processes.

The scope of this work includes the design of the ODC gripper. The gripper design is subjected to engineering analysis including simulation to verify design fitness, as well as conducting physical tests to study the functional behaviour of the gripper during operation. Engineering analysis is conducted to ensure that the gripper is fit for production use. This work contributes to improved worker safety and increased productivity, which leads to lower production cost, and ultimately improves the company revenue when double chlorination process is automated.

2. MATERIAL AND METHODS

The approach used to solve the problem was to use grippers to transport single-chlorinated gloves to the second chlorination tank. In the production line, the rubber gloves dangle from the formers after the stripping unit. The gripper will be inserted into the glove. Then, the gripper grasps the glove and forms a watertight seal. Afterwards, the gripper brings the glove to be submerged in chlorine water.

Figure 1 shows the gripper inserted into the glove through the cuff. The glove was stripped from the former but still hanging by the fingers. At this stage, the glove cuffs were exposed. This allowed the gripper to be inserted through the cuff.

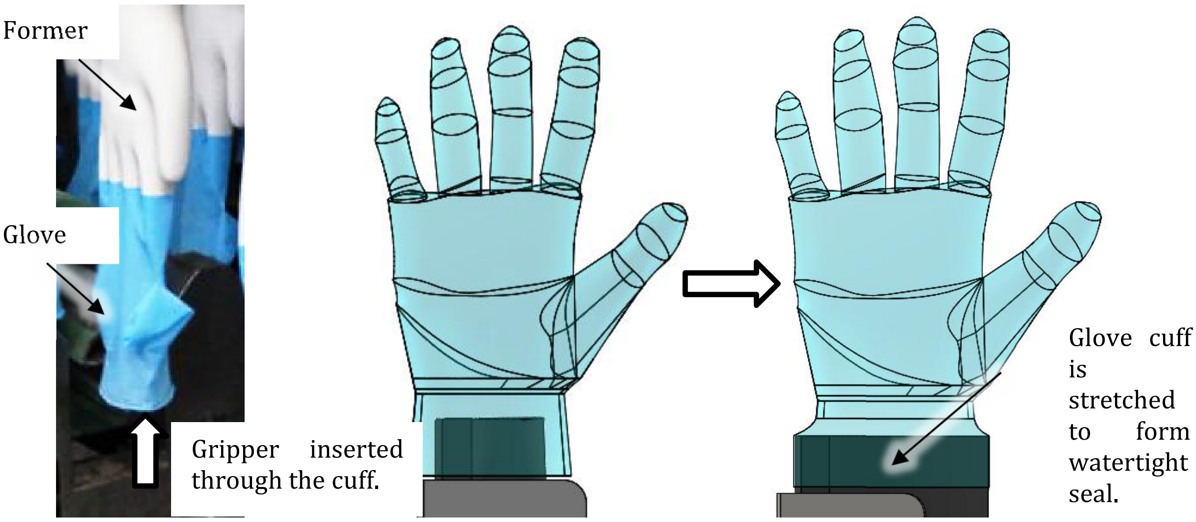

Figure 1. Gripper inserted into glove through cuff.

Literature review was conducted to identify glove production conditions relevant to this work. The glove is submerged in 1000 p.p.m. chlorine water [9], and gloves produced with lower chlorine concentration have better physical properties than those produced with higher chlorine concentration [1]. Chlorine is detrimental to the physical properties of the glove, thus over-chlorination must be prevented [1], with maximum chlorination period tested at 5 minutes [9]. The glove is dried at 120ºC for 20 minutes [9]. Bearing life is commonly rated at 1000000 cycles [10], thus it is reasonably safe to design the gripper to perform its intended function up to this level of working cycle.

2.1 Gripper Design Specifications

The gripper must be designed to fulfil the following requirements:

i. The gripper must fit gloves from S- to L-size.
ii. The materials used in the gripper must withstand at least 1000 p.p.m. chlorine water.
iii. The gripper must withstand at least 120ºC operating temperature.
iv. The gripper must form a watertight seal along the glove cuff circumference to fully submerge the glove under chlorine water, without the solution entering the glove for 5 minutes.
v. The gripper must withstand at least 1000000 working cycles.

The 200mm of space is available between adjacent glove formers on the production line. To fit the gripper into the space, the gripper dimension must not exceed 200mm in any direction.

The gripper designed had an overall dimension of 118mm × 28mm × 107mm in the format of length × width × height. Thus, the gripper designed fulfils the dimension constraint posed by the production line setup.

The 316 stainless steel and EPDM rubber were selected based on literature review. 316 stainless steel is chlorine resistant from -34ºC to 350ºC without cracking or pitting corrosion [11]. EPDM (Ethylene Propylene Diene Monomer) rubber seal is compatible with chlorine water and is appropriate with static seal [12]. EPDM rubber blend can maintain its physical properties after being exposed to 5000 p.p.m. chlorine water for 500 hours [12].

