A Novel Clamp on a Trackless Forging Manipulator and Its Mechanical Characteristics Analysis

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Abstract: A novel clamp of a trackless forging manipulator is proposed. The assembly model of the forging manipulator with the novel clamp is built with software of Solidworks. In order to increase the stability of clamp, single-layer clamp of forging manipulator is changed into double-layer clamp. Inner clamp and outer clamp can be controlled by their own driving cylinder separately. The mechanism of rotate base is designed. The structure interference checking for the forging manipulator with the novel clamp is carried out. Stresses and deformations of main parts of the clamp, such as clamp arms, pin and draw ring are all analyzed. The strengths of main parts of clamp are proved to be satisfied the demand.

Keywords: Forging Manipulator, a Novel Clamp, Pin, Draw ring, Mechanical characteristics

1 Introduction

Forging production plays an important role in equipment manufacturing. The proportion of forged parts in all industries is very large, accounting for about 85% in the aviation industry, 80% in the automotive industry, 90% of electrical and instrumentation industries, 70% of agricultural machinery production industry [1-3]. With the development of precision forming and no less cutting technology, the manufacturing industry pursue reducing production costs, improving product performance and quality. The need for efficient forging equipment is increasing [4-5].

Forging manipulator is one of important auxiliary forging machines during forging production. Auxiliary forging machine in forging production is relatively used for a long time. There are two main types of forging manipulator, the orbital manipulator and the trackless operator.

In general, the orbital manipulator can be divided into three forms: full mechanical manipulator, all-hydraulic manipulator and mechanical hydraulic hybrid operating machine. The most current application is the track type forging manipulator.

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Trackless manipulator is flexible in operating with a larger range. It can not only service for forging operation, but also can work for a workshop, both inside and outside transportation.

But almost every forging manipulator have not the function of discharging forging blank from heating furnace. The processing of charging and discharging is finished by extra charge machine or discharge machine [6,7]. Therefore, preparation time before forging is prolonged and production efficiency decreases. Moreover, it puts forward a higher requirement for space and investment of workshop when forging manipulator and charge/discharge machine coexist.

In this paper, a novel forging manipulator is proposed in order that it can withstand the multiple functions including assistant forging, charging and discharging. The novel clamp design of the manipulator is carried out on the base of calculation of clamping force. The structure interference checking is finished after the model of forging manipulator with a novel clamp is built. The stress and displacement of main parts, such as clamp arms, draw ring and pin, are analyzed with software.

2 Novel clamp Design of the manipulator

The main function of the manipulator is to hold the work-piece.The clamping device of forging manipulator is mainly composed of tension mechanism and clamp.

2.1 Calculation of clamping force

The calculation of clamping force required by the operator is generally calculated according to the balance of force and torque according to the maximum weight (G)and the longest work-piece (holding torque M). But, the clamp is often rotating in the working process of the manipulator. Clamp position is always changing. So the stress of the clamp is constantly changing. The clamping force is also different. Therefore, clamping forces for the various location should be calculated in order to take the maximum force as design load. For the sake of simplicity, this paper only discusses the clamp level and vertical position.

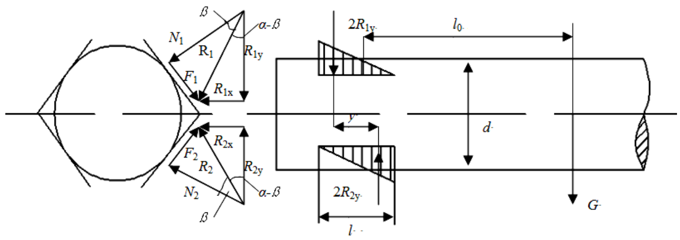
2.1.1 Calculation of clamping force in horizontal position

When the clamp locates in horizontal position (shown in Fig.1). $N_1$is the force from upper half camp and N_2 lower half , F_1 and F_2 are friction between clamp and work-piece.$R_1$and R_2 are the counter-force respectively from upper and lower parts of the jaws.$R_{1y}$and $R_{2y}$are vertical component of R_1 and R_2 respectively. Moment balance can be obtained by (Fig.1b).

$$2R_{1y}\text{-}G(l_0\text{-}\frac{y}{2})=0 \tag{1}$$

$$2R_{2y}\text{-}G(l_0+\frac{y}{2})=0 \tag{2}$$

Where, 1_1 is the distance between the center of the forgings and the center of the clamping pin shaft; y is the axial distance between force N_1 and N_2, generally, y = (1/2～2/3) l (width of jaw).



