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Performance materials with variations of tractor drive wheel fin angle and low-cost manufacturing analysis

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Abstract

Nowadays, the demand for workers in the agriculture industry has decreased and there is a need for rising mechanization in the agriculture process. The agriculture process that requires mechanization is cultivating. The rice cultivator has to be as light as possible, so requires a lighter material but is also strong enough. The correlation between the rice transplanter tool and the wheels is closely related to soil conditions. The selection of wheel materials is considered based on the characteristics of the planting area. In addition, another influence variable is the angle of the fin in the rice transplanter wheel. Material of rice transplanter wheel has been established, these are 1023 carbon steel sheet, AISI 1020 steel cold rolled, AISI 316 stainless steel. The angle of the fin was varied, these are 30, 35, and 40, this fin will give an effect on the traction result of rice transplanter wheel movement. The combination of lightweight material and the appropriate fin angle of the rice transplanter wheel has the best traction result. As a result of this research, the suitable material for the rice transplanter wheel was carbon steel and the fin's angle was 30. This research involved a comparison and analysis of material strength under various fin angles. The evaluation of stress criteria was conducted using design values to determine the most reliable final product design. The paper contributes by illustrating how to represent the final decision on the combination of design and materials, incorporating a cost index assessment.

Keywords:
AISI, FEM, material, wheel, fin angle.

1 Introduction

In this era, mechanization in the agriculture industry is needed because hard to find workers for the agriculture sector, and mechanization in agriculture will increase the effectiveness of land productivity and economically it is expected to grow up farmer's income [1]. Agricultural mechanization uses tractors to speed up land preparation activities, allowing farmers to grow crops on time during the growing season. According to the research [2], the use of tractors in Ethiopia has increased, while the ownership of livestock that can be used to plow the fields has decreased.

Thus, according to the study [3], it is technically the most efficient use of tractors, but economically uses the most efficient buffalo shows based on capacity and cost. The research indicates that farmers in the Bantul district are willing to try innovations depends on their preferences for those innovations and the risks they must accept [4]. Two-wheeled tractors are utilized in the process of delivering numerous necessities of Indonesian farmers such as seeds, fertilizers, equipment, and many types of agricultural products. The trailer design of the tractor has flaws because it is not designed for all types of land or specifically for flat land, and no wheel type design is suitable for all types of land [5]. A lean tractor wheel type designed and tested the use of that is used for other functions (besides plowing) in rice fields; however, this type of wheel still requires modification for transportation purposes in various fields [6]. Cage wheels were created for sloping and terracing land in rice fields [7].

The process of soil compaction involves a decrease in soil volume, notably in the air-filled portion, and an increase in bulk density as a result [8]. Increased machine weight, intensive cropping, short crop rotations, excessive machinery use, and poor soil management are some of the factors that contribute to undesirable soil compaction [9]. Globally, the rate of soil compaction is increasing [10]. To reduce one of the causes of soil compaction by making the tractor's weight as light as possible. That way mobility becomes easier. Even though it is light, the design must consider its function and strength. The fins on the wheels are a critical component that is often subject to damage. Repairs can be executed at the welding shop, but they are frequently limited by spare parts, so iron plates are used instead of fins [11]. ASTM A36 steel was chosen [12], which is widely available on the market as a raw material for the manufacture of transport tractor chassis.

Under constant driving conditions, torque redistribution on tractor wheels slightly increases with higher translational speed due to dynamic impact frequency and traction load fluctuations [13]. Analyze traction and energy indicators of tractors with varied tire types, examining spectral densities for frame accelerations, engine crankshaft speed, mover axis torque, and traction force across tire models [14]. The high press wheel loads adversely affected the percentage germination of the crops [15]. The vertical load on each drive wheel will increase by 6.7% [16]. Based on their research, the load distribution is transmitted to the wheel, which requires an increase in strength and ground-gripping force. The influence of wheel materials on fin angle and ground-gripping force presents an intriguing area of study.