Table 1 shows the material properties of SUS316 stainless steel and EPDM rubber. The gripper was made of two materials. The rigid structure was made of JIS G4314 Grade SUS316 stainless steel. The flexible rubber seal was made of ASTM standard D-1418 EPDM rubber. Using standardized materials ensures that material properties are consistent. Fabricating the gripper with the specified materials also ensures that the gripper behaviour will be accurately described by this paper.

Table 1. Standard material properties of SUS316 and EPDM

Material Properties	JIS G4314 SUS316	ASTM D-1418 EPDM
Density (g/cm^3)	8.2	0.86
Elastic Modulus (GPa)	195	5.394
Poisson's Ratio	0.27	0.49
Shear Modulus (GPa)	77	-
Tensile Strength (MPa)	515	33
Yield Strength (MPa)	172	-
Maximum Elongation (%)	-	100 – 400
Maximum Service Temperature (ºC)	1480	140

2.2 Comparison with Alternative Grippers

Patents on gripper design were reviewed for design inspirations. The "external-internal gripper" [13] contains a spring-loaded mechanism to control the gripper configuration: force is used to overcome the spring tension to close the gripper, and the spring automatically opens the gripper once the force is released. The "Walton pickup device" [14] applies tension onto the target object (fabric) and uses the reaction force to tightly grasp the object. The "passive elastic membrane gripper" [15] has a pliable surface that deforms to facilitate interfacing with irregularly-shaped objects. The "robotic end of arm gripper" [16] has an elastomeric surface that deforms to contact the interior surface of the cylindrical target object across the entire circumference.

However, the reviewed gripper designs could not be used to achieve online double chlorination. These grippers could not form a watertight seal with the gloves. This project referenced the spring-loaded mechanism and deforming elastomeric surface to design a new gripper. A new clamping mechanism was added to the new gripper to compress the rubber seal. This compression allowed the gripper to fit through the glove cuff. Because the gripper can be inserted into the glove through the cuff, the rubber seal can expand inside the glove to form the watertight seal required.

2.3 Engineering Analysis with Simulation

A 3D model of the ODC gripper design was generated and shown in **Figure 2**. The 3D model provided detailed dimensions for the overall gripper assembly and individual components, as well as showing clearance between components to ensure that the required gripper motions were not obstructed.

Figure 2 also shows the gripper simulation meshing structure, which was divided between the rigid structure and the rubber component. The rigid stainless steel structure was expected to exhibit significantly lower deformation compared to the elastic rubber seal, so the mesh could be coarser to reduce computing power needed. The 316 stainless steel components had mesh with average element size of 7.72mm. Because the rubber seal was designed to deform into a complex shape, the mesh of the EPDM rubber component was specially refined at 3.68mm average element size so the smaller mesh led to better simulation results accuracy.

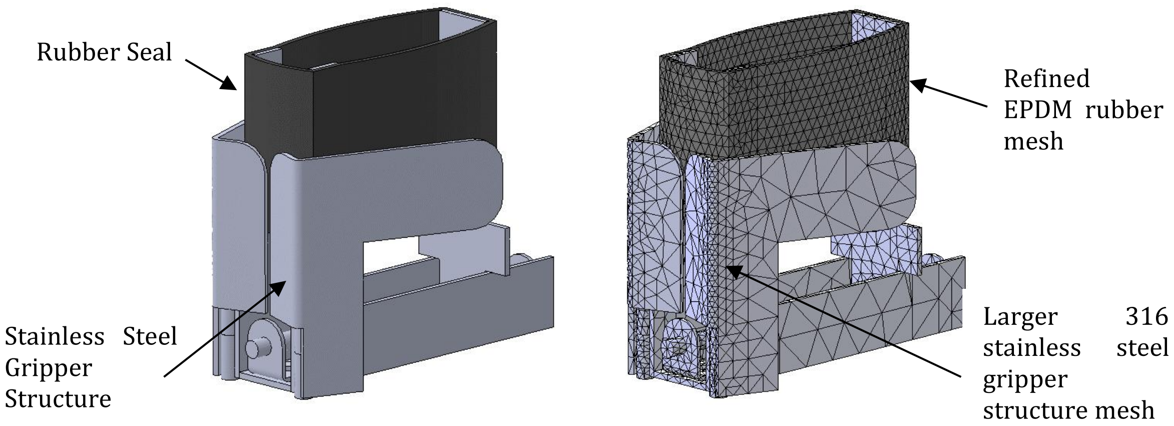

Figure 2. 3D Model and meshing structure of the ODC gripper.

Engineering analysis included conducting stress-strain simulation and fatigue analysis. Stress-strain simulation was to determine the strength of the gripper when subjected to various forces during 1 operating cycle. Fatigue analysis was for verifying the gripper durability when it was subjected to high number of working cycles.

2.3.1 Stress-Strain Simulation

Stress-strain simulation was conducted to investigate possible gripper failure over 1 working cycle. The stress indicated possible yielding of the stainless steel components, whereas the strain represented the elongation of the rubber seal.

