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Improvement of Jaw Crusher Design by DEM & FEA Approach

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Abstract - Jaw Crushers are used as primary crusher at quarries, mines, and concrete recycling operations. Rocks, Rubbles and Slags are broken into small particles in jaw crusher under the high pressure exerted by moving and stationary jaws of crusher.
Crushing Pressure created by jaw crusher depends on design parameters such as; drive shaft eccentricity distance, toggle plate position, drive shaft revolution speed etc. In this study, Discrete Element Method (DEM) and Finite Element Analysis (FEA) approaches are used to obtain optimum design for crushing performance of crusher and the operation of the crusher for various type of materials. DEM & FEA approaches are applied as coupled to investigate both the crushing force occurring on broken materials and the reaction forces on toggle plate, drive shaft, support points. Computer aided DEM & FEA approach simulation results are verified with experimental stress measurements applied on prototype crusher.
Results are given in force and gradation graphs and discussed in terms of optimum parameter design.

Index Terms - Discrete Element Method, Finite Element Method, Jaw Crusher, Experimental Stress Analysis.

INTRODUCTION

Jaw Crushers are classified in the group of Pressure Type crushers due to its material size reducing technique. They are generally run as primary crusher to carry out first crushing operation at high pressure on rocks, rubbles & slags [1], [2]. Also, they are named depending on the maximum size of material crushed in the jaws. In this study, jaw crusher, which have capability to crush material size of 1100 mm is examined.
Jaw Crushers consists of main components named as stationary jaw, moving jaw, toggle plate and eccentric drive shaft. They run with four bar mechanism principle as it shown at Fig.1.

Fig. 1

Components of the four-bar mechanism are eccentricity at the drive shaft, moving jaw and toggle plate. Dimensions and positions of the four-bar components have vital impact on crusher and operation performance.
The components dimensions and positions are directly related with pressure exerted by crusher and energy consumed at the operation.
On the other hand, crushed material (ore) breakage characteristic is another variable which effect the crusher
performance and design. Generally, JK Tech AB-T10 method [3] or Tavares Breakage Model Approach [4], [5], [6] are applied to obtain fragment distribution and minimum energy level necessary to start fragmentation on the material.
Considering this information, jaw crusher design procedure can be classified in two steps as, design of jaw crusher kinematics and design of jaw crusher pressure force.
In present studies, these two cases were analyzed. In this study, coupled working forces created by kinematics of crusher and crushing process were analyzed as transient by ANSYS Mechanical and ROCKY DEM integration.
Research is divided into two main steps. At first step DEA (Discrete Element Analysis), FEA (Finite Element Analysis) and Kinematics of Jaw Crusher were examined by simulations hold by ROCY DEM 4.3.2 and Ansys Mechanical 19.2. At the second step, experimental stress analysis has been executed on prototype crusher to compare actual results with simulation and analysis done at first step.
At the first step of study, reaction forces and moving curve of the components are obtained by kinematic solution of jaw crusher mechanism for various cases. Depending on the kinematic solution results, geometries used at DEA have been designed and crushing simulations were run at ROCKY DEM 4.3.2 software. Also, forces on the moving jaw and fragmentation distribution of

the crushed material are the outputs of the crushing simulation. Forces on the jaw crusher obtained from ROCKY DEM simulation results have been imported into ANSYS Mechanical to simulate the effects of kinematic and crushing forces as coupled on the jaw crusher component. Stresses on the components of jaw crusher, and the fragmentation distribution of crushed material have been obtained for different conditions at the first step. Also, the reaction forces occurring on the joints due to crushing forces and kinematics of jaw crusher have been obtained and of simulation.
The study is aimed to apply a new approach at jaw crusher design via integration of ROCKY and ANSYS software. Parametric simulation capabilities of the ANSYS Workbench were used to obtain optimum component dimensions depending on the simulation and analysis results.
Furthermore, energy consumption and the crushed material gradation distributions are important design parameters either, so these have been considered as design criterion to define optimum working conditions and service life.

THEORY

In this work, kinematic analysis, bulk material motion and breakage analysis are adopted. Firstly, kinematic analysis is used and then from obtained results DEM analysis performed. Motion characteristics of the mechanism is examined by the help of the kinematic analysis. For that analysis, the loop closure equation (LCE) is written as a vectorial form [7]. In Fig.1, four bar mechanism is shown.

