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Research Article

Design Optimization of Road Wheel Used in Tracked Armored Vehicles

Tolga VURUR[1]*, Recep KILIÇ[2]

[1] Sakarya University of Applied Sciences, Faculty of Technology, Mechanical Engineering Department, 54050, Turkiye
* **Corresponding Author Email:** Y215009102@subu.edu.tr - **ORCID:** 0009-0003-1262-1648

[2] Sakarya University of Applied Sciences, , Faculty of Technology, Mechanical Engineering Department, 54050, Turkiye
Email: recepkilic@subu.edu.tr - **ORCID**: 0000-0003-1580-1997

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Abstract:

Road wheels are carrier wheels located between the track system and the vehicle body in combat vehicles such as Tanks, Armored Personnel Carriers and Self-Propelled Howitzers. The design and durability of the mentioned wheel is of great importance in terms of the survivability of the armored vehicle. The analysis of the Road Wheel, which includes the steel rim and the rubber coated on it within the track system, is discussed in the study conducted. In order to ensure the production of the Road Wheel, which can be used in tracked armored vehicles weighing approximately 47 tons, with domestic means and to increase the diversity of suppliers in production, alternative solutions were investigated in order to make design changes in the currently used road wheels. In the studies conducted; the design dimensions of the reinforcement ring on the road wheel and the mounting distance to the road wheel were changed and compared using a computer-aided analysis program (Abaqus), and the strength and safety coefficient of each design created were given. The design closest to the safety coefficient was obtained from the values found.

1. Introduction

The wheels located on the underside (undercarriage) of a tracked vehicle, mounted on the vehicle body and working integrated with the track system are called Road Wheels. Road Wheels are wheels that support and guide the tracks in military vehicles (Howitzers, Tanks or Armored Personnel Carriers) and ensure equal distribution of the load while the vehicle is moving on various terrains. Road wheels are an important component of the suspension system located on the body of the tracked vehicle. It contributes to the mobility, balance and ease of maneuverability of the vehicle. It plays an important role in absorbing shock and vibration while providing support and traction during operation of the vehicle. An example road wheel is shown in figure 1. Road wheels produced with overseas facilities are manufactured from SAE 4140 material using the deep drawing method. In the researches, it was observed that the existing possibilities do not allow the production of SAE 4140 quality material with deep drawing process or it would increase the cost. In order to provide

Figure 1. *Road Wheel*

production with domestic resources and to increase supplier diversity in production, design changes in road wheels or alternative solutions have been investigated.
In the studies conducted; the studies in the literature on road wheels used in tracked vehicles were examined, the road wheel used in the said vehicles

was modeled in a computer-aided design program (Creo Parametric 3.0) and converted to step format. Then, static analysis was performed in the finite element analysis program (Abaqus) environment and the loads resulting from the analysis were proportioned to the yield values of the materials to be used in the manufacture of the road wheel.

By comparing the results obtained, the distance of the reinforcement rings designed for the manufacture of the road wheel used in the tracked armored vehicle weighing approximately 47 tons to the road wheel rim and the varying width and length values were compared and the optimum design was obtained.

Deng et al., conducted a comparative analysis of the static loading performance of rigid and flexible road wheels. In their study, a new road wheel was introduced to overcome the shortcomings of the traditional road wheel. The static loading performance of both wheel types was investigated and the effect of the applied vertical load on the maximum stress and deformation was investigated. As a result of the numerical investigations, it was determined that the flexible road wheel provided better contact pressure homogeneity than the rigid road wheel [1].

Deng et al. introduced a new type of road wheel with composite flexible structure, which has great potential to improve the lightness level, maneuverability and ride comfort of tracked vehicles. In order to study the effect of nonlinear stiffness of flexible road wheel on ride comfort of a typical tracked vehicle, they constructed the stiffness model of flexible road wheel by fitting the load-deflection curve obtained from static loading experiment to the road wheel [2].

Nallusamy et al. studied on the analysis of static stress in alloy wheel of passenger car. They used ANSYS software to simulate the test conditions and analyzed the stress distribution and fatigue life of the wheel [3].

Nabaglo et al., described the kinematic and dynamic relationships within the suspension system. They grouped the vehicle elements into several subsystems such as suspension, road wheels and tracks. As a result of the comparison analysis of the vertical forces acting on the road wheels of the real tracked armored vehicle and the vehicle model, they stated that they showed a high level of similarity [4].

Raju et al. have studied on the evaluation of fatigue life of aluminum alloy wheels under bending loads. Fatigue life of alloy wheel was estimated by finite element analysis simulating realistic test conditions. Maximum stress locations of the wheel were observed by finite element analysis and then the calculated fatigue life and experimental values were studied. In this parametric study, reliable fatigue life estimation was determined and suitable safety factor was suggested for fatigue life estimation under rotary bending test [5].