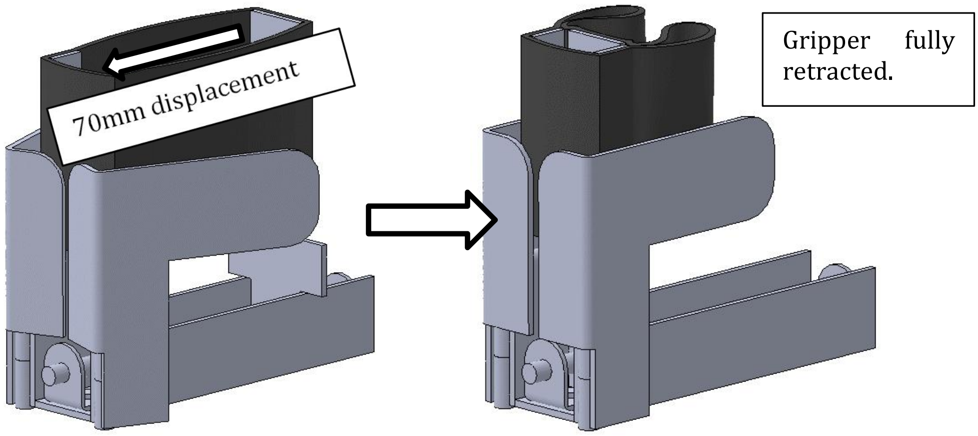

Figure 3. Displacement on gripper in stress-strain simulation.

The gripper was assigned 70mm displacement to operate the gripper from the fully extended state to the fully retracted state as shown in **Figure 3**. The simulation results would produce maximum von Mises stress value and safety factor plot of the stainless steel components. The simulation would also produce maximum principal strain value of the rubber seal to calculate the safety factor. Reasonable minimum safety factor was set at 2 because the gripper was considered non-life-threatening if failed [17].

2.3.2 Fatigue Analysis

Fatigue analysis was conducted to determine damage on the ODC gripper after 1000000 working cycles consisting of fully retracting and fully extending the gripper. The analysis was done by using the same setup as the stress-strain simulation and adding the fatigue data of stainless steel [18] and rubber [19], then extending the simulation to 1000000 working cycles.

2.4 Gripper Functionality and Reliability Testing

In addition to engineering analysis, physical tests were also conducted. Physical tests were necessary to investigate the design aspects of the gripper that could not be represented accurately in simulations.

2.4.1 ODC Gripper Physical Prototype Fabrication

Figure 4 shows the ODC gripper prototype fabricated based on the design with actual material. The rubber seal was made from EPDM rubber adhered onto the stainless steel gripper structure using Loctite 406 adhesive. The prototype was subjected to gripping test and heating test.

Figure 4. ODC Gripper prototype in extended and retracted state.

2.4.2 Gripping Test

The ODC gripper was designed to grip rubber gloves, hence the interaction between the rigid gripper and flexible rubber gloves was complex and physical testing was necessary to verify that the gripper behaviour with the glove samples was per design intent. Thus, a standalone testing rig was fabricated; the gripper prototype was installed onto the testing rig in a specific position and operated using an Arduino-Uno-controlled stepper motor. This setup ensured that the position and gripping action of the prototype were consistent for every gripping test.

To conduct the gripping test, the glove sample was suspended above the gripper prototype, with the cuff positioned 10mm below the top of the rubber seal (**Figure 5**). The gripper was held in the retracted position by the rig. When the gripper was triggered, the gripper rose 10mm deeper into the glove and forced open by the spring (**Figure 5**). The grip condition was recorded, and the test was repeated 20 times each with S-, M-, and L-sized samples.

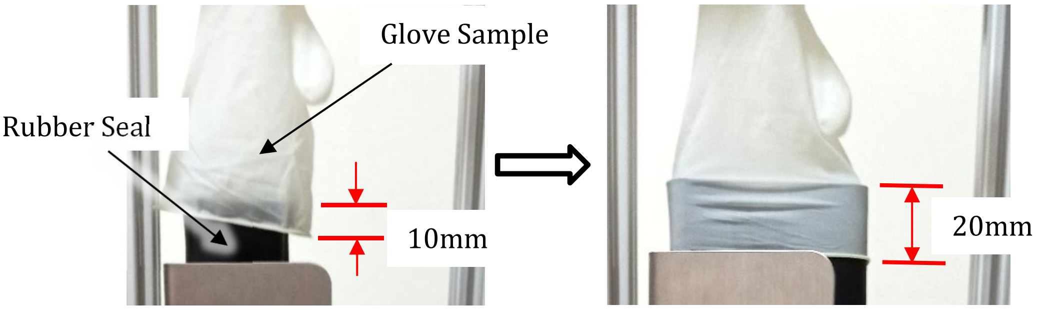

Figure 5. Glove gripping process of the ODC gripper prototype.

2.4.3 Heating Test

Heating test was conducted to determine the effect of heat on the different materials used in the gripper prototype fabricated. To conduct the heating test, the gripper prototype was placed in the testing oven at 125ºC for 48 hours. Then, the prototype was removed from the oven and cooled at room temperature. The conditions of gripper components were then recorded. The prototype was again subjected to gripping test to verify that gripper function was unchanged.