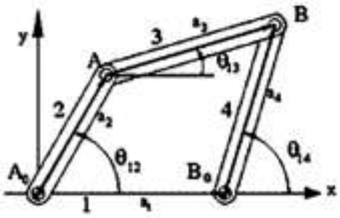


Fig 1

From LCE, equation is as follow in vectorial form:

$$A_0A + A = A_0B_0 + B_0B$$

In terms of complex number:

$$a_2e^{i\theta_{12}} + a_3e^{i\theta_{13}} = a_1 + a_4e^{i\theta_{14}}$$

From above definition, two equations could be derived. One is obtained from the imaginary part and other one is from the real part. a2, a3, and a4 are the constant values. However, θ_{12}, θ_{13} and θ_{14} does not known. There are 3 unknowns but there are only two equations. In order to overcome this problem, one of the angles should be eliminated. After solving equations, the final equation will be as:

$$\theta_{14} = 2tan^{-1}\left[\frac{-B \pm \sqrt{(B^2 - 4AC)}}{2A}\right]$$

Where;

$$A = \cos\theta_{12}(1 - K_2) + K_3 - K_1$$
$$B = -2\sin\theta_{12}$$
$$C = \cos\theta_{12}(1 + K_2) + K_3 + K_1$$
$$K_1 = \frac{a_1}{a_2}$$
$$K_2 = \frac{a_1}{a_4}$$
$$K_3 = \frac{a_1{}^2 + a_2{}^2 - a_3{}^2 + a_4{}^2}{2a_2a_4}$$

For the simulation, kinetic analysis of the four-bar mechanism of jaw crusher are applied and then DEM simulation is considered. Also, Particle analysis is carried out on Rocky DEM ESSS software.
To understand behavior of the bulk solids numerically, DEM method is used. Behavior of the bulk solid include both phenomena solid and fluid motion. In DEM method, motion of each particle is related to the time. Detailed schema of Rocky DEM ESSS is shown Fig.2 [8].

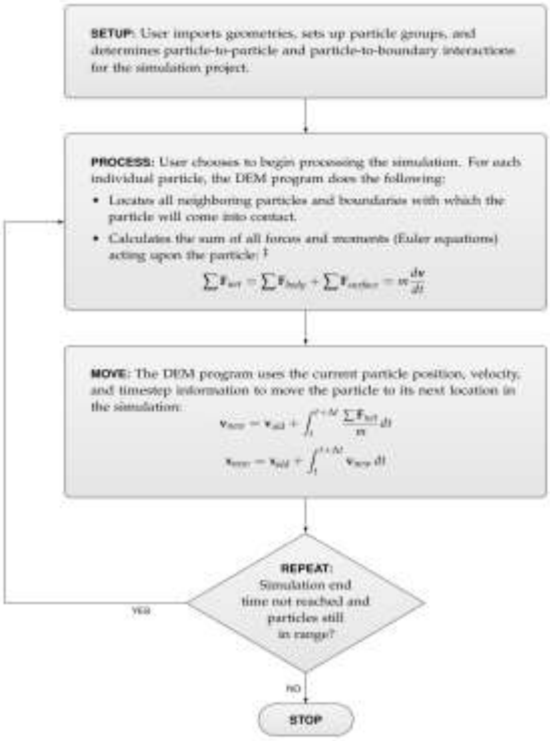


Fig 2

In jaw crusher, another important analysis is breakage of the particle. In particle breakage model, two types of approach are used widely which are Ab-t10 and Tavares model. In this work, Ab-t10 model is used. Ab-t10 model is developed by the Julius Kruttschnitt Mineral Research Centre (JKMRC) [9]. The Ab-t10 particle breakage experiment is performed according to Voronoi Fracture algorithm. Value of t10 is accepted as a thinness and breakage index.

Behavior of the particle impact rapture could be characterized by using t10. When a relation between t10 and specific breakage energy is established, specific energy consumption could be estimated by the particle size distribution which obtained from t10 values. t10 value is calculated by formula below:

$$t_{10} = M[1 - \exp(-\frac{Se_{cum}L}{L_{ref}})]$$

Where, M is maximum t10 value and S is Selection function coefficient. In addition, these values are estimated by JKtech's drop weight test and these values differ for each material [10], [11],[12].

GEOMETRY AND SIMULATION SETUP

Fig.3 shows the configuration of the jaw crusher and geometrical and operation parameters are given in Table 1. Jaw crusher mainly, consist of moving jaw, eccentric shaft, flywheel and toggle plate. The jaw has specific motion to break feed material by the means of eccentric shaft. while jaw width is 1100 mm, gaps from upper side is 650 mm. Other most important parameter is the type of the gradation. Properties of gradation and size distribution are given in Table 2 and Table 3 respectively. Also, polyhedron shaped gradation (Fig.5) is selected. Its vertical and horizontal aspect ratio are 1.5 and 0.75 respectively.