The novelty of this study is the use of 1023 carbon steel sheet, AISI 1020 steel cold rolled, and AISI 316 stainless steel sheet for the tractor's wheel structure. The tractor's traction is closely related to the fins on the wheels. Traction capability is enhanced as wheel slip decreases. Slip is reduced when the fins dig into the ground thoroughly [17]. The wheel fins of a hand tractor will be designed in this study using a variation of the alpha tilt angle of 30°, 35°, and 40°. The angle is then applied to each of the three different materials. Simultaneously, it is necessary to reduce test costs and shorten the time it takes for new products to enter the market [18]. A Finite Element Method (FEM) simulation is utilized to reduce iterations by evaluating the performance of a product design in achieving stress and strength requirements. Modeling and simulation techniques can be widely used to represent the evolving behavior of agricultural machinery and products derived from real-world physical systems [19].

A series of studies have utilized the finite element method to optimize the design of various components of rice transplanters. Chen (2022) focused on the chassis, using the method to revise the model and avoid resonance during operation [20]. Selvan (2014) developed a pull-type transplanter, optimizing the ground wheel diameter and picker-finger width [21]. Sun (2016) designed a rotary transplanting mechanism, using the method to analyze and optimize the trajectory and attitude of the planting paw [22]. These studies collectively demonstrate the effectiveness of the finite element method in enhancing the performance and efficiency of rice transplanters.

This research compared and analyzed materials strength with the various angles of fins. Then the performance of the stress criteria be evaluated by design value to define the most reliable final product design. So, this paper contributes to how to represent the final decision all of design and materials combination with cost index assessment.

2 Method

2.1 Design and Strategy

This research delivered a design strategy for the assessment of the preliminary model of a rice transplanter wheel with various fin angles and materials candidates. To determine the optimality of the design, Finite Element Analysis (FEA) was conducted by incorporating parameters such as fin angle and material type, thus resulting in stress evaluation. The outcomes of the stress evaluation were processed using a scoring diagram to determine the appropriate material selection. The scoring encompasses four criteria: cost, stress value, safety factor, and resilience of the material. Based on strength (von misses stress) requirements are needed. The design strategy was considered based on the material costs. The step process method to conclude the results of the FEM simulation based on stress assessment compared to material costs can be seen in Fig. 1.

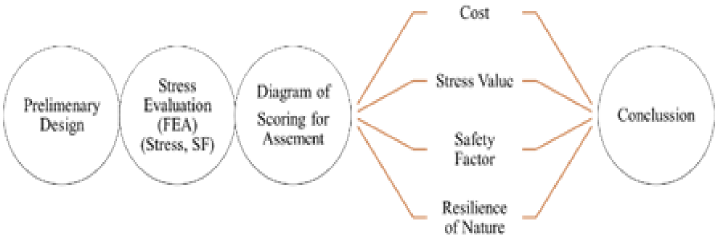


Fig. 1. Design strategy of tractor tire transplanter.

First of all, after the design modeling is carried out, the FEA simulation results must be evaluated to find out whether the von mises stress on design criteria meets the desired requirements or not. If the stress result already meets the requirements, then it can be considered to have succeeded in the stress requirements.

2.2 Simulation and Parameter Setup

Parameters of the steel wheels were set by dimension and angle variations of the Fin are shown in point A as seen in Fig. 2, The angle variations of fins are 30, 35, and 40. As the design, the inner diameter of the wheels is 508 mm, 12 fins, and the width of the wheel is 40 mm.