2.4.4 Water Immersion Test

Water immersion test was conducted to check for liquid seepage through the rubber seal. This work used liquid contact indicator (LCI) tapes to detect liquid seepage through the rubber seal into the glove sample. When exposed to liquid, the white LCI turns red. Thus, if the rubber seal failed and liquid entered the glove, the LCI would turn red as a visual indication.

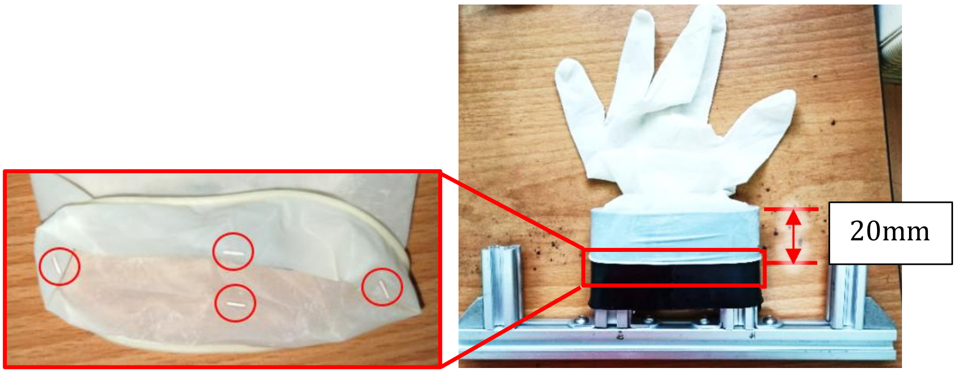

Figure 6. The LCI Placement on Glove and Glove Sample Attached to Jig.

Figure 7. Glove sample submersion under water.

A water immersion testing jig was fabricated. The jig incorporated a rubber seal identical to the one on the gripper prototype. To conduct the water immersion test, 4 LCIs were placed 10mm measured from the cuff inside the glove (**Figure 6**). The glove sample was fitted 20mm over the rubber seal on the jig (**Figure 6**). The assembly was submerged under plain water, ensuring the water level was 10mm above the cuff opening (**Figure 7**).

The glove was left submerged for 5 minutes, then the assembly was removed from the water and left to dry in static air. The colours of the LCI tapes were examined and recorded when the assembly was dried. The water immersion test was repeated using five glove samples for each S-, M- and L-size, with a total of 15 tests conducted.

2.5 Standardized Test Methods

The EPDM rubber seal and compression spring were two components in the gripper that experienced significant deformation during operation. The mechanical properties of these components must be verified using standardized tests.

2.5.1 ASTM D412 Tension Test for EPDM Rubber

The ASTM D412 tension test was used to measure the tensile stress, yield point, and tensile strength of the EPDM rubber specimen [20]. The testing procedure was as follows:

1) A dumbbell-shaped specimen was prepared from EPDM rubber following the dimensions shown in **Figure 8** [20].
2) The specimen dimension was inputted into the universal testing machine settings.
3) The specimen was placed in the grips of a universal testing machine.
4) The machine grip separation rate was set to 50mm/min [20].
5) The specimen was stretched until rupture.
6) The tensile stress, yield point, and tensile strength of the specimen were recorded from the values displayed by the machine.

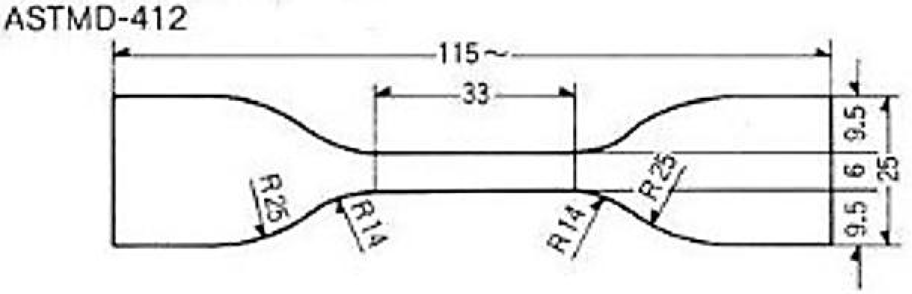

Figure 8. Dumbbell-shaped EPDM rubber specimen dimensions.

The material properties from the tension test shall conform to the values listed in Table 1.

2.5.2 ASTM A125 Compression Test for Helical Spring

The requirements for the compression spring specifications depend on the exact glove production line that the gripper is applied to. The spring design considerations are:

i. The preload spring force when the gripper is completely opened must be sufficiently high to fully stretch all the glove samples.
ii. The spring must be able to compress to solid height without failure.
iii. The spring at solid height must be sufficiently short to fit inside the fully-closed gripper.