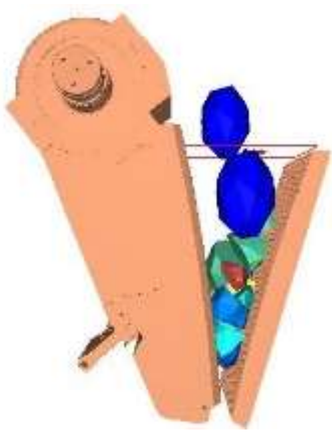


Fig 3

Table 1 **Particle Size Distribution**

Parameters	Values
Feed rate (t/h)	700
Speed of flywheel (rpm)	200
Eccentric shaft (mm)	15,20,25
Moving Jaw (mm)	1089
Toggle Plate (mm)	230, 225, 220

Table. 3

Size (mm)	Cumulative (%)
500	100
300	40
200	30
100	20
50	10

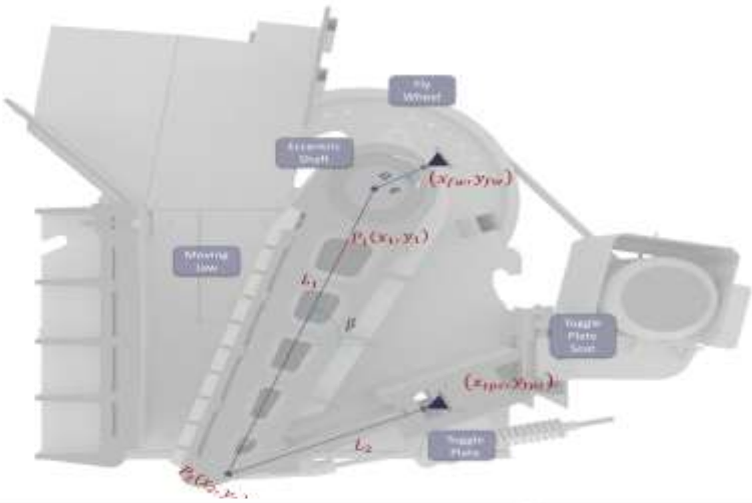
Table 3

Parameter	Value	
	Particles	Crusher
Density (kg/m^3)	1500	7850
Young's Modulus (GPa)	10	100
Poisson's ratio	0.3	0.3
Static friction particle to crusher	0.3	
Dynamic friction particle to crusher	0.3	
Restitution Coeff. particle to crusher	0.3	
Static friction particle to particles	0.7	
Dynamic friction particle particles	0.7	
Restitution Coeff. Particle to crusher	0.3	

Fig 4

In addition, kinematic simulation is in ANSYS Workbench and coupled with ROCKY DEM. All numerical solutions were performed in workstation. Computer has properties such as TESLA V100 GPU 3.8 GHz and 208 GB RAM. Average solution time is 38 hours, and 5 different cases are examined in total.