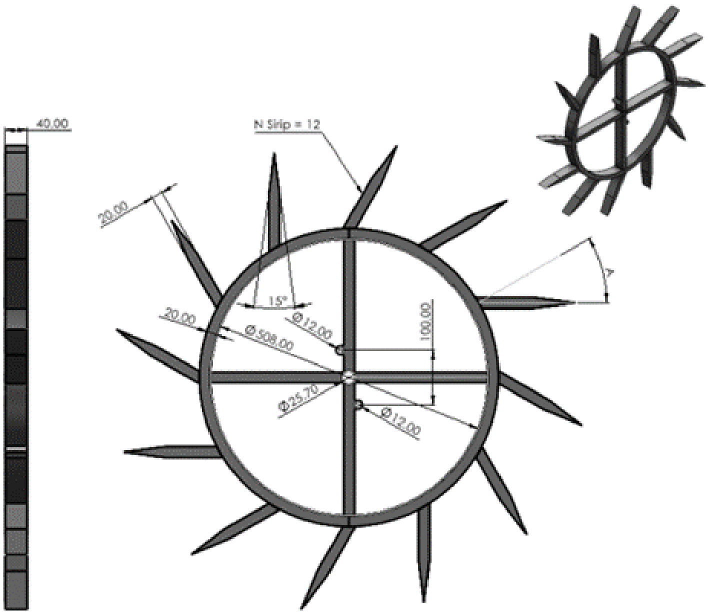


Fig. 2. Dimension of steel wheel tractors.

Boundary conditions in simulation also considered the material of tractor steel wheels, there were 3 materials used in this research, 1023 carbon SS, AISI 1020 steel cold rolled, and AISI 316 SS (Table 1). All material was set by Solidwork material properties and load force was set by the weight of the tractors that distributed on two wheels. From 3 fin angle variations and 3 materials, there are 9 combinations of fin angle and materials. Furthermore, the best combinations will determine the design for the tractor's wheels.

Table 1. Material properties

Materials	Yield strength	Mass density	Poisson's ratio
1023 carbon steel sheet	282.7 MPa	7.858 g/cm^3	0.29
AISI 1020 steel cold rolled	350 MPa	7.87 g/cm^3	0.29
AISI 316 stainless steel	172.4 MPa	8.00 g/cm^3	0.27

Assume in the field conditions, the depth of rice mud is 280 mm, refer to these conditions there are 4 active fins. Active fins are shown in Fig. 3. Then shear stress of the soil will distribute the pressure on 4 fins. The shear strength of the soil is the force of resistance exerted by the grains of soil against pressure or tension. Soil shear strength can be expressed by the coulomb Eq. 1.

$$\tau = c + \sigma \,\mathrm{tg}\, \varphi \quad (1)$$

Based on Eq. 1 [23], τ represents soil shear stress, and c is soil cohesion. The normal stress in the failure plane is expressed by σ, and then φ is the angle of soil shear.

As the Eq. 1 we got soil stress from soil cohesion added by normal stress in failure plane times tangent of the angle of soil shear value.

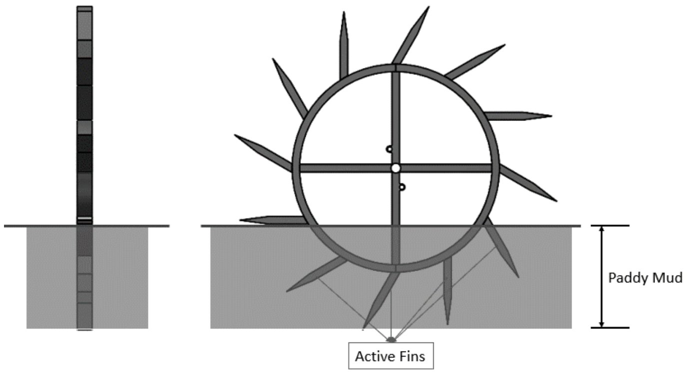


Fig. 3. Conditions in rice fields as simulations references.

Fig. 4 illustrates the clockwise rotation of the steel wheel, the weight of the tractor directed towards the W direction, and the normal force acting on the fins at point N. Subsequently, it is essential to determine the optimal combination of material selection and fin angle.