Wong developed a simulation program (NTVPM) that analyzes the impact of design inputs on the vehicle's overall performance by measuring the pressure exerted by a tracked vehicle's road wheels on the track links under varying road conditions [6].

Deng et al. introduced a new flexible road wheel with hub-hinge-ring combined structure to improve the buffer damping performance and light weight level of tracked vehicles [7].

Cleare, G.V., argued that as a result of the use of tracks in armored military vehicles, the contact surface of the vehicle with the ground increases, the track part will be buried in the ground and therefore the maneuverability will decrease, the power required for movement will increase, wear will occur at the joints of the tracks due to the strain, but the use of tracks will be advantageous as the weight of the armored military vehicle increases [8].

Dong Ma et al. aimed to contribute a new model and solution algorithm of tracked vehicles by utilizing the coupling between track-wheel-terrain interaction[9] .

Bodin A introduced a new tracked vehicle that will be used to study the effect of different vehicle parameters on mobility in soft snowy terrain. Field tests were conducted in heavy snow to investigate the effect of ground pressure on the vehicle's traction performance. The vehicle used in the tests has ten road wheels [10]

Choi et al. have created studies on the vibration control of a tracked vehicle equipped with Electro-rheological suspension units (ERSU). The algorithm related to the speed of the vehicle body and the rotational angular velocity of the road wheel has been used [11].

In their research, J. Yamakawa and K. Watanabe created a motion analysis model to evaluate the driving performance, steerability and stability on rough terrain for tracked vehicles with high mobility [12].

Anıl Dhır and Seshadrı Sankar conducted a comparative study aiming to show the effect of various wheel models on the driving of high mobility tracked vehicles [13].

Hou et al. stated that the more the number of wheels of the tracked vehicle, the higher the mobility of the vehicle on soft terrain. Under the premise of meeting the weight and size area, they stated that increasing the number of wheels as much as possible can effectively improve the mobility of the vehicle [14].

Kunsoo Huh and Daegun Hong developed a track tension monitoring methodology to estimate the track tension under various maneuvering tasks, such as driving on sloped or rough roads, turning on flat

or sloped roads, etc. They obtained kinetic models for the road wheel to calculate the track tension around the sprocket under turning condition [15]. Dudzinski et al. stated that double flange road wheels are generally applied in rubber track and belt undercarriages of tracked vehicles due to their many advantages. They showed that the amount of energy lost due to the interaction between the double flange road wheel and the rubber track or belt is affected by the contact pressure distribution between the road wheel and the track [16].
This research, unlike other studies in the literature, aims to obtain a cost-effective design using existing facilities that meet design inputs instead of a product that already exists but takes a long time to produce and is costly.

2. Material and Methods

2.1 Modeling and Finite Element Analysis

The road wheel rim, wheel rubber and reinforcement ring that make up the road wheel to be used in design optimization were modeled in the 3D drawing program Creo Parametric as shown in figure 2 and then imported into the Abaqus program for analysis.

Figure 2. *Creo Parametric Modeling of the Components of the Road Wheel.*

While making the analysis, the steel rim, wheel rubber and track system values created for the road wheels are the same, and only the dimensions and welding distances of the reinforcement ring welded to the steel rim have changed. While comparing the analysis results, the design and location of the welded reinforcement ring have been decisive

2.2. Material Mechanical Properties

The mechanical properties of SAE 8620, SAE 4140, ERD 3957 to be used in the road wheel design optimization and the wheel rubber materials to be coated on the road wheel rim are given in table 1.

2.3. Loads

Here, the impact forces on the road wheel of a tracked military vehicle while it is traveling on the field were investigated. The force components resulting from the road wheel hitting an obstacle on the vehicle are shown in figure 3.

Table 1: *Material properties used in the finite element model.*

Material Type	Modulus of Elasticity E (MPa)	Poisson Ratio ν	Yield Stress σy (MPa)
SAE 8620	205 E3	0,28	675
SAE 4140	205 E3	0,28	1113
S420MC (ERD 3957)	205 E3	0.28	420
Rubber Wheel	37	0.45	-

Accordingly, the forces generated on the road wheel are given in equation 1, equation 2 and the resultant force is given in equation 3.

$$Fx = \frac{M \cdot v_1^2 (\cos\theta - 1)}{R\theta} \qquad (1)$$

$$F_y = \frac{M \cdot v_1^2 \cdot \sin\theta}{R\theta} + p + w + k_y \qquad (2)$$

$$F = \sqrt{Fx^2 + Fy^2} \qquad (3)$$

It is written as [17].