The procedure to perform the compression test is as follows [21]:

i. The spring free height was measured with a straight edge.
ii. The spring was placed between the jaws of a universal testing machine.
iii. The test load and displacement were inputted into the testing machine.
iv. The spring was compressed to solid height.
v. The spring solid height was recorded.

The test load used must be less than 50% of the spring solid capacity [21]. The spring solid capacity is calculated using (1) [21].

$$P = Gd^4F/8ND^3 \tag{1}$$

where:

$G = 11 \times 10^6$ psi = effective torsional modulus of elasticity
d = nominal wire diameter, in.
D = mean spring coil diameter, in.
F = spring deflection = free to solid, in.
N = number of active turns = (solid height/bar diameter) – 1.5
P = solid capacity of spring, lb.

The spring passes the ASTM A125 compression test if both the free length and solid height do not deviate more than 1.59mm [21].

3. RESULTS AND DISCUSSION

The following sections present the ODC gripper design with explanations on the gripper mechanism and the working step of the gripper. Both the results obtained from the engineering analysis through simulation and experimental testing were discussed in the following sections.

3.1 ODC Gripper Design Explanation

The ODC gripper design was shown in Figure 9, in both its extended and retracted states.

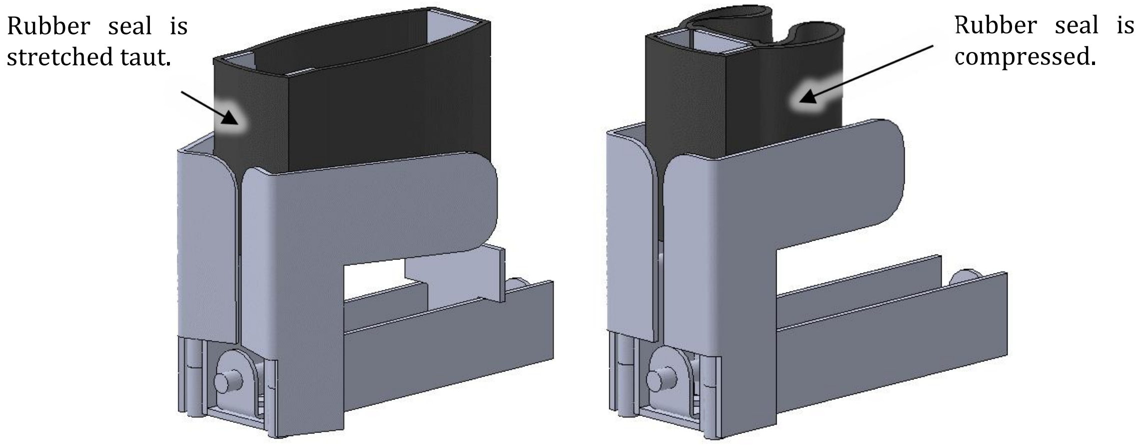

Figure 9. The ODC gripper design in extended and retracted state.

A spring-loaded mechanism is incorporated in the gripper, which keeps the gripper in the extended state and stretching the rubber seal taut across the gripper jaw. When force is applied to retract the gripper jaw, the rubber seal is collapsed inwards. Two metal plates on both sides compress the rubber seal into the final form factor that is sufficiently compact to fit into any glove size through the cuff opening.

3.2 Stress-Strain Simulation Results

Figure 10 shows the von Mises stress from the simulation for the stainless steel components. The graph was plotted along the midplane of the gripper assembly. The stainless steel components experienced maximum von Mises stress of 2.50 × 10^7 N/mm^2, or 25.0 MPa. The stainless steel components would not permanently deform because the maximum stress recorded was less than the yield strength.

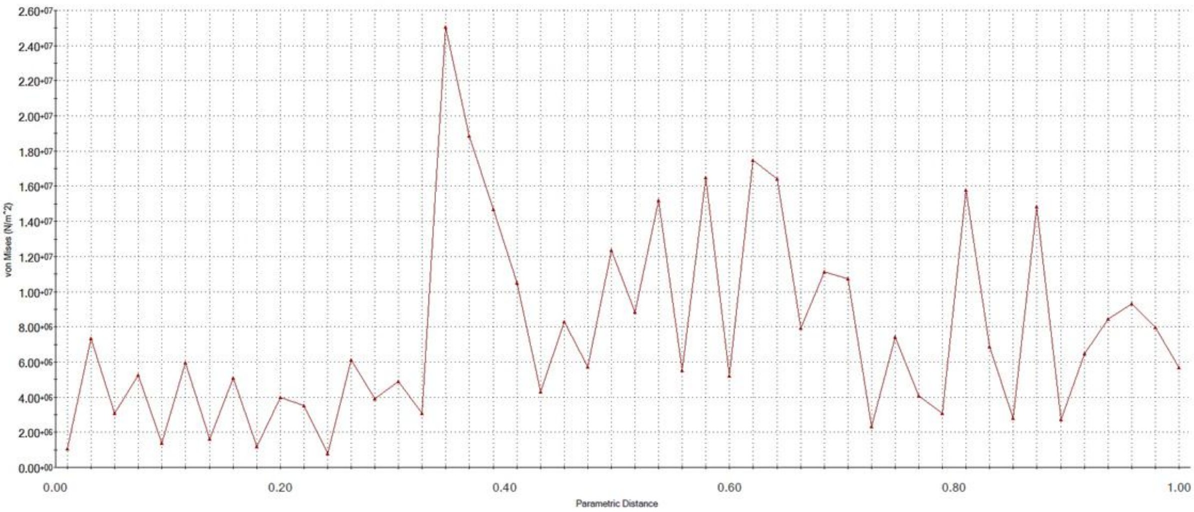

Figure 10. Von Mises graph.