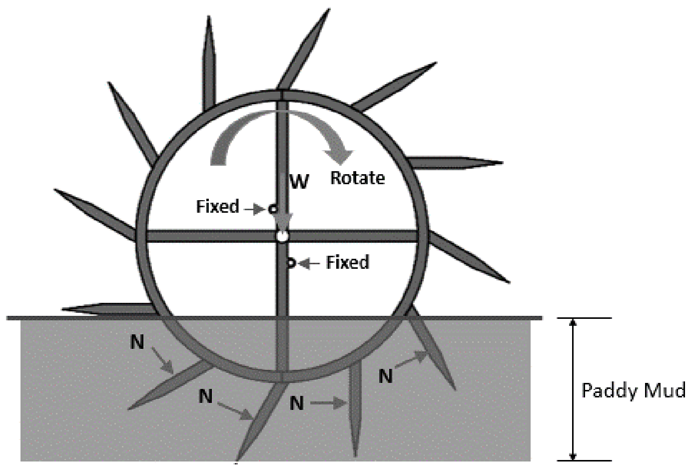


Fig. 4. Direction of force and rotation on steel wheel.

It requires scoring with selection criteria and focuses on comparing each combination by the weighted sum of the ratings [24]. The sequence of the scoring of each criterion is shown in Fig. 5.

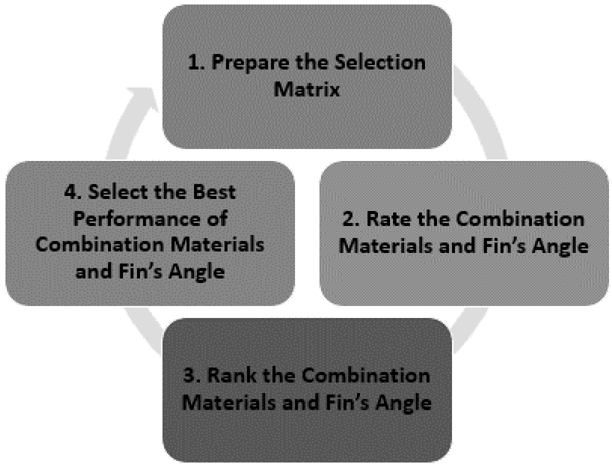


Fig. 5. The sequence diagram of the scoring.

After preparing the selection matrix then make a rating of the combination materials and fin's angle to get the score which have the best performance and criterion. Weighted scores are calculated by multiplying the raw scores by criteria weights. The score calculation for each combination can be expressed as Eq. 2.