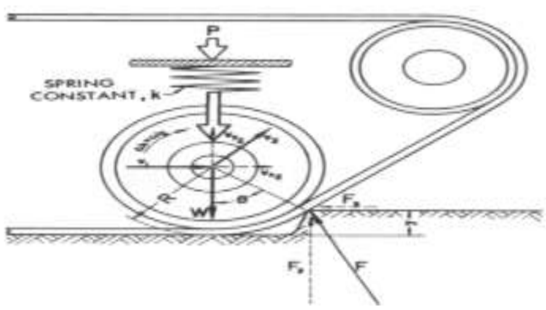

Figure 3: *Impact Force Components on the Road Wheel.*

The situation in which the forces acting on the road wheel will be calculated is determined as the situation where a tracked vehicle travelling at a speed of 48 km/h hits an obstacle of 127 mm height. Accordingly, the values of the parameters in equations 1 and 2 will be as follows
M: Road Wheel group mass=312 kg (Hydraulic Suspension Unit (HSU) + 2 road wheels)
v: Vehicle speed = 48 km/h = 13.33 m/s
R: Road wheel radius = 350 mm
y: Vertical obstacle height = 127 cm
P: Static load on road wheel = 38421.846 N
w: Weight of the road group = 3060.72 N
ky: Force on Hydraulic Suspension System = 40000 N

θ: The angle value formed by the road wheel hitting the ground (0.88 radians) is given in Equation 4.

$$\theta = \arccos\left(\frac{R-y}{y}\right)$$

The total weight of the vehicle is 47000 kg and it has 24 road wheels. The resultant force resulting from the calculations has an effect on the 2 wheels in the road wheel group. This situation was evaluated during the analysis and the force per unit wheel was calculated. Accordingly, the force per wheel was found to be 115 kN.

In addition to the different force values mentioned above, another situation is when the vehicle passes through a 60° ramp as shown in figure 4.

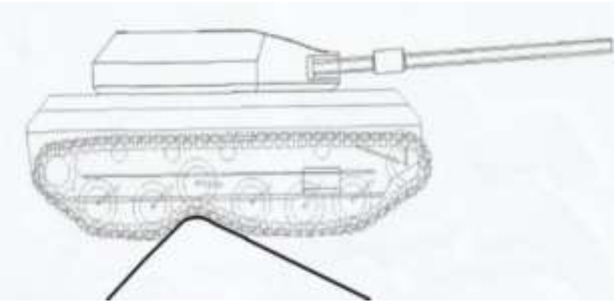

Figure 4.*Case of passing through a 60° ramp.*

If the vehicle passes over a 60-degree ramp, the maximum load on the road wheels will occur when the entire weight of the 47-ton vehicle (460 kN) is on the 4 road wheels, left and right. If the total weight falls on the 4 wheels in the road wheel group (2 wheels in the right road wheel group, 2 wheels in the left road wheel group), the load per wheel will be approximately 11.75 tons (115 kN).

As indicated in figure 5, the 11.75 ton load is transferred to the road wheel by the flanged connection on the HSU arm to which the wheel is mounted, along the flange surface. For this reason, the 11.75 ton load is distributed equally over the center of the flanged connection surfaces on the road wheel. When these conditions are taken into consideration, the road wheel design load to be determined must

Figure 5.*Road Wheels mounted on HSU.*

cover each of the above-mentioned conditions. In other words, it will need to represent the worst case. Therefore, the design load of the road wheel group is determined as 230 kN. Since there are two road wheels in a road wheel group, the load on one of them is calculated as 115 kN. The force applied to the road wheel is applied to all nodes on the surface as 115 kN.

2.4 Boundary Conditions

The degrees of freedom in the Z direction of the joint points on the road wheels flange surface and bolt holes are reset. In order to restrict the forward or backward movement of the road wheel, all degrees of freedom of the node points on the surface where the rigid plate representing the pallet link on which it steps is in contact with the ground are reset to zero. The finite element model created for the solution and the necessary boundary conditions are shown in figure 6 and figure 7.

2.5 Mesh

Before starting the finite element analysis, mesh optimization was performed to determine the mesh