Fig.6



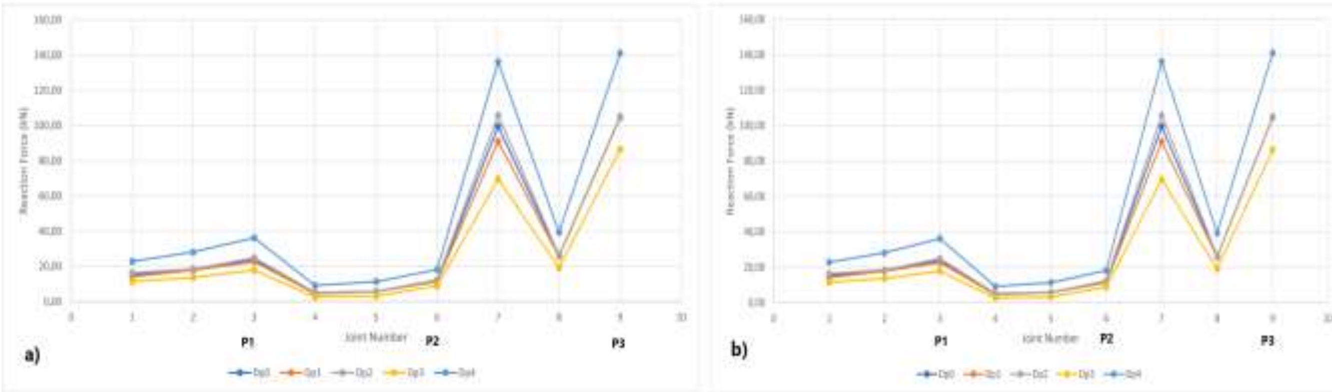


Fig. 7

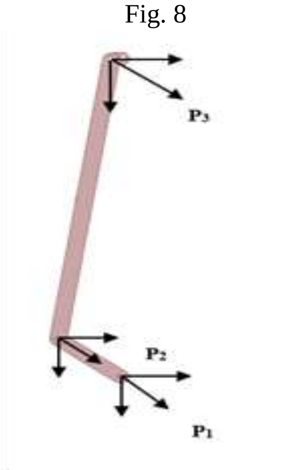
RESULT AND DISCUSSION

As it has already mentioned at introduction part, simulations performed at two steps. Joint reaction forces due to the kinematics of the various jaw crusher geometries was obtained at the first step. Crushing simulations are realized on selected geometries, depending on the results of the first step. The effects of the parameters on it were examined. optimal working parameters were obtained to increase efficiency and service life.

A. *Kinematic analysis.*

In order to determine positions of the joints, kinematic analysis was performed. Eccentric shaft (e), moving jaw (L_1) and toggle plate (L_2) was considered as four-bar mechanism which is presented at Fig.9. Also, to describe motion of the linkages, four-bar mechanism was modelled.

Fig. 8



To determine best dimension, eccentricity distance and toggle plate linkage was assigned as parametric in ANSYS Rigid Body Dynamics. Before performing analysis, real size mass and inertial forces were assigned to linkages.

Two case of the four-bar mechanism were examined. For each case, parametric analyses were performed to examine 3 critic joint's reaction forces. Examined joints were presented in Fig 6. Parametric dimensions are given in Table 1. Also, 5 different combinations were examined for each case and there are 10 different combinations in total.

The first case is called as support from lower which is demonstrated in Fig.7a. Fig.8 represent reaction 9 reaction forces for the three joints. Forces in X, Y direction and total reaction forces were shown. Five combinations were examined. Firstly, for the default dimension, reaction forces of P_1, P_2 and P_3 were obtained which are 23.6 kN, 11.82 kN and 104.79 kN respectively. Highest reaction force occurred in eccentric joint which is nearly 110 KN. Secondly, the length of the toggle plate was extended and reduced by 10 mm. However, changing length of the toggle plate did not changed reaction forces. Secondly, effects of the eccentric shaft linkages length were examined. The next modified parameter is eccentric shaft linkage. Eccentric linkage length reduced by the 5 mm and the reaction forces were increased at all joints. Joints P_1 and P_2 were increased by 53.6% but P_3 increased by 34.6 % which is nearly 140kN. Moreover, length of it reduced by 10 mm. Reaction forces at all joints were decreased. While reaction forces decreased by 24.4% and 24.3% respectively at joints P_1 and P_2, it is decreased by 17.5% at joint P_3.