$$S_j = \sum_{k=1}^{n} r_{ij} w_i \tag{2}$$

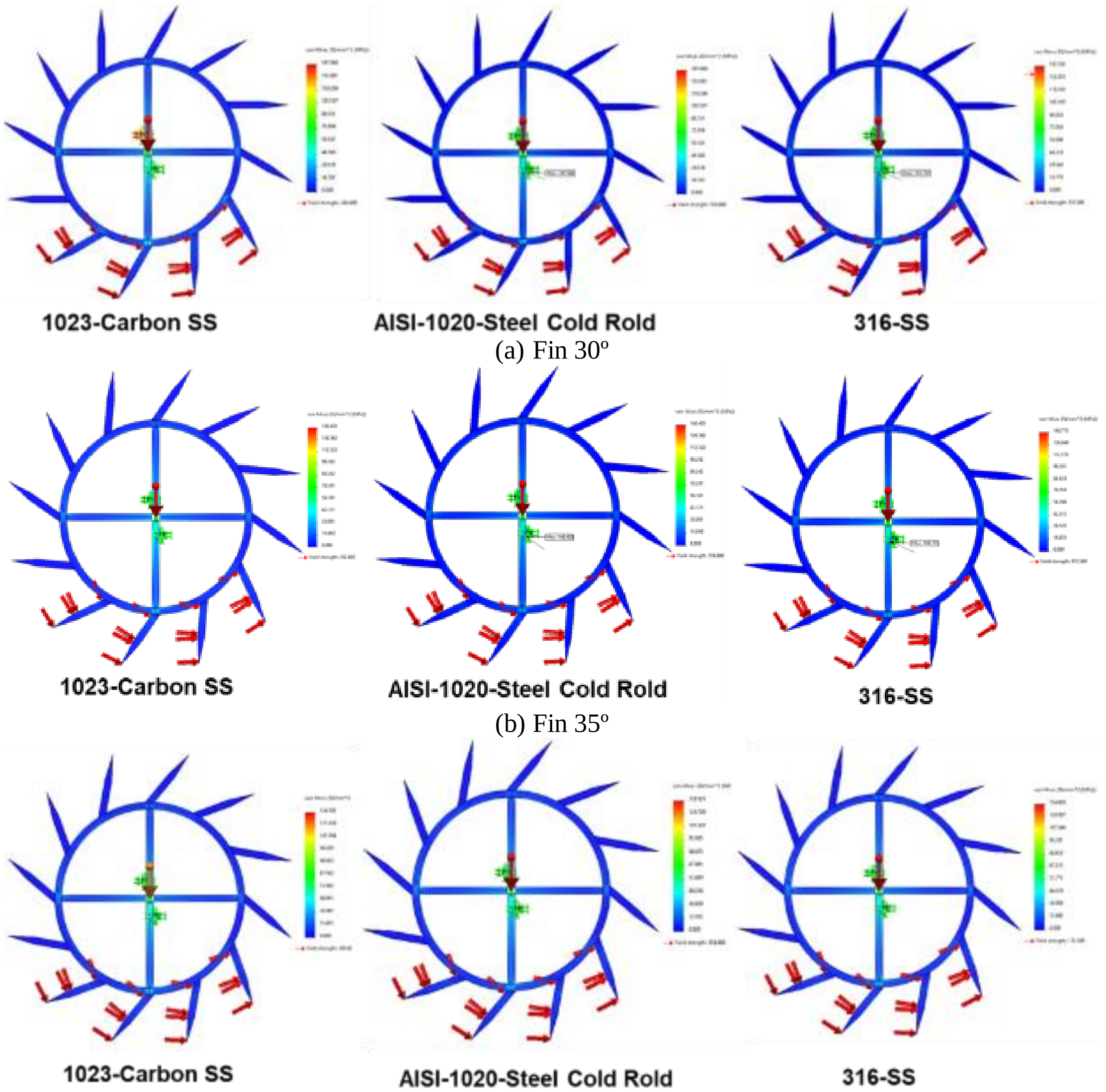
Whereas, r_{ij} is the raw rating of combinations j for the ith criterion, w_i is weighting for ith criterion, and the number of criteria (n), and then the total score for combinations j is expressed by S_j in Eq. 2 [25].

The selection matrix in these papers is used to consider the best combinations, there are the weights of the steel wheel, cost of material, stress value, safety factor, and resilience in nature. The criteria weights of each selection matrix are 25, 40, 15, 10, and 10 respectively. The cost of materials has the highest criteria weight then followed weight of the steel wheel because in agriculture technology especially for rice transplanter tractors requires the cheapest and the lightest product. For the raw rating score, there are 3 levels, the best, medium, and the lowest, and the values are 3, 2, and 1 respectively.

3 Results and Discussion

Based on the static simulation analysis, the effects of angle and material variables on stress values were examined. The discussion focuses on two key areas: the impact of the critical load distribution area on the dipped wheel fins and their response to soil pressure.

The meshing step is discretizing the volume model into elements. The results of the meshing process in this study used a standard solid mesh type. The Jacobian point for mesh cases with high quality is 16 points. The standard tolerance on this mesh modeling is 0.5 mm. The mesh quality comparison between the three model parameters can be shown in Table 2. Based on the simulation, the stress visualization of the overall variable in this model is shown in Fig. 6.