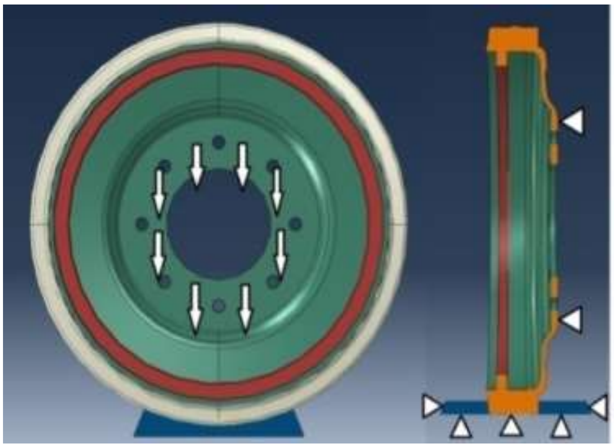

Figure 6.*Finite element model boundary conditions.*

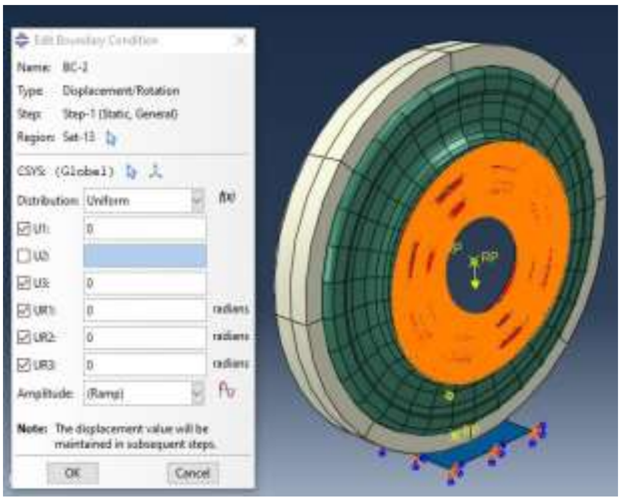

Figure 7. *Finite element model boundary conditions*

***Table 2**: Number of elements and nodes used in the finite element model and maximum stress values*

NO	MESH	MAX.STRESS (MPa)	ELEMENT	NODE
1	4 mm MESH	452	175585	220871
2	5 mm MESH	452	110692	140779
3	6 mm MESH	596	70906	93514
4	7 mm MESH	634	42704	59555
5	8 mm MESH	638	30886	43939
6	9 mm MESH	729	20563	30601
7	10 mm MESH	813	16314	24289

range to be used. The meshes created at different ranges were continued until the maximum stress range was close and the ideal mesh range was investigated. The number of elements and nodes used in the finite element model of the analyzed Road Wheel and the maximum stress values are given in table 2.

As a result of the analysis, since the tension values resulting from the force applied to the road wheel of the mesh values in the 1st and 2nd rows in table 2 are the same, 5 mm spaced mesh will be used in the analyses to be performed from now on.

3. Results and Discussion

The deep drawing method is widely used in the metal industry [18]. If the deep drawing method of the road wheel is considered to be manufactured, the material to be used in this case is the ERD 3957 (S420MC) numbered material. If ERD 3957 quality steel, which is suitable for deep drawing, is used in the production of the road wheel and 115 kN load is applied to it, the stress value on it will be 420 MPa as shown in figure 8. Since the yield strength of ERD 3957 quality steel is 420 MPa, the result is equal to the yield strength. In other words, since the maximum stress is thesame as the yield strength, the desired safety condition

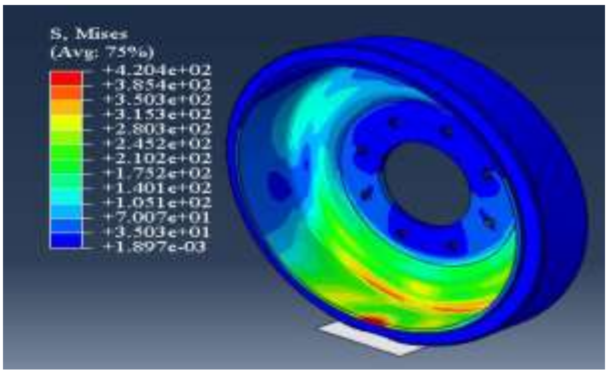

***Figure 8.** Road Wheel made of SAE 3957 material without reinforcement hoop*

cannot be achieved. For this reason, a design without a reinforcement ring is not possible with the deep drawing method.

This situation shows that ERD 3957 quality steel cannot be used with the current design and new ways must be found to increase the strength of the wheel. In order to reduce the stresses on the road wheel to lower levels, it was considered to make a rim reinforcement on the inner surface of the road wheel as an alternative. The new design resulting from welding the part in question with MIG welding needs to be optimized in the most effective way. In order to increase the strength, the reinforcement ring to be welded should have optimum thickness, width and welding distance to the rim surface so that it does not increase the weight of the road wheel too much. When making a design change, parameters such as the diameter of the road wheel, the number of HSU holes connected to it and their locations are dimensions that cannot be changed on the road wheel. In order to reduce the stresses on the surface of the road wheel to lower levels, a rim reinforcement was made on the inner surface of the steel rim. The technical drawing of the planned ring reinforcement is shown in figure 9. The b, h and d parameters here represent the height, width and distance from the outer surface of the reinforcement ring, respectively In order to finalize these parameters, different values were given to each parameter. The maximum load (115 kN) was applied to the created combinations and the situation in which the most