(a) **(b)**

Fig. 1. Clamping at horizontal position

R_{1y} and R_{2y} can be got from equation (1) and equation (2).

$$R_{1y}=\frac{2l_0-y}{4y}G \tag{3}$$

$$R_{2y}=\frac{2l_0+y}{4y}G \tag{4}$$

R_{1x}、R_{2x} can be got from Fig.1 (a).

$$R_{1x}= R_{1y}\tan(\alpha\text{-}\beta) \tag{5}$$

$$R_{2x}= R_{2y}\tan(\alpha\text{-}\beta) \tag{6}$$

Where, α is the half of angle between two jaws (°), β is the angle of friction，β = arctg f，f is the friction coefficient between work-piece and jaws.

Then, clamping force in horizontal position P_h can be calculated by equation (7).

$$P_h= R_{1x}+R_{2x} \tag{7}$$

2.1.2 Calculation of clamping force in vertical position

The analysis of clamping force in vertical position is more complicated than that in horizontal position, which can be divided into two states, namely, no deflection and deflection of forging parts.

When the clamping moment $M = GL$ provided by the upper and lower jaws is not large, the forging does not deflect, and its axis coincides with the horizontal axis (shown in Fig. 2).

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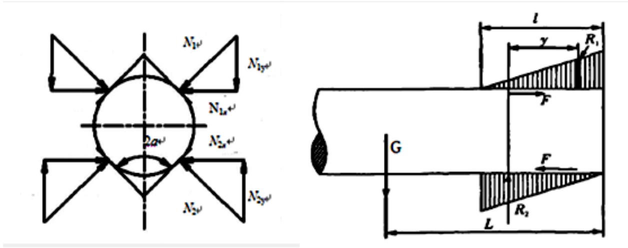

(a) (b)

Fig. 2. Clamping at vertical position

N_l and N_2 respectively indicate the positive pressure of the upper and lower jaws on forgings. N_1x, N_1y, N_2x and N_2y are the components of N_l and N_2 in horizontal and vertical directions. a represents half of the jaw Angle. L is the jaw width. F indicates the friction force between the tongs and the forge. R_1 and R_2 are respectively the force of clamping force between clamps of jaws. G is the weight of the forging. L is the distance from the center of the forging to the end of its jaws. Y is the distance between R_1 and R_2 of upper and lower clamping forces.

The following equations can be got from the equilibrium relation between the force in the vertical direction and the torque at $R_{1.}$

$$R_1+G=R_2 \tag{8}$$

$$R_2y+Fh= G\left[L-\frac{1}{2}(l-y)\right] \tag{9}$$

The diameter of work piece is d, f is the friction coefficient between work-piece and jaws. So,

$$F=2N_1f=fR_1/sin\ a \tag{10}$$

$$h=dsin\ a$$

Then,

$$Fh=fR_1d \tag{11}$$

Substitute the equation (11) into equation (8) and equation (9). The equation (12) and equation (13) can be got.

$$R_1=\frac{2L-y-l}{2y+2fd}G \tag{12}$$

$$R_2=\frac{2L+y-l+2fd}{2y+2fd}G \tag{13}$$

It can be seen from equation (12) and equation(13) that the clamping force of clamps in vertical position is related to the diameter of the work piece and the width of the jaws, which is independent of the angle of the clamps.

When the clamping moment M=GL provided by the clamps is larger, the counter-force acting on the jaws will cause the jaws to rotate around the pin shaft. Φ is the angle between axis of work piece and horizontal axis. There is a relative slip between the forging and the jaws. Then friction, f_1, f_2 are produced .The work piece and jaws rotate at the same time until the action line of R_1 passes through the pin shaft center of the pliers and stop till the action line of N_2y and f_2 passes through the pin shaft center of the clamp(shown as Fig.3).