(a) Fin 30°

(b) Fin 35°

(c) Fin 40°

Fig. 6. Von mises stress value of tractor wheel.

Table 2. Mesh setup

Model parameters	Total nodes	Total elements	Maximum aspect ratio	% of elements with aspect ratio < 3	Percentage of elements with aspect ratio > 10	Mesh quality
Fin 30°	67654	33470	23.007	0.502	0.260	High
Fin 35°	67626	33470	46.314	0.463	0.439	High
Fin 40°	67563	33419	23.007	0.622	0.601	High

The model structure that represents stress concentration is at the lower center pin connection of the wheel, see Fig. 7. The stress value is taken from 7 nodal points on the radius filet closed to the fixed joint. The design failure of those structures can be known if the value of the von mises stress is greater than the yield stress of the material [26]. The von mises stress of fin at 40 degrees is the lowest, but at 30 degrees is higher stress than at 35 degrees. In the normal plane, the wheel fin angle configuration of 30 degrees receives ground pressure with a relatively larger friction area than at angles of 35 and 40. So the fin 30 degrees is the largest stress.

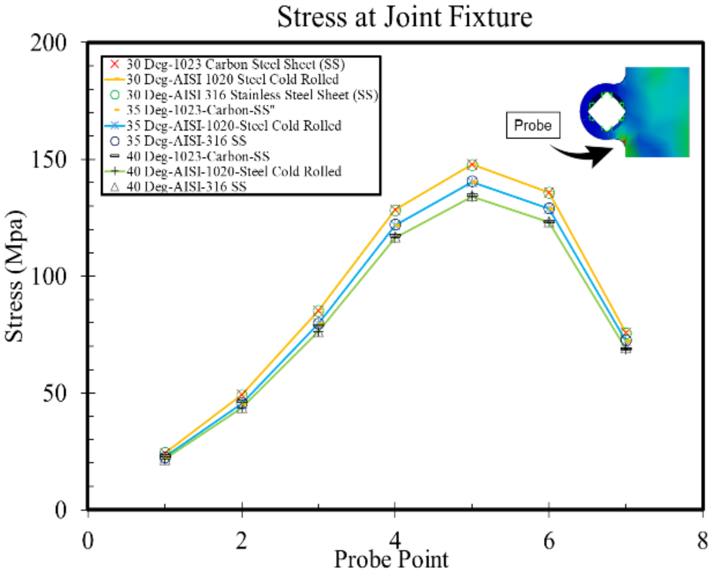


Fig. 7. Stress at join fixture.

The trend of stress on each fin with material variations can be seen in (Fig. 8, Fig. 9, and Fig. 10). The simulation results with static limit conditions consider the instantaneous loading of the rotating wheel and the depth of touching in clay. The position of the fins (A-D) at the moment the wheel touches the ground has a difference in the angle of rotation. The simulated probe is placed at the connection point between the fins and the wheels. There are 9 nodal points on each joint to be analyzed.