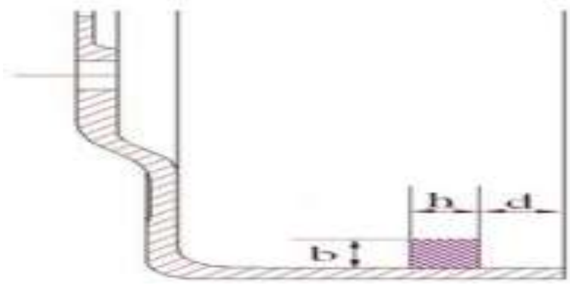

***Figure 9.** Reinforcement Ring Design Parameters.*

Table 3. *Hoop Reinforcement Design Parameters and Maximum Stresses.*

Model number	b (mm)	h (mm)	d (mm)	Maximum Stress (On Reinforcement Ring) (MPa)	Stress on Wheel Rim (MPa)	Safety Factor on the Reinforcement Ring	Safety Factor on Wheel Rim	Deformation on the road wheel (mm)	Additional Mass (kg)
1	15	20	20	567	314	1,190476	1,33758	11,28492928	4,38
2	15	20	40	529	311	1,275992	1,350482	11,43628216	4,38
3	25	15	15	539	270	1,252319	1,555556	10,45933437	5,38
4	25	15	30	567	275	1,190476	1,527273	10,69566154	5,38
5	25	25	10	373	240	1,809651	1,75	9,874764442	8,97
6	25	20	15	442	251	1,527149	1,673307	10,06204224	7,18
7	25	20	20	441	252	1,530612	1,666667	10,12867832	7,18
8	20	20	20	512	285	1,318359	1,473684	10,79221725	5,79
9	20	20	30	504	287	1,339286	1,463415	10,89555264	5,79
10	20	25	20	442	276	1,527149	1,521739	10,49292374	7,24
11	20	25	25	435	273	1,551724	1,538462	10,53700447	7,24
12	20	25	30	425	273	1,588235	1,538462	10,58219051	7,24
13	23	20	20	485	270	1,391753	1,555556	10,49764824	6,63
14	24	20	20	471	265	1,433121	1,584906	10,40306664	6,9

suitable stress and safety coefficient resulting from the analysis would be obtained was investigated.
Table 3 lists the values of the design parameters of the hoop reinforcement and the stress values occurring in these combinations. In the table in question, the positions of the reinforcement rings of different sizes welded on the road wheel rim relative to the steel rim, the stresses formed on the reinforcement ring and the steel rim, the safety coefficients and the amount of additional mass formed are given. As a result of the analysis, it is seen that the maximum stress occurs on the reinforcement ring. The safety coefficient on the reinforcement ring was obtained by dividing the yield strength of the material (SAE 8620) used in the production of the reinforcement ring by the maximum stress, which yields different results in each design. After finding the safety coefficient on the reinforcement ring, the stress values on the steel rim were examined. By hiding the reinforcement ring model, the stress values on the steel rim are revealed. The safety coefficient on the steel rim was obtained by dividing the yield strength of the material from which the steel rim was manufactured (ERD 3957) by the stress value on the steel rim. As a result of the variable reinforcement ring design, it is seen that different stresses and, as a result, different safety coefficients occur on the road wheel, as stated in table 3. In the light of the results, the safety coefficient graph resulting from the maximum stress on the reinforcement rings welded in various sizes and on the steel rim is given in figure 10.
When selecting the reinforcement ring to be mounted on the road wheel rim, the stress value that occurs on the wheel rim and the reinforcement ring as a result of the applied load is the determining factor.When the Engineering Design Handbook [17] prepared by the AMCP United States Army Metarial Command is examined, it is seen that the safety coefficient values of various parts found in tracked armored vehicles vary between 1.2 and 2. However, having a safety coefficient close to 2 will increase

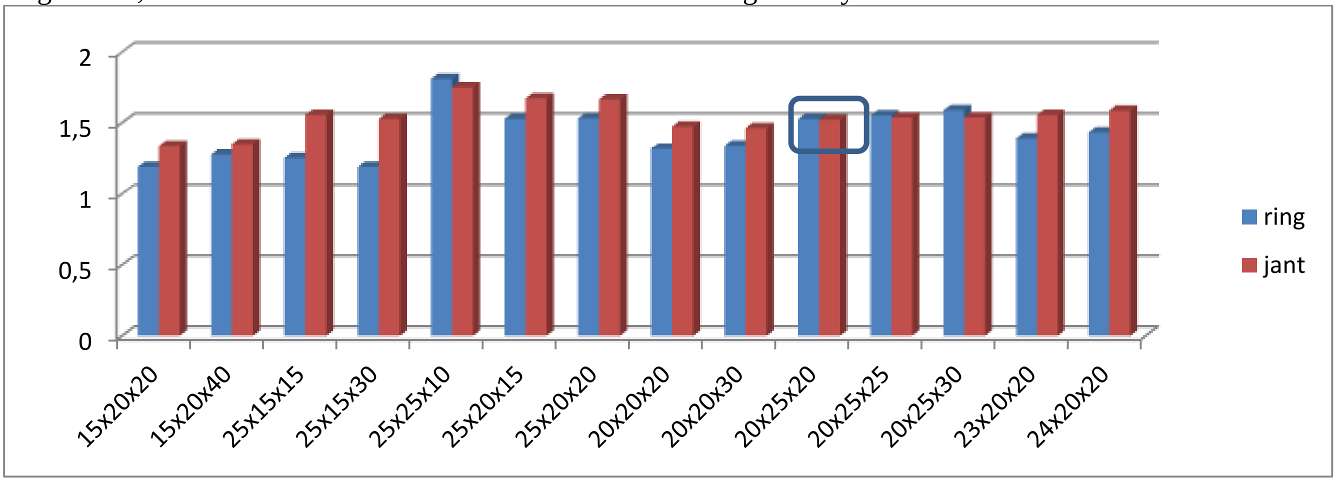

Figure 10. *Safety coefficient on the reinforced ring and steel rim mounted in various sizes.*