The moment balance equation can be got as following.

$$R_1\delta_s\text{-}GL=0 \tag{14}$$

Where, L is the distance between center of gravity of work piece and the center of the lower pin.δ_s is the vertical distance between the center of the lower pin and the joint force R_1.

$$\delta_s=\delta\sin(\varnothing+\beta_s) \tag{15}$$

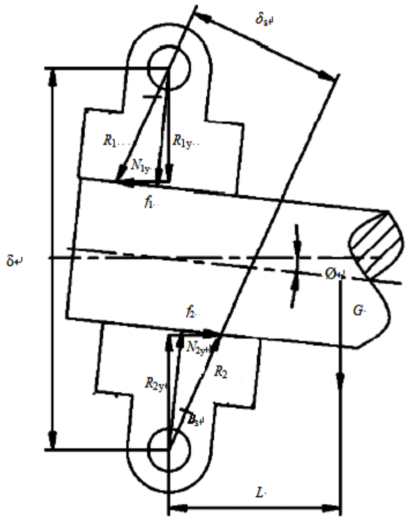

Fig. 3. The forgings stress at Vertical position

Where, δ is the distance between the pin centers of upper and lower clamp (mm). $\varnothing$ is the allowable rotation angle of work piece, $\varnothing$=0～4°. β_s is equivalent friction angle， β_s = arctan (f/sin$a$).

Equation (16) can be got from equation (14) and equation (15).

$$R_1=\frac{GL}{\delta\cdot\sin(\phi+\beta_s)} \tag{16}$$

R_{1y} can be calculated by equation (17).

$$R_{1y}= R_1\cos(\varnothing+\beta_s)=\frac{GL}{\delta\cdot\tan(\phi+\beta_s)} \tag{17}$$

R_{2y} can be calculated by equation (18).

$$R_{2y}= R_{1y}+G=\left[1+\frac{L}{\delta\cdot\tan(\phi+\beta_S)}\right]G \tag{18}$$

R can be calculated by equation (19).

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$$R = R_{1y} + R_{2y} = \left[1 + \frac{2L}{\delta \cdot \tan(\phi + \beta_s)}\right] G \tag{19}$$

2.2 Design of novel clamp

The main technical parameters of the forging manipulator are as follows.

1. The nominal carrying capacity of the work piece held by the manipulator G＝50000N；
2. Clamping torque M=75000N・m；
3. The size limit of work piece for clamping. d_{min}~d_{max}=275-740mm；
4. Clamp extension L=1400mm；
5. The speed of manipulator v=50m/min；
6. The rotate speed of jaw n=16r/min；
7. The rotate diameter of jaw D=1250mm.

The mechanics properties of material used for main parts of clamp are shown in Table 1.

Table 1. Material mechanics performance properties

Name of part	material	σ_s /MPa	[σ]/ MPa	elasticity modulus(MPa)	Poisson ratio	Density(kg/m3)
Clamp arm	42CrMo	950	527.8	2×105	0.3	7800
pin	40Cr tempering	490	272.2	2×105	0.3	7800
ring	20CrMo	685	380.5	1.9×105	0.3	7800

Clamp includes clamp arms, clamp sleeve; draw ring and slider four main elements. 3D model of each part of improved clamp is built with Solidworks software refers to the parameters of existing parts [2-4]. Clamp arm is changed from one layer to double layers with a long arm and a short arm, the hole for assembly clamp arm and clamp sleeve is changed from one to two, slider from one to two. All parts are assembled and then structure interference of the improved clamp mechanism is checked. Inner structure of novel clamp is designed and shown on Fig. 4.