Fig. 10

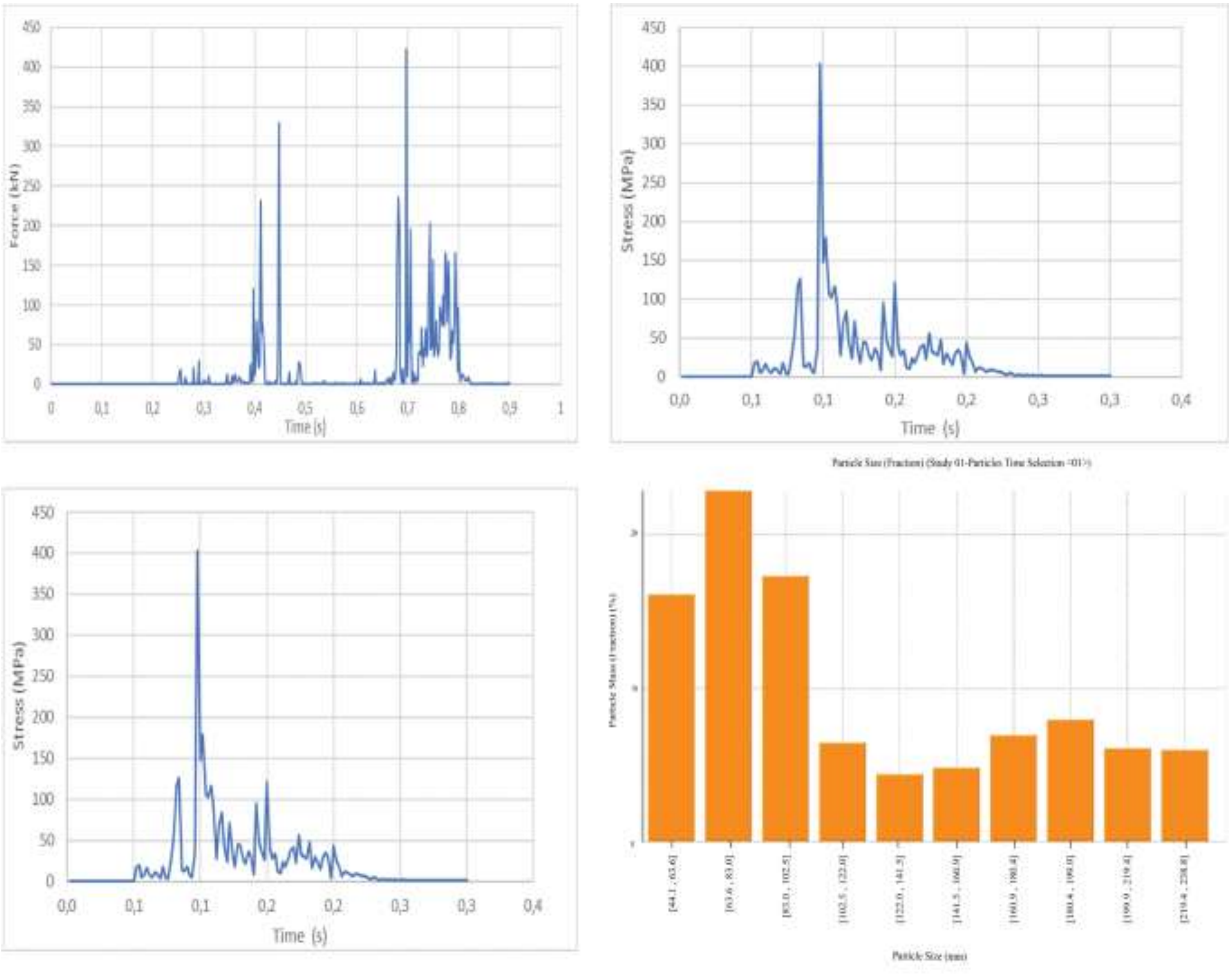


Fig. 11