safety, but it will also increase the weight of the road wheel and the wheel rubber. Accordingly, the safety coefficient is targeted to be 1.5 in the road wheel design.

When starting the analysis studies, the situation of welding a reinforcement ring with a height of 15 mm was started in order to give an idea. As a result of the analysis, since the safety coefficient was found to be lower than 1.5, the analysis studies were continued by increasing the height. After the height of the reinforcement ring was set to 25 mm, the safety coefficient was found to be around 1.8, and a more safe situation was created.

The analyses were continued with the reinforcement ring height being 20 mm and the safe zone was achieved. Then, the stage of determining the width of the reinforcement ring and the distance of the ring from the outer surface was reached. The criteria here are that the safety coefficients on the reinforcement ring and the steel rim are close to each other and to the value of 1.5, the deformation on the road wheel is less and finally the additional mass is as little as possible. Considering all these situations, it becomes clear that it is ideal to design in the dimensions in the 10th row in table 3 (20x25x20mm) and in the area marked in figure 11.

In this design, the maximum stress on the reinforcement ring is 442 MPa as shown in figure 10, and the maximum stress on the road wheel is 276 MPa as seen in figure 12. Accordingly, the road wheel s_{pt} in equation 4 and the safety factor $s_{tç}$ in the reinforcement ring equation 5 are calculated as follows.

$$s_{pt} = \frac{Yield\ Strength}{Maximum\ stress} = \frac{420\ MPa}{276\ MPa} = 1{,}52 \quad (4)$$

$$s_{tç} = \frac{Yield\ Strength}{Maximum\ stress} = \frac{675\ MPa}{442\ MPa} = 1{,}52 \quad (5)$$

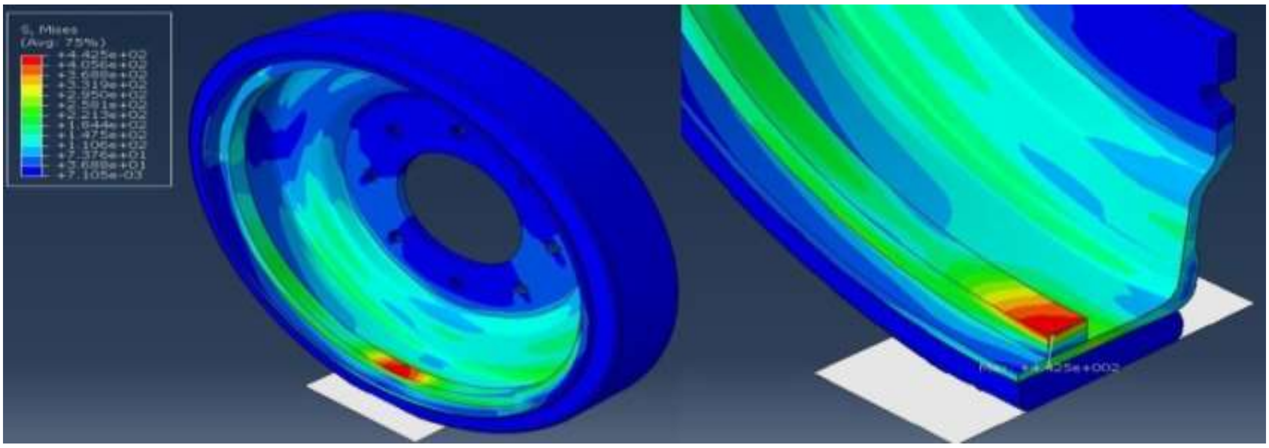

Figure 11.*Maximum stress on the reinforcement ring with dimensions of 20x25x20 mm.*