The factor of safety indicated extra stress that the component can withstand. With reference to Table 1, the yield strength of stainless steel is 172MPa. Calculated using (2), minimum factor of safety of stainless steel = 6.88 > 2. Therefore, the components were not at risk of yielding.

Figure 11 shows the principal strain plotted along the surface of the EPDM rubber seal at maximum deformation. The maximum principal strain recorded was 0.2425 or 24.25%.

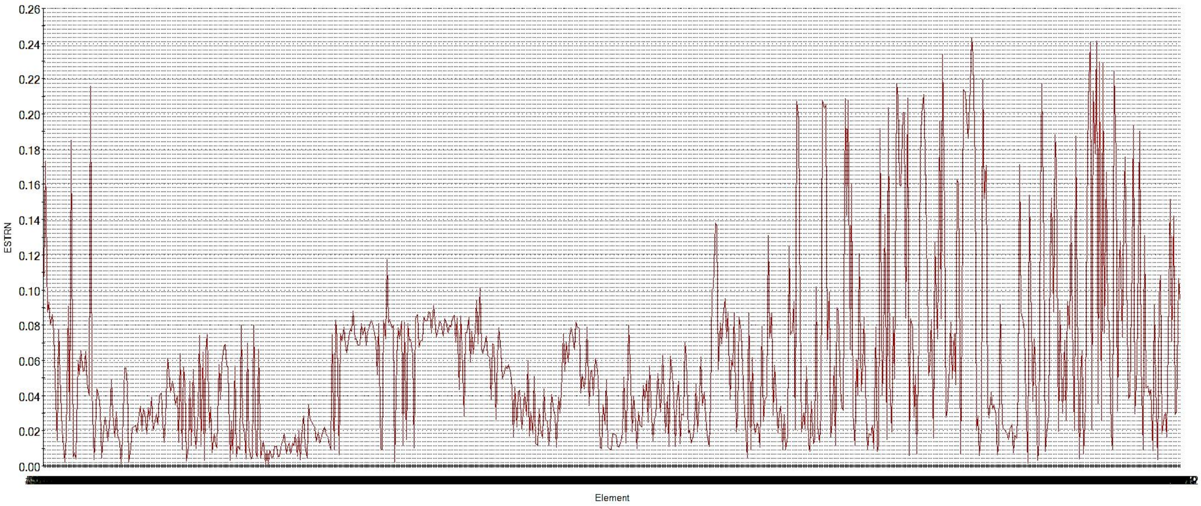

Figure 11. Principal strain graph.

EPDM rubber can elongate 10 100% without failure as shown in Table 1, thus 24.25% strain was within the allowable range of elongation. Thus, the rubber seal design will not fail.

Calculated using (3), minimum factor of safety of EPDM rubber = 4.123 > 2. Therefore, the rubber seal will not crack when it is fully flexed.

$$FoS_{ss} = \sigma_{yield}/\sigma_{vm} \tag{2}$$

where:

FoS_{ss} = factor of safety of stainless steel
σ_{yield} = yield strength of stainless steel = 172MPa
σ_{vm} = maximum von Mises stress recorded = 25.0MPa

$$FoS_{EPDM} = \varepsilon_{max}/\varepsilon_{principal} \tag{3}$$

where:

FoS_{EPDM} = factor of safety of EPDM rubber
ε_{max} = maximum allowable elongation of EPDM rubber = 100%
$\varepsilon_{principal}$ = maximum principal strain recorded = 24.25%

3.3 Fatigue Analysis Results

The gripper was subjected to stress-strain simulation extended by 1000000 working cycles consisting of fully retracting and extending the gripper jaw in the fatigue analysis. After 1000000 cycles, the gripper experienced no damage. Thus, the design was proven to be free from fatigue failure within the expected service life.

3.4 Gripping Test Results

The gripping tests were conducted as per the setup mentioned previously. After the glove was grasped by the gripper, the condition of the grip was inspected. Two conditions must be met to constitute a successful grip:

i. Glove sample was stretched taut by the gripper and laid flat against the rubber seal.
ii. No visible gaps were present between the rubber seal and the glove surface. The second condition stating no visible gap was the first stage of confirmation for water tightness, which was again verified by conducting the water immersion test.

Conversely, the grip was considered failed if at least one of the conditions was not met.