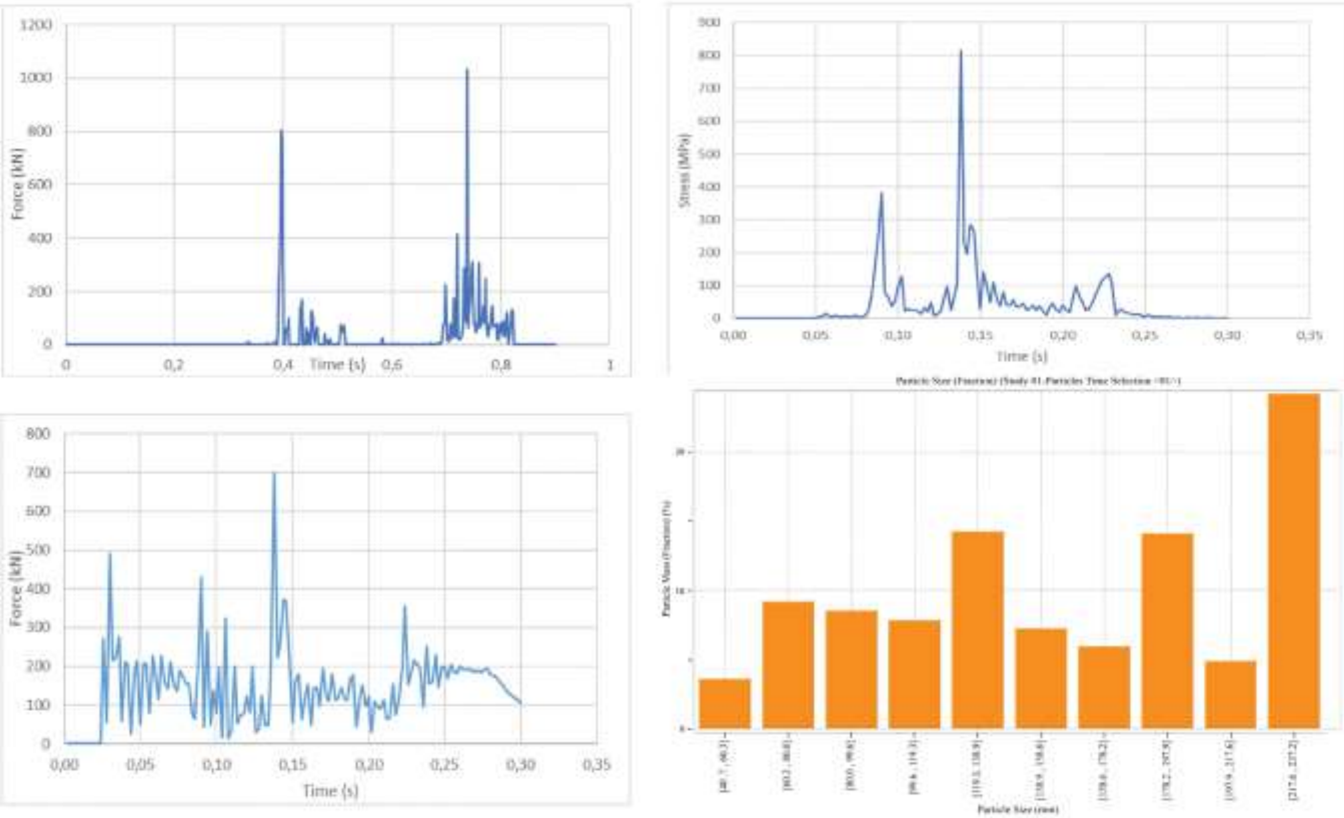
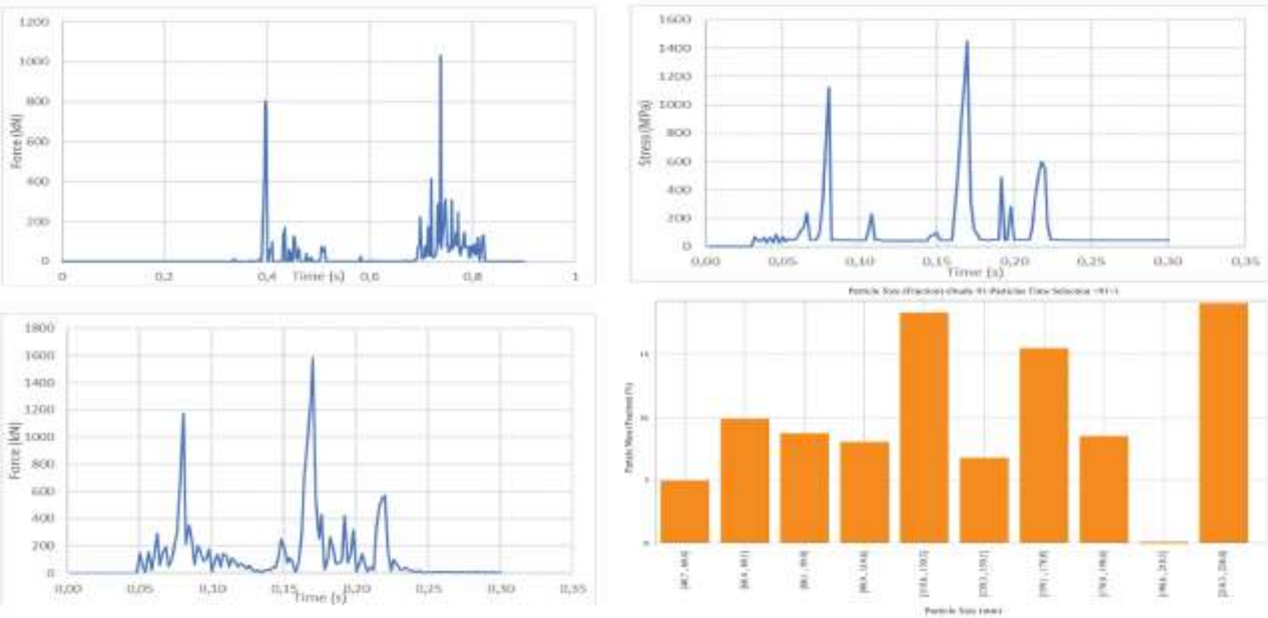