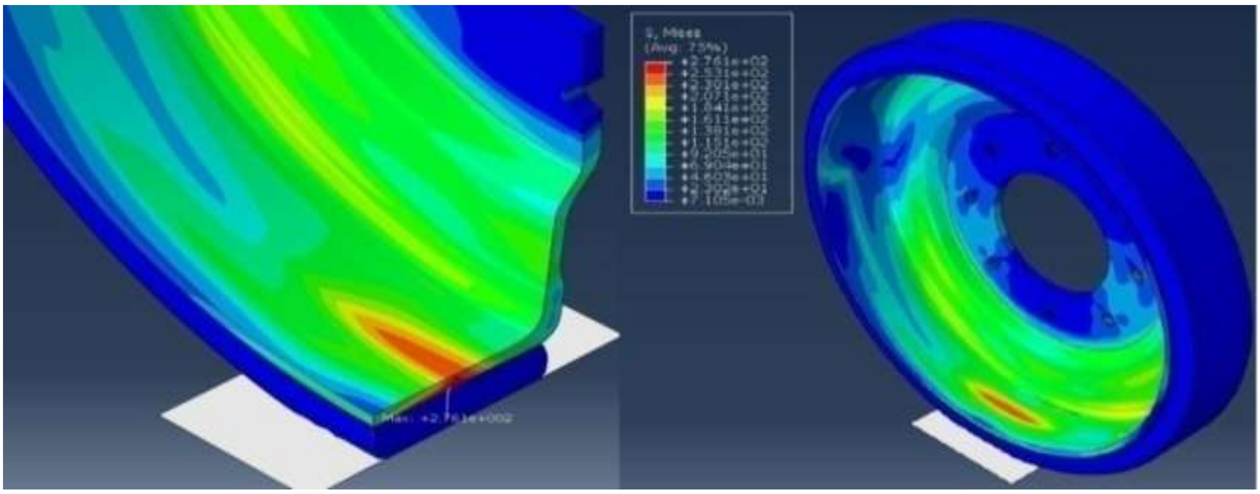

Figure 12. *Maximum stress on the Road Wheel rim when a 20x25x20 mm reinforcement ring is used. (Reinforcement Ring is hidden.)*

If the model without a reinforcement ring is considered to be manufactured by forging method, SAE 4140 quality material can be used. In case of using SAE 4140 numbered material, the safety factor that will occur is as stated in equation 6.

$$s_{4140} = \frac{Yield\ Strength}{Maximum\ stress} = \frac{1113\ MPa}{452\ MPa} = 2{,}46 \qquad (6)$$

It is found as. Then, it has been observed that a design without a reinforcement ring can be used if SAE 4140 numbered materials are used.
The track link used in armored tracked vehicles works by contacting the road wheel as shown in figure 13 in order to continue its movement in the same direction and smoothly.

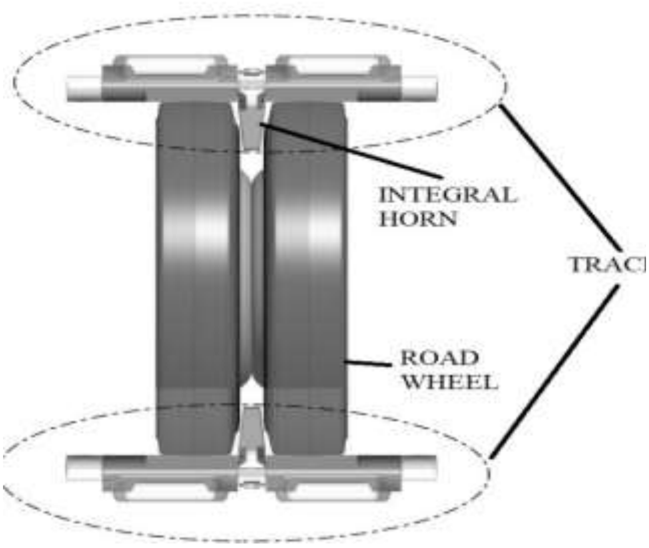

***Figure 13.** Pallet link working with road wheel*

As the vehicle moves, the integral horn on the pallet rubs against the road wheels to keep the pallet in line, causing wear. The wear increases when the vehicle turns left or right. This wear causes the service life of the road wheel to decrease and wear out over time. In order to prevent this situation and increase the durability and life of the road wheel rim, a wear plate is welded to the surfaces where the integral horn comes into contact, as in figure 14, and the wheel is covered with rubber. By welding wear plate on the rim of the Road Wheel, the life of the material is increased and its strength is also increased. When the new design is analyzed after the wear plate is added to the Road Wheel, which is determined as the ideal reinforcement ring, the maximum stress applied on it is 403 MPa, as indicated in figure 15. When the safety factor of the wear plate design is calculated as given in equation 7;