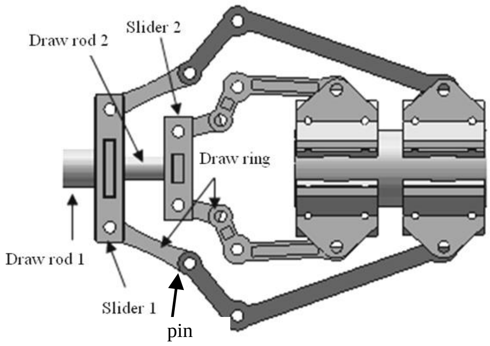

Fig. 4. Inner structure of novel clamp

Because most of forging blanks are long shafts and rods and the stability of single-layer clamp is bad, single-layer clamp of forging manipulator is changed into double-layer clamp. Shorter inner clamp and longer outer clamp working together can discharges the forging blank from heating furnace and inner clamp can clamp forging blank and transport it to forging hammer with a high operating stability and reliability. Stability of clamp increases after double-layer clamp is adopted. Inner clamp and outer clamp can be controlled by their own driving cylinder separately with separate control system.

Track of forging manipulator is changed by wheels and the type of forging manipulator is changed from track to trackless because the track forging manipulator can only move along the track and its space of operating is limited. Trackless forging manipulator can move between heating furnaces and forging hammer freely.

The forging manipulator with double layer clamps and base rotate mechanism can complete both forging manipulator and charge/discharge machine's function then charge/discharge machine can be substituted. Traditional forging manipulator is shown on Fig. 5. The novel forging manipulator is shown on Fig. 6. The structure interference checking for the virtual prototype model is done and the result of interference checking is satisfied.

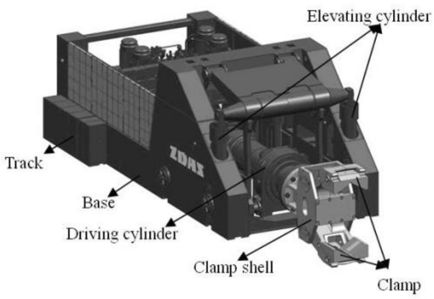

Fig. 5. Traditional forging manipulator

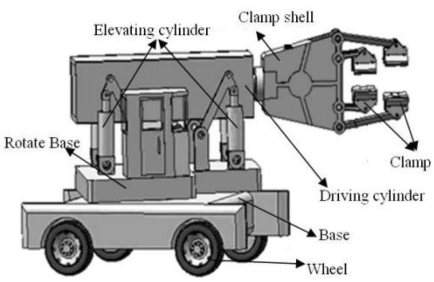

Fig. 6. Novel forging manipulator

2.3 The structure interference checking

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COSMOS motion is used to simulate the main motion of the forging manipulator with the novel clamp. Constraints are set for each component too. The motion parameters are set according to the steps of clamping-platform rotation-tongs-clamp rotation and so on. Displacement is taken as the mode of motion and expression style is adopted as the type of motion parameters setting in this paper. The setting of specific motion pairs is shown in Table2.

Table 2. Connection and parameters setting

Step	Motion morphology	Type of kinematic pair	The setting of parameters
1	Clamping by external clamp arm	rotary pair	STEP(TIME,0,0D,3,10D)
2	Clamping by internal clamp arm	rotary pair	STEP(TIME,3,0D,5,10D)
3	Rotating of platform	rotary pair	STEP(TIME,5,0D,10,360D)
4	The downward movement of the front of the clamp	sliding pair	STEP(TIME,10,0,15,-200)
5	The upward movement of the front of the clamp	sliding pair	STEP(TIME,15,0,20,-400)
6	Rotating of clamp	rotary pair	STEP(TIME,20,0D,25,360D)

The rotation pair defines the angle, the beginning time and the end time of the component rotation. For example, STEP (TIME, 0, 0D, 3,10D) in Table2 means external clamp arm rotates from 0 second, lasts for 3seconds, rotate 10°. As for sliding pair, STEP (TIME, 10, 0, 15,-200) means the front of the clamp move downward from 10^{th} second to 200mm.

While the motion of the forging manipulator with the novel clamp is simulated, one point of outside and upside of jaw mouth is selected as the reference object. The trajectory tracking diagram of the clamp is obtained shown in Fig. 7.