Fig. 12



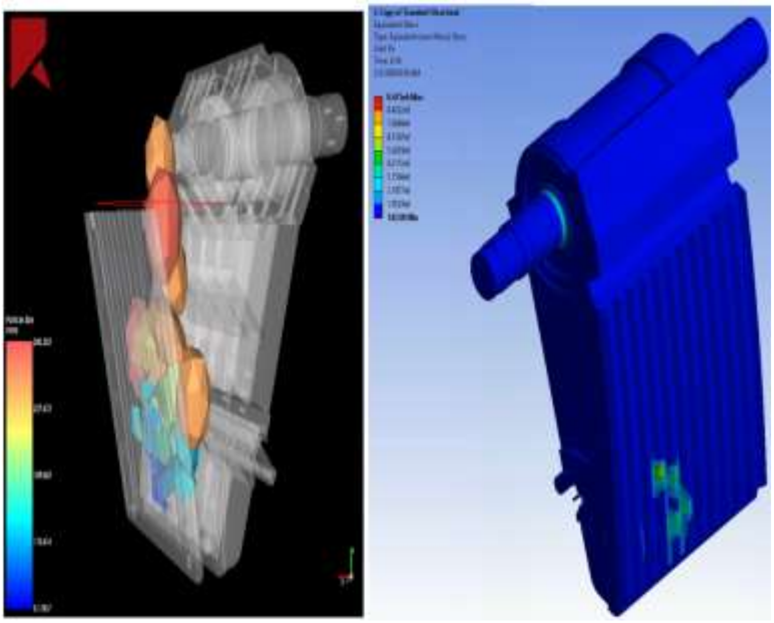
The second case is called as support from upper as shown in Fig.6b. Five combination were examined as well as in the first case. For the default linkage lengths, reactions forces are 17.96 kN, 17.9 kN and 63.71 kN. As, changing length of the toggle plate didn't affect reaction forces at joints. However, changing the length of the eccentric linkage affects reaction forces as well as in the first case. Adding 5 mm to the eccentric linkage, reaction forces increase almost by 34% for each joint. Meanwhile, adding to 10 mm to this linkage, reaction forces increase almost by 73% at joints P_1 and P_2 while 67.8% increase is observed in joint P_3.
As comparing both cases, it is clear that, there is large effects compared to toggle plate linkage when length of the eccentric linkage.

B. Crushing Simulation Results

Depending on the kinematic simulation results, four bar mechanism which the toggle plate supported from bottom side type was studied at crushing simulation which is visually described in Fig.13.

It is come out from kinematic simulation that, toggle plate length has not important effect on reaction forces occurring on joint so that toggle plate length is used as constant. However, eccentricity distance on the drive shaft has important effect on the reaction forces occurring on the joints. Hence, the effect of the drive shaft eccentricity was examined on the crushing performance and the jaw crusher components stresses under the loading.

Fig. 12 and 13



Firstly, the jaw crusher was simulated with 15 mm eccentricity distance and the forces on the toggle plate, stresses on the moving jaw, crushing gradations results obtained with the help of Rocky DEM and Ansys Mechanical integration (Fig.10).

Secondly, the jaw crusher was simulated with 20 mm eccentricity distance and the forces on the toggle plate, stresses on the moving jaw, crushing gradations results obtained with the help of Rocky DEM and Ansys Mechanical integration (Fig.11).

Thirdly, the jaw crusher was simulated with 25 mm eccentricity distance and the forces on the toggle plate, stresses on the moving jaw, crushing gradations results obtained with the help of Rocky DEM and Ansys Mechanical integration (Fig.12).

The simulation results done by integration of Rocky Dem and Ansys Mechanical are summarized at Table.4.

According to simulation results, increasing of eccentricity distance have not improving effect on crushing gradation while it is causing high reaction forces. The reason of this situation is detected as, higher eccentricity in drive shaft increase stroke length at the tip of moving jaw hence bigger

Simulation Results

Simulation No	**1**	**2**	**3**
Eccentricity (mm)	15	20	25
Avg. Stress (MPa)	32	52	122
Avg. Toggle Plate Reaction Force (Tons)	12	16	20
Crushing Gradation (mm) |		**%**	
40-60	16	4	5
60-80	22.5	9	10
80-100	16.5	8	9
100-120	6	7	8
120-140	5	15	18
140-160	5	8	8
160-180	7	7	15
180-200	8	15	8
200-220	7	5	0
220-240	7	22	19