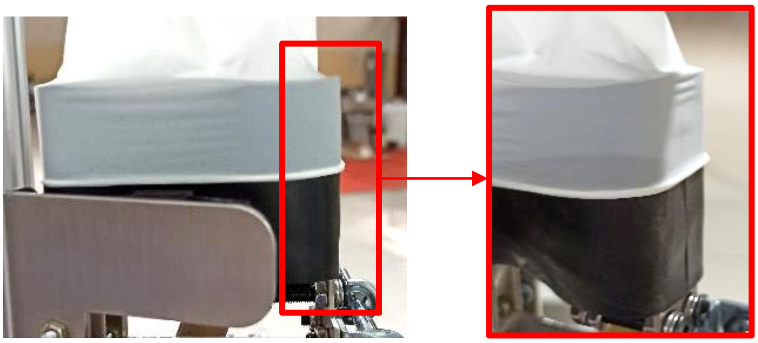

Figure 12. Sample of a Successful Grip.

Figure 12 shows a sample of a successful grip; the glove was stretched against the rubber seal. The glove cuff wrapped neatly around the rubber seal. When viewed from the right side, the glove was shown to bend around the corner without forming gaps.

Three sizes of gloves were tested, namely S-, M- and L-size. Twenty tests were conducted for each size. Therefore, a total of sixty gripping tests were done, and the gripping test results were recorded in Table 2. If the gripper could grip the glove sample successfully, a "🏱" mark was recorded in the cell. If the gripper failed to grip the glove sample, then a "🏳" mark was recorded instead.

Table 2. Gripping Test Results Compilation

LEGEND: Successful Grip = 🏱; Failed Grip = 🏳

Glove Size	**Gripping Test Number**																			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
S	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱
M	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱
L	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱	🏱

The gripper prototype had a 100% gripping success rate for the sixty instances of test conducted. Therefore, the result shows that the gripper fulfilled the gripping requirement.

3.5 Heating Test Results

For the heating test, the gripper prototype was put into an oven according to set temperature of 120ºC for 48 hours; the results were tabulated in Table 3.

Table 3. Tabulation of Heating Test Results

Components	**Component Condition Observation After Heating**
316 Stainless Steel Gripper Structure Including Spring	No cracks or deformation observed. No change in spring flexibility.
EPDM Rubber Seal	No cracks, discolouration, or hardening were observed.
Loctite 406 (Ethyl Cyanoacrylate Adhesive)	Rubber seal held by the adhesive detached from the stainless steel gripper structure.

The heating test results showed that both the stainless steel and rubber components in the gripper did not exhibit any observable changes after heating. The spring behaviour was also unchanged after being subjected to high temperature. Therefore, the materials used to fabricate the components were appropriate. Because the components were unaffected by heat, thus the components fulfilled the design requirements.

However, the rubber seal detached from the stainless steel gripper structure during the heating process. The rubber seal was initially attached to the gripper using adhesive. Therefore, the adhesive was concluded to be an unsuitable joining method. To overcome this problem, a different method to join the rubber seal to the gripper structure was devised.

3.6 Water Immersion Test Results

The water immersion test was conducted following the setup mentioned previously. The colour of the LCI tapes were inspected after the glove sample dried.

Table 4. Tabulation of Water Immersion Test Results

LEGEND: No Colour Change for All 4 LCIs = 🏱; Colour Change = 🏳

Glove Size	**Water Immersion Test Number**				
	1	**2**	**3**	**4**	**5**
S	🏱	🏱	🏱	🏱	🏱
M	🏱	🏱	🏱	🏱	🏱
L	🏱	🏱	🏱	🏱	🏱

Table 4 shows the water immersion test results. The result of the water immersion test was determined by inspecting the colour of the LCI tapes. If all 4 LCIs remained white in colour, the watertight test indicated that the rubber seal prevented any water from entering the glove. In this case, a "🏱" mark was recorded in the table. Conversely, if any LCI turned red, the test indicated that the seal failed to keep water out of the glove. A "🏳" mark was recorded in this case.

The water immersion test showed that no colour change was recorded in all 15 tests. Therefore, the rubber seal was verified to have 100% success rate in preventing liquid seepage into the glove samples. The seal design was concluded to be effective for gloves ranging from S- to L-size, up to 5 minutes of static liquid submersion.

3.7 Simulation and Physical Test Results Conclusion

To conclude, the engineering analysis results show that the gripper design has acceptable strength shown in minimum safety factor higher than 2 and withstands fatigue damage for at least 1000000 working cycles. No failure was observed in the gripping test and heating test, thus the gripper functional requirement was verified. However, a problem faced was when the adhesive in the gripper prototype failed during heating test, and required a solution by redesigning the method of attaching the rubber seal to the stainless steel components.

3.8 Enhanced ODC Gripper Design

A simple solution to address the adhesive failure would be to drill holes into the rubber seal and attach the rubber component using threaded fasteners. However, the screw holes weaken the rubber seal, causing the rubber to crack when flexed. Therefore, the redesigned ODC gripper added a locking mechanism to install the rubber seal, as shown in Figure 13. The redesigned rubber seal was held in place by a pair of plates squeezing from both sides. A glove support structure was also added to keep the gripped glove upright.