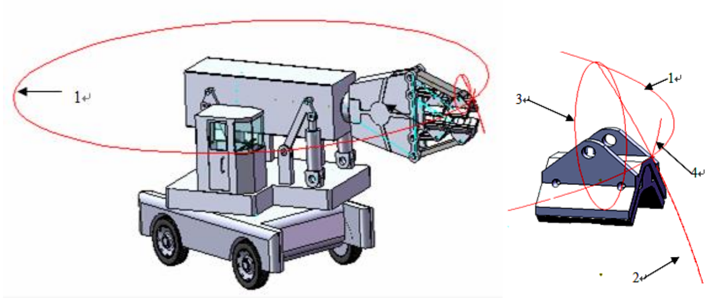

Fig. 7. The jaw track diagram of clamp

Every trajectory line on the enlarged part of Fig. 7 stands for one kind of motion style. Line1 stands for the rotation of the rotation of platform within 360^{o}. Line2 stands for the up-down motion of jaw moth following jaw rod. Line 3 stands for the rotation of jaw rotate with its own axes. Line 4 stands for the open-close motion of the jaw.

3 Modelling of Novel forging manipulator clamp

3.1 FEM analysis of novel clamp

Mechanical analysis of main parts are done on the base of novel clamp model in order to check whether the strength of novel clamp can meet the demand of work condition.

The mechanical analysis of inner clamp and outer clamp work separately bearing maximum load in vertical position are finished. Mechanical analysis of inner/outer lower clamp is done because it bears larger force than upper clamp. The FEM analysis results of inner/outer lower clamp are shown on from Fig. 8 to Fig. 11.

Fig. 8 and Fig. 9 show that the positions of maximum displacement in inner and outer clamp are identically in the joint of clamp arm and clamp mouth with pin. Maximum displacement value of outer clamp is 0.010259 mm and inner clamp is 0.002896 mm. The deformation of inner clamp is smaller than outer clamp because it is shorter than outer clamp despite of the same load in the maximum displacement position.

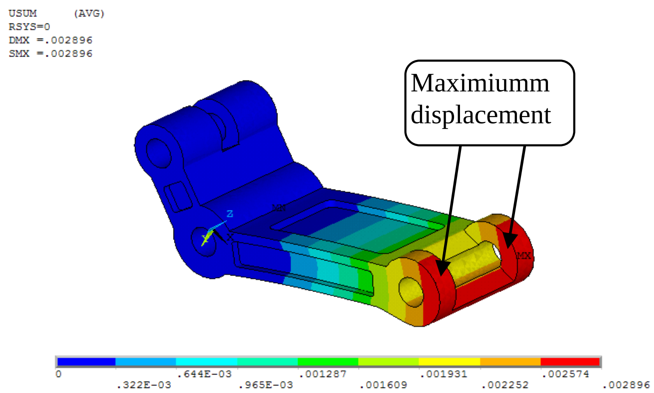

Fig. 8. Deformation distribution of inner lower clamp

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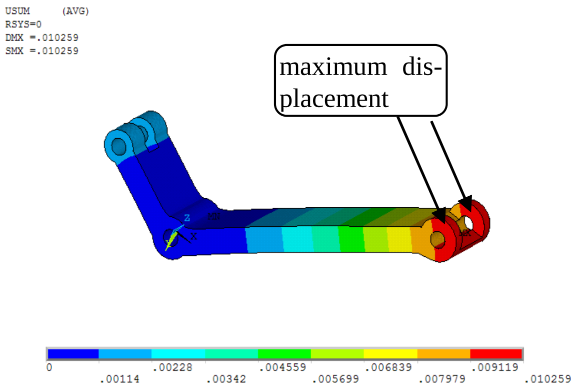

Fig. 9. Deformation distribution of outer lower clamp

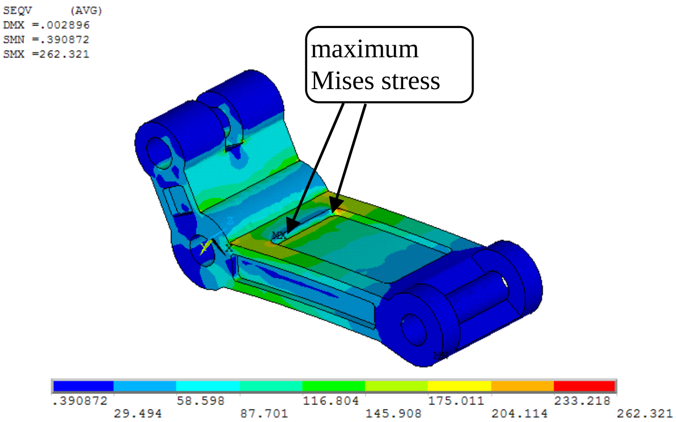

Fig. 10. Mises stress distribution of inner lower clamp

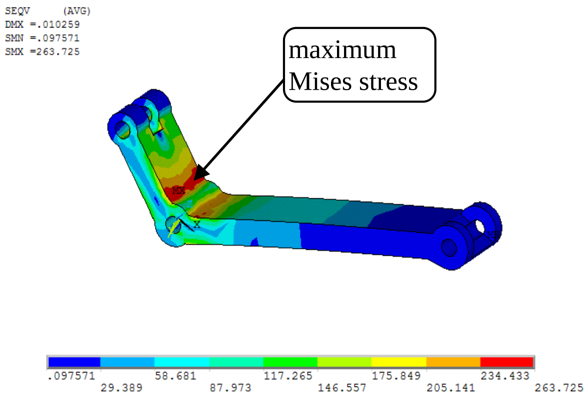

Fig. 11. Mises stress distribution of outer lower clamp

Fig. 10 and Fig. 11 show that the position of maximum stress in outer lower clamp is in the root of clamp back arm with maximum stress value 263.725MPa. However, the position of maximum Mises stress in inner clamp is in the edge of upper surface groove with maximum Mises stress value 262.321MPa. Clamp arm is made of 42CrMo whose allowable stress is 527MPa [5]. The maximum Mises stresses of inner and outer clamp arm are in the range of allowable stress and it satisfies the demand of strength.

3.2 FEM analysis of pin

The pin between clamp arm and draw ring bears shear. Especially the pin between outer lower clamp arm and draw ring bears the maximum shear. The position of pin is shown on Fig. 9. The FEM analysis results of pin are shown on Fig. 10 and Fig. 11.

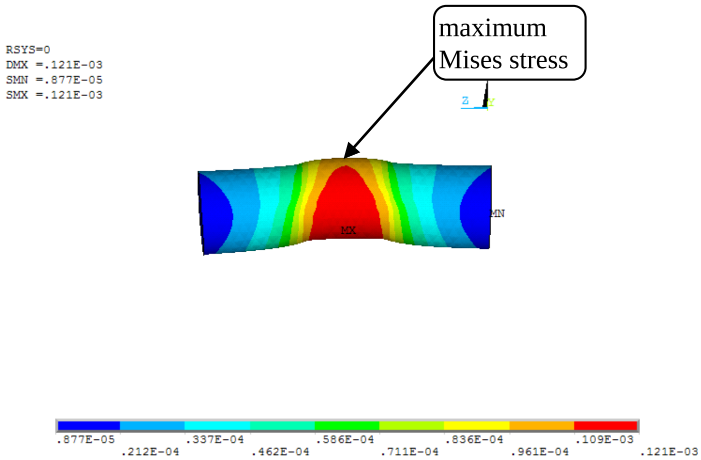

Fig. 12. Equivalent displacement diagram of Pin

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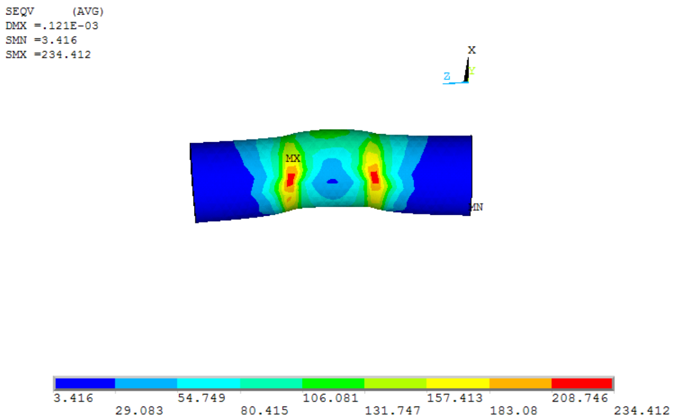

Fig. 13. Stress diagram of Pin

Pin bends along the direction of ring centre line. The maximum deformation of pin appears on the half arc surface on which pin contact with draw ring with value of 0.121 ×10-3mm. Meanwhile, the maximum Mises stress is present to the joints of pin and draw contact zone and pin and clamp arm contact zone with the maximum Mises stress value of 234.412MPa. Pin is made of quenched and tempered 40Cr whose allowable stress is 272Mpa [5]. The maximum Mises stress of pin is in the range of allowable stress and it satisfies the demand of strength.

3.3 FEM analysis of draw ring

Draw ring bears the force from drawing mechanism which draws the clamp arm rotate by pin during forging. Clamp will abnormal operate when the strength of draw ring is not enough. Therefore, deformation and stress analysis of draw ring is necessary. The maximum force locates on draw ring of lower clamp arm among all draw rings. The draw ring model of lower clamp arm is shown on Fig.12. The FEM analysis results of draw ring are shown on Fig.13 and Fig. 14.

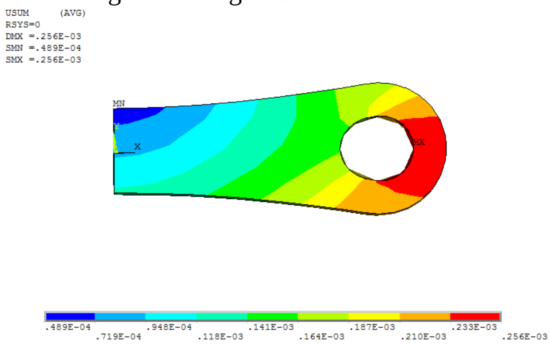

Fig. 14. Equivalent displacement diagram of Draw Ring

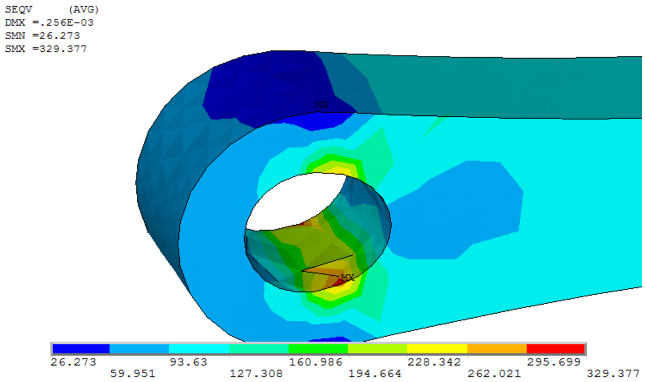

Fig. 15. Stress diagram of Draw Ring

The maximum equivalent deformation of draw ring is 0.256×10^{-3}mm and occurs in the direction of draw ring. Draw ring is elongated with the maximum elongation 0.47×10^{-3} mm. The maximum Mises stress appears on the edge of left and right half arc of circle hole surface with the maximum Mises stress value 329.377 MPa. Draw ring is made of 20CrMo which allow stress is 380.2 Mpa [5]. The maximum Mises stress of draw ring is in the range of allowable stress and it satisfies the demand of strength.

4 Conclusion

1. The result of structure interference checking for the virtual prototype model gives a proof of novel trackless double-layer forging manipulator.
2. The FEM analysis results of main parts of the clamp show that the strength of novel clamp is proved to be satisfied the demand.
3. The novel forging manipulator can be used in forging process as a multifunctional tool not only to finish assistant forging manipulator but also to take and convey work piece from reheating furnace.

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