Table 2

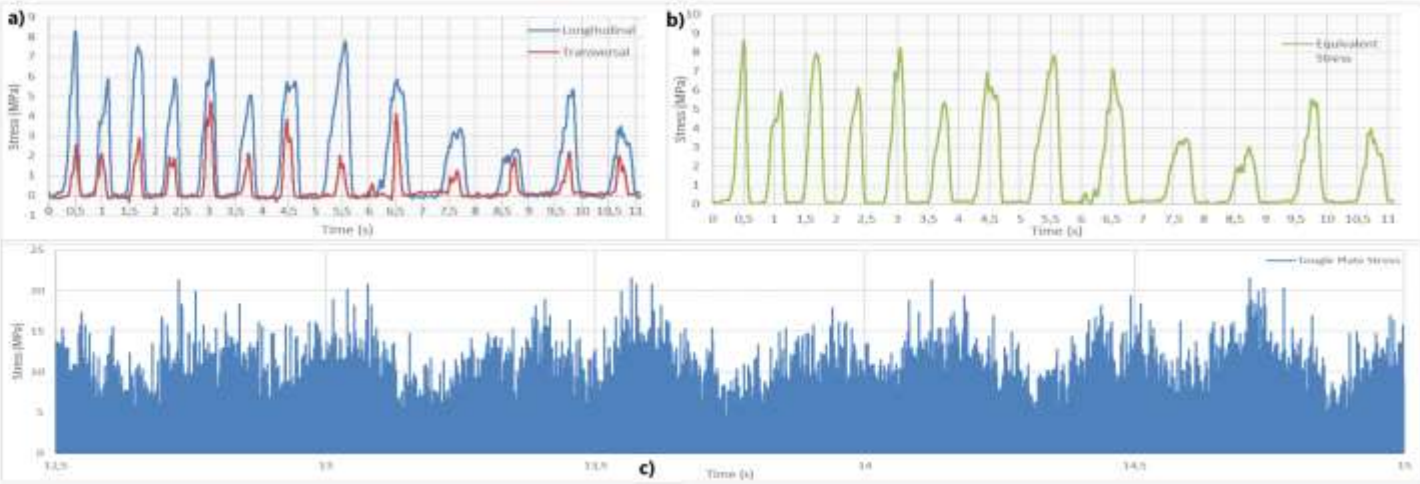


Fig 14

size of materials leaves the crusher. On the other hand, it is understood from the results, higher eccentricity in drive shaft is obviously causing higher forces and stresses on the components due to this reason service period of the crusher is shortening.

The most desired crushing gradation results and reaction forces were obtained at the case 1, where the eccentricity in drive shaft is 15 mm. It is understood from this study that, higher eccentricity lengths have negative effect on both crushing performance and reaction forces.

STRESS MEASUREMENT

Depending on the simulation results, prototype jaw crusher design has been completed and stress measurements on the machine has been done by DEWE 43-A data acquisition system.

Strain gauges were mounted on toggle plate and moving jaw to obtain equivalent stress values. Due to the loading types, toggle plate's strain gauge was mounted at longitudinal direction and moving jaw's strain gauges mounted on back side at both longitudinal and transverse directions.

Stress measurements results are representing at Fig. 14 and the stress analysis results at the points where the strain gauges were mounted on machine are representing at Fig. 15.

Fig 15

According to the stress measurement results at Fig.14a, the stresses on the moving jaw's toggle plate connection region is fluctuating in the range of 4 MPa – 9 MPa. Also, the stress measurement results at toggle plate are representing on Fig.14b and it is seen that stress values on the toggle are fluctuating in the range of 6 MPa – 23 MPa.

As mentioned in Fig.14c stress analysis results at related points on moving jaw obtained at 7 MPa – 8 MPa range. Additionally, the stress analysis results on the toggle plate are around 20 MPa – 26 MPa range.

Based on the stress measurement and analysis results, it is seen that the stress values on the operating jaw crusher components are converging to simulation results as shown Fig16. However, higher large stress jumps observed in simulation result. The main reason is that high stresses are occurred at material crushing contact point which measuring those points by strain gauge is not possible.

CONCLUSIONS

Consequently, the outputs of simulations hold on with the help of Rocky DEM & Ansys Mechanical integration are coherent with experimental stress measurement results. These results showing that, FEA and DEA techniques are appliable at the design of jaw crushers.

The aim of the study was that examining of the moving jaw, toggle plate and effect of eccentricity on the crushing operation.

However, obtained logical results showing that design of other components of the jaw crusher can be studied with DEA & FEA techniques in future works.

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