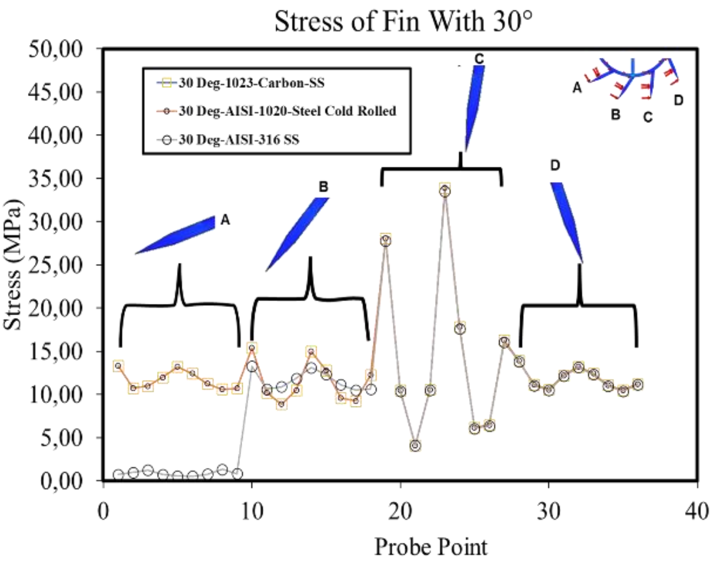


Fig. 8. The stress of the fin with 30 degrees at the ground.

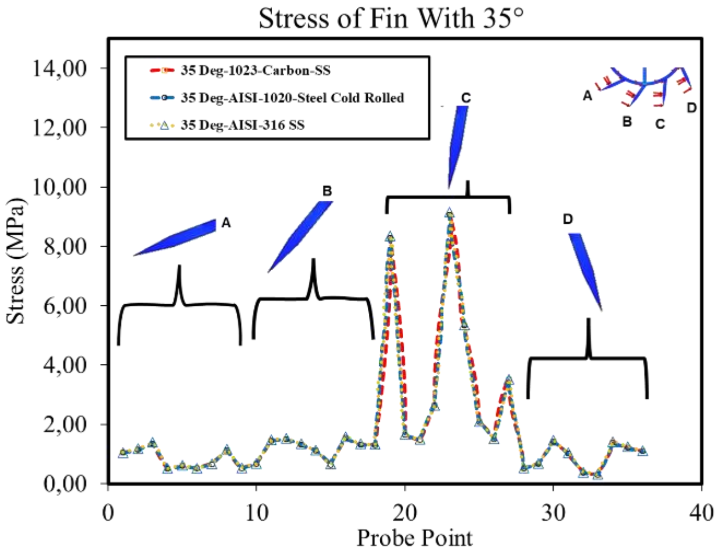


Fig. 9. The stress of the fin with 35 degrees at the ground.

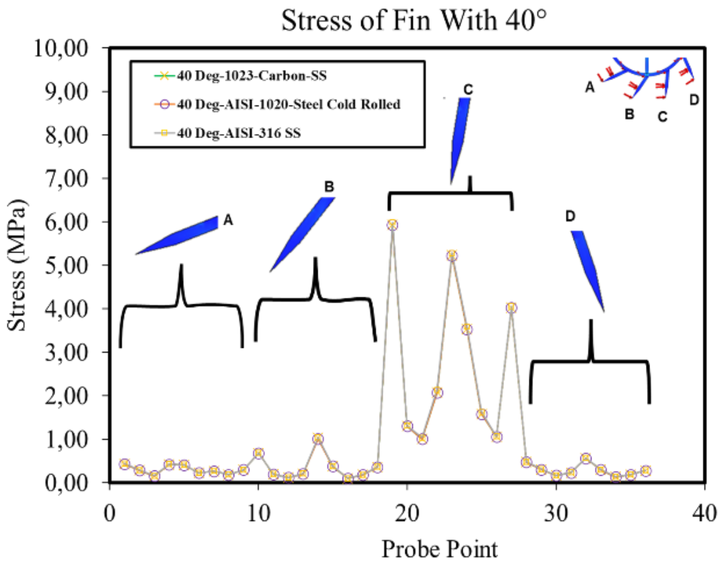


Fig. 10. The stress of the fin with 40 degrees at the ground.

At an angle of 30°, overall, the three materials have the highest stress at position C reaching almost 35 MPa. Whereas for position A, AISI 316 SS fell sharply with zero stress values. The highest position at the next angle is still position C, with a maximum stress of approximately 9 MPa and 6 MPa (respectively).

The Safety Factor (SF) value in the joint fixture obtained from the simulation results is considered for this design assessment. The magnitude of the safety factor value in each variation can be shown in Table 3.