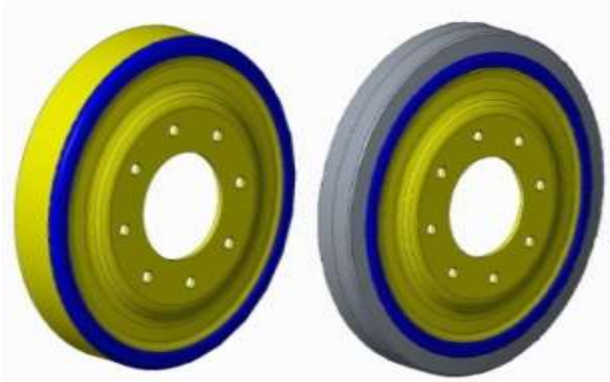

***Figure 14.** Road wheel with wear plate welded on*

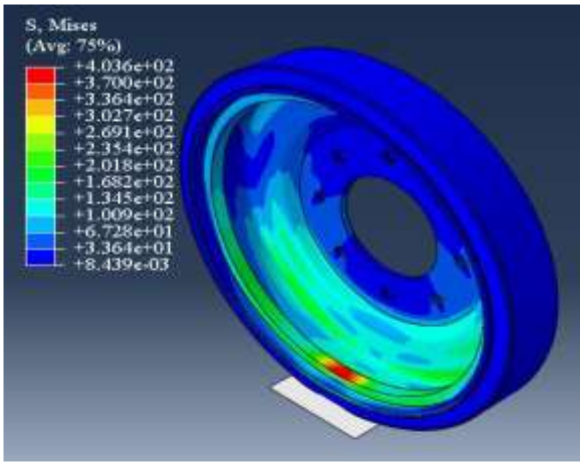

***Figure 15:** Maximum stress on the Wear Plate Road Wheel*

$$s_{pt} = \frac{Yield\ Strength}{Maximum\ stress} = \frac{675\ MPa}{403\ MPa} = 1{,}67 \quad (7)$$

It is found as. Welding a wear plate to the wheel rim surface increases the strength and the total weight increases by 2.56 kg. If the reinforcement ring is not welded and a wear plate is added to the wheel rim, a deformation of 12.04 mm occurs on the upper surface of the road wheel as indicated in figure 16.

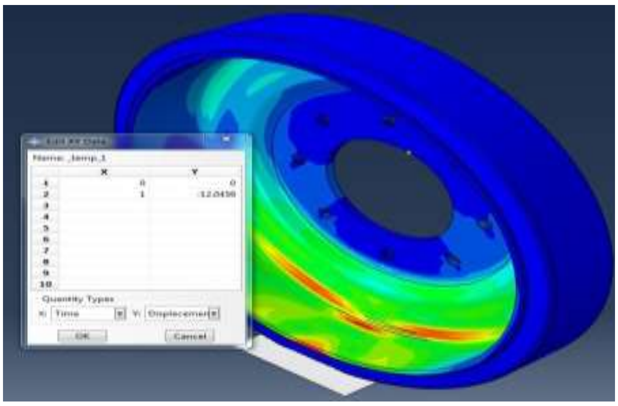

***Figure 16.** Road wheel with welded wear plate without reinforcement ring.*

In case of using the reinforcement ring with dimensions of 20x25x20 mm, which is in the 10th place in table 3, the displacement in the road wheel is 10.49 mm, while in case of not using the reinforcement ring, the displacement amount is analyzed as 12.04 mm. According to these results, it is not appropriate to use a road wheel rim made of ERD 3957 material without a reinforcement ring. Similar papers reported in literature [19-21].

4.Conclusions

Tracked armored vehicles are of great importance for military operations. These vehicles are preferred due to their mobility, durability, reliability and firepower in difficult terrain conditions. However, one of the key components that make these features of tracked armored vehicles possible is the walking system.

For manufacturing units, high production speed, low technical risk and minimum cost are the most important issues to be considered in material production. In the light of the obtained data, the modeling and analysis of the road wheel for a tracked armored vehicle weighing approximately 47 tons was carried out in a way that would reduce the dependency on foreign countries in the production of the road wheel in the walking system of a tracked military vehicle, enable purchases to be made from the domestic market within short delivery times and increase competition for supply activities. After these studies, it is suggested that two different steel road wheel designs and manufacturing are suitable. One of them is the design in which the reinforcement ring is used and the other is the design without the reinforcement ring.

If a road wheel with a reinforcement ring is preferred, the rim can be manufactured by deep drawing using the material numbered ERD 3957 and welding the reinforcement ring made of SAE 8620 material, which is easy to weld. It has been observed that the safety factor will increase as the thickness of the reinforcement ring used in the road wheel increases. However, this process will add extra weight to the vehicle on which the Road Wheel will be mounted. After the applied loads, the stresses on the Road Wheel and the reinforcement ring welded to the wheel were analyzed separately and the ideal design was tried to be achieved by adjusting the most optimum ring thickness and distance.

In the design of the Road Wheel without reinforcement ring, if steel raw materials of SAE 4140 quality are used, it must be manufactured by forging method. However, this situation is not preferred because it will cause an excessively safe design and decrease the variety of suppliers that can produce with domestic possibilities.

In addition to all these situations, it has been determined that by adding a wear plate to the road wheel rim, the strength will increase, the deformation caused by the contact of the pallet surface can be reduced, but the weight will increase. Instead of eliminating the road wheel rim as a result of the wear that occurs over time due to the friction of the pallet against the road wheel, the service life will be increased by removing the wear plate welded on it and renewing the wheel rim without any damage.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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