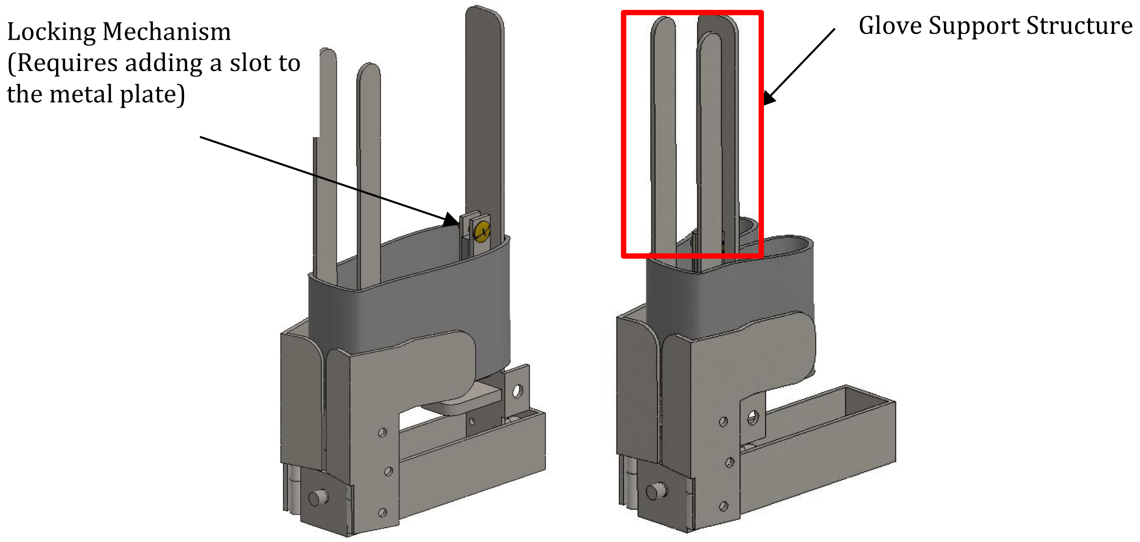

Figure 13. Enhanced ODC Gripper Design in Extended and Retracted States.

Engineering analysis were repeated on the enhanced ODC gripper design. Table 5 compares the simulation results between the enhanced and previous gripper designs. The stainless steel component strength is lower because the locking mechanism added an opening in the gripper jaw. However, the safety factor of 4.095 is still more than 2, thus the components are free from yielding failure. The locking mechanism in the enhanced design provided more space for the rubber seal to flex, thus improving the rubber safety factor to 6.983. Both gripper designs are also free from fatigue failure.

Table 5. Simulation Results Comparison between Previous and Enhanced Gripper Design

Simulation Type	Simulation Results	Enhanced Gripper Design	Previous Gripper Design
Stress Simulation	Max von Mises Stress (MPa)	42.08	25.00
	316 Stainless Steel FoS	4.087	6.880
Strain Simulation	Max Principal Strain	0.1432	0.2425
	EPDM Rubber FoS	6.983	4.123
Fatigue Analysis	Gripper is undamaged by fatigue for at least 1000000 working cycles.		

As an overall, the enhanced gripper design outperforms the previous design in terms of the rubber seal durability. The reduced stainless steel safety factor still meets the strength requirement; hence the stainless steel component strength is not compromised.

4. CONCLUSION

A gripper was designed for the online double chlorination of rubber gloves. A rubber seal on the gripper is compressed into a compact form factor and fits through the glove cuff opening. Once inserted into the glove, the rubber seal extends, stretching the glove cuff taut against the rubber seal to form a watertight seal. The watertight seal is required to fully submerge the glove under chlorine water for complete coverage of chlorination, without liquid seeping through the cuff opening. The ODC gripper was designed to be fabricated with 316 stainless steel and EPDM rubber for chlorine resistance. Stress-strain simulation verified that both the stainless steel and rubber components in the ODC gripper design achieved safety factor of more than 2 and fulfilled the design requirement. Fatigue analysis proved that the gripper design is free from fatigue damage for at least 1000000 cycles.

A prototype of the ODC gripper was fabricated and subjected to physical tests. The gripping test proved that the gripper prototype can successfully grip gloves from S- to L-size. The water immersion test proved that the rubber seal can prevent liquid seepage into gloves from S- to L-size for 5 minutes of submersion under static water. The heating test showed that the 316 stainless steel components and the EPDM rubber seal were undamaged by the heat, however the adhesive attaching the rubber seal to the gripper structure failed. A redesign was done to improve the attachment method of the rubber seal onto the stainless steel gripper structure by adding a locking mechanism. The redesigned gripper in overall outperforms the previous gripper design. The ODC gripper extended industry automation to include double chlorination process. Therefore, the project contributes to improved worker safety and increased productivity, leading to lower production cost and ultimately better company revenue.

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