Overall, the SF value in each variation averaged is over 1. However, the fin with an angle of 30 with the AISI 316-SS material failed due to the SF value of <1. SF becomes important to decide on the final design, where if the SF value is small then it has a low rating. Otherwise, if the SF value is higher, then the rating value will be greater.

The design parameter of the assessment considers the stress value in the maximum and fin areas presented. The scoring results are shown in Table 4. Design criteria in this study agree that if the reach of stress is lower, it gets a high rating, instead, if the stress is higher, it gets a lower rating.

Table 3. Safety factor in join fixture

SF of fin 30 degree			SF of fin 35 degree			SF of fin 40 degree		
1023-carbon-SS	AISI-1020-cold rolled	AISI-316-SS	1023-carbon-SS	AISI-1020-cold rolled	AISI-316-SS	1023-carbon-SS	AISI-1020-cold rolled	AISI-316-SS
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	2.81	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	1.62	3.00	3.00	2.16	3.00	3.00	2.26
2.32	2.72	1.08	2.41	2.87	1.41	2.41	3.00	1.47
2.01	2.37	0.90	2.10	2.49	1.23	2.10	2.61	1.28
2.19	2.58	1.02	2.29	2.71	1.34	2.29	2.84	1.40
3.00	3.00	1.82	3.00	3.00	2.37	3.00	3.00	2.49

Table 4. Final design scoring

Selection criteria	Weight	30 degree - 1023 carbon steel sheet		30 degree - AISI 1020 steel cold rolled		30 degree - AISI 316 stainless steel sheet		Angle
		Rating	Weight score	Rating	Weight score	Rating	Weight score	
Weight of steel wheel	25	3	75	2	50	1	25	30
Cost of materials	40	2	80	3	120	1	40	
Stress value at joint fixture (1-9)	10	2	20	3	30	1	10	
Stress value of fin (1-9)	10	1	10	2	20	3	30	
Safety factor (1-9)	10	2	20	3	30	1	10	
Resillience in nature	5	1	5	2	10	3	15	
	100	Total	210		260		130	
Selection criteria	Weight	35 degree - 1023 carbon steel sheet		35 degree - AISI 1020 steel cold rolled		35 degree - AISI 316 stainless steel sheet		Angle
		Rating	Weight score	Rating	Weight score	Rating	Weight score	
Weight of steel wheel	25	3	75	2	50	1	25	35
Cost of materials	40	2	80	3	120	1	40	
Stress value at joint fixture	10	3	30	2	20	1	10	
Stress value of fin	10	2	20	3	30	1	10	
Safety factor	10	2	20	3	30	1	10	
Resillience in nature	5	1	5	2	10	3	15	
		Total	230		260		110	
Selection criteria	Weight	40 degree - 1023 carbon steel sheet		40 degree - AISI 1020 steel cold rolled		40 degree - AISI 316 stainless steel sheet		Angle
		Rating	Weight score	Rating	Weight score	Rating	Weight score	
Weight of steel wheel	25	3	75	2	50	1	25	40
Cost of materials	40	2	80	3	120	1	40	
Stress value at joint fixture	10	1	10	3	30	2	20	
Stress value of fin	10	2	20	3	30	1	10	
Safety factor	10	2	20	3	30	1	10	
Resillience in nature	5	1	5	2	10	3	15	
		Total	210		270		120	

In the results of the indexation rating, the equal stress value was obtained so that it would get a high rating value if the yield stress was greater.

4 Conclusion

This study represents in sequence steps of final design selection with consideration of the types of material, cost, and stress value of the tractor driving wheels. The fin angle variable is simulated to determine the resulting stress performance. So that the stress value is a comparison and becomes a determining assessment criterion. The results show that among the 9 design variables, tractor wheels with AISI 1020-steel cold rolled material with an angle of 40° have a weighting score of 270 the highest among others. So that the design is most suitable for tractors with clay shear stress characteristics in this study.

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