Acta Technica 62, No. 3B/2017, 337–346

Numerical simulation and experimental research of 65Mn steel based on equal channel angular extrusion[1]

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Abstract. For agricultural machinery tools, low service life and serious wear in use, the process of 65Mn steel applied to agricultural machinery tools by equal channel angular extrusion was simulated by Deform-3D software and Solidworks software. And then , the 65Mn steel was subjected to equal channel angular extrusion (ECAE) process at high temperature, and then the effect of ECAE on microstructure and mechanical of 65Mn steel was investigated. The results show that the simulation result is consistent with the experimental data. Grain size of the 65Mn steel decreased after ECAE. The microhardness of specimens after ECAE were higher than those of specimens without ECAE . Therefore, ECAE processing can improve the organization and performances of the material.

Key words. Equal channel angular extrusion; 65Mn steel; numerical simulation; plastic deformation..

1. Introduction

Equal channel angular extrusion, referred to as ECAE ,what was developed to obtain pure shear strain, used to change the size, multiple processing and special deformation textures [1]. ECAE effectively refined grain [2]–[5]. The 65Mn steel

[1]The authors would like to thank the Funds of department of agriculture nonprofit industry research project (No. 201303011-4) and "twelfth five-year" positions scientists specific of modern agricultural industry technology system (No. CARS-04-PS23) and key research projects of higher education in Henan province (No.18B460002).

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has high hardness, hardenability better, less carbon and low prices and so on. The 65Mn steel are applied to agricultural machinery tools which are used for tillage of the soil and can provide good soil for crop production. But due to direct contact with soil, poor operating conditions and serious wear, lots of 65Mn-made parts still need to be replaced every year ,accompanied with high manufacturing costs [6]–[7]. Many scholars at home and abroad systematically carried out research to improve the 65Mn steel friction and wear properties of various processing methods, such as chemical coating [8], surface laser hardening [9], surface chromizing [10] and cladding cemented carbide [11] and conventional heat treatment process. Now surface treatment of 65Mn steel is generally used and improves the strength and hardness of surface material to some extent, but its effect is not ideal.

Due to disadvantages of instable treatment effect, inconsistent structure of surface with base material, and poor material toughness, they will affect overall performance of 65Mn steel and prevent its service life from being extended. Also, these treatments are carried out on the surface of 65Mn steel, and thus its wear resistance will degrade suddenly after occurrence of reduced superficial wear resistance or wear-out surface layer. Therefore the strength, toughness and hardness of 65Mn steel base do not only affect its mechanical properties, but also are key factors to improve its wear resistance.

In this study, 65Mn steel was prepared by ECAE, which could effectively refine the microstructure of the material and improve the mechanical properties and wear resistance of 65Mn steel.

The key to the success of the experiment is the design of mold parameters and the sample heating temperature and the extrusion routes and so on. The author uses Deform-3D software to simulate the process of treating 65Mn steel, and then carry out the experimental study to verify the simulation results. Research results are important in improving wear resistance of soil cultivating parts and extending their service life, reducing farming costs and promoting the operation level of agricultural machines in China.

2. Experimental and numerical simulation on hot extrusion molding method

The schematic diagram of ECAE was shown in Fig. 1. The mold consists of upper die, lower die and mandrel. The main process parameters of the ECAE mold include: the intersection angle Phi and the diagonal angle Psi, the outer arc radius R and the inner arc radius r. ECAE die structure parameters within a particular angle Φ and strain diplomatic setting of the angle Ψ squeeze, thus affecting the grain refinement effects.

When samples through ECAE die in two intersecting angles, pure shear deformation of specimen subjected to shear force and shear deformation of the equivalent strain effects on grain refinement. Regardless of the channel between sample and mould friction and the diplomatic angle Ψ $0°$, Segal [12] based on total strain of pure shear mechanical principles are derived the formula

$$\overline{\varepsilon_N} = \frac{2N}{3^{1/2}} \cot\Phi \ . \tag{1}$$

In the formula N is extrusion number. Then Iwahashi [13] scholars such as being credited Ψ after effects gives the following formula

$$\overline{\varepsilon_N} = \frac{N}{3^{1/2}} [2\cot(\frac{\Phi}{2} + \frac{\Psi}{2}) + \Psi\cos(\frac{\Phi}{2} + \frac{\Psi}{2}) \ ] \, . \tag{2}$$

Internal dynamic recrystallization grain size of the material caused by shear deformation, with the increase of ECAP, materials to further refine, Crystal dislocations occurred, further deformation, through grain boundary sliding and grain rotation axis can be obtained in the manner of ultra fine grain structure [14]. Enhancement of grain refinement using Hal–Perch formula [15] description

$$\sigma_s = \sigma_0 + kd^{-1/2} \, . \tag{3}$$

In the formula σ_s is the flow stress and σ_0 is the lattice friction and d is the grain diameter and k is material-related parameters and index n get 0.5.

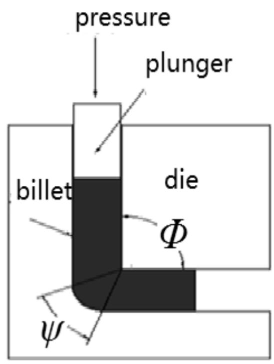

Fig. 1. Schematic illustration of ECAE die

Equal channel angular extrusion processing 65Mn Steel process was simulated to use Deform-3D Software. Equal-channel angular Extrusion die was to set up by solidworks software. Mold design three dimensional model dimensions 180 mm × 120 mm × 130 mm (see Fig. 2), the design mold channel cross section dimensions 10 mm × 10 mm. Design Interior angle $\Phi = 120°$ mold, outside corner there is a small circle, RADIUS r for 4 mm. Stencil is then transformed into *.STL file format import to Deform-3D software, simulation.

Experimental sample material for the 65Mn steel, Sample shape set 9.9 mm × 9.9 mm × 100 mm, set sample temperature 950 ℃, to automatically divide a sample grid, set the extrusion speed, design time of 8.7 seconds, design number 260, the friction coefficient 0.2.

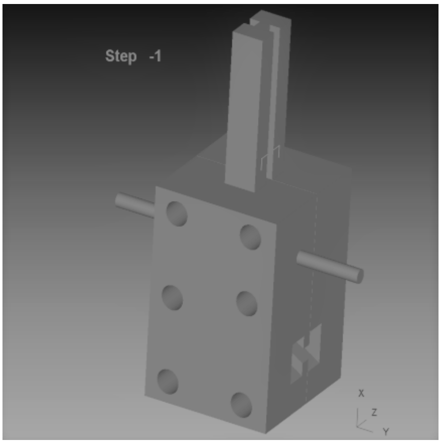

Fig. 2. The die of equal channel angular extrusion

Fig. 3. Four column hydraulic press with die assembly

In order to verify the simulation results, the ECAE die was made of 5Cr4W5Mo2 V(RM2) die steel. The experimental material was a 40 mm diameter high-quality 65Mn steel rod, which was cut into 9.6 mm × 9.6 mm × 90 mm extrusion samples by using a wire cutting machine. Grind and polish the 65Mn steel samples, and then lubricate with glass lubricant. Keep the surface-treated samples at 850 °C for 30 min, and meanwhile preheat the ECAE mould at 500 °C for 1 h. Take out the samples and the mould simultaneously, and put the samples into the mould quickly for ECAE process (see Fig. 3). Anneal the extruded samples at 500 °C.

3. Simulation results and analysis

3.1. Equivalent stress analysis

Figure 4 shows the equivalent stress distribution 90 steps of 65Mn steel extruded by ECAE. known that equivalent stress distribution is not uniform. The temperature

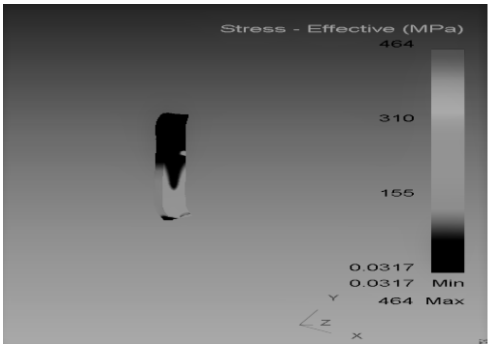

Fig. 4. Equivalent stress distribution of step (90)

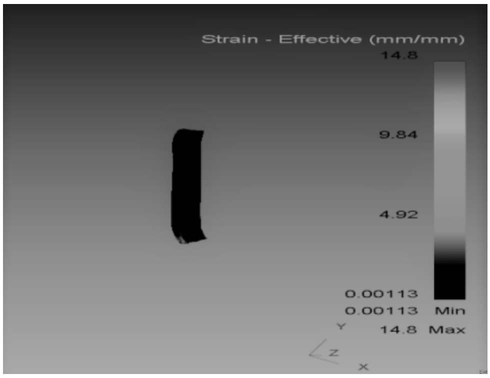

Fig. 5. Equivalent strain distribution (90)

of the sample is drastically reduced due to heat transfer during the extrusion process. Sample surface and internal by shear force is not consistent. sample has a large shear deformation at the corner of the channel. The maximum value of the equivalent stress is mainly concentrated at the corner of the channel. Maximum reach 464 MPa, which indicated that this region began to appear grain refinement. Extrusion process of friction existed between the sample and the channel, the actual experiment should pay attention to choose to use graphite lubricant to reduce friction in the channel, bear in mind the equal-channel angular set, to prevent accumulation of metal stuck in this area. This is the key to the success of the experiment. the Interior angle is designed 1200 in this test. Compression of the sample is smoothing.

3.2. Analysis of equivalent strain

Figure 5 is the 65Mn steel effect profile. 65Mn Steel head make chamfer to move out, and not uniform. The middle part of the corner after equal channel angular extrusion occurred large plastic deformation, strain reaches the maximum. The shape changes less when squeeze out. The figure shows that strain in the middle of the sample distribution is relatively uniform. Strain increase in the specimen head and tail, occurring large deformation. Internal strain distribution is relatively uniform in the middle shows material uniform grain is average.

3.3. Load analysis

As Fig. 6 shows, the mandrel is subjected to a load that change with the downward movement of the mandrel. At began due to sample also did not contact channel corner so load is zero with displacement changes. When contact with the channel angle, due to the large shear force occur, the load began to gradually increase to the final maximum, the process is the plastic deformation of the material, this figure show we provides top Rod need imposed maximum pressure, due to the factors that extrusion process temperature heat transfer and friction resistance. The load fluctuates on the graph.

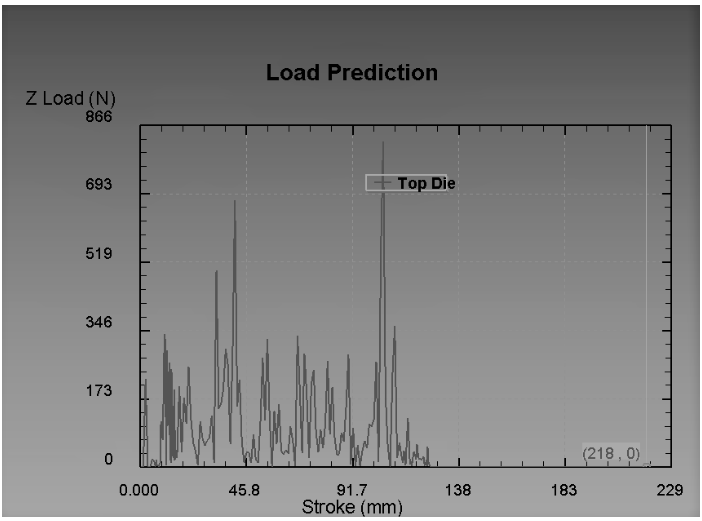

Fig. 6. Load changing with the displacement map

3.4. General level of velocity analysis

Figure 7 shows is material flow velocity profile in extrusion processes. This figure is taken to intercept the middle part of the sample to analysis. It can be seen from the figure and the flow rate is relatively uniform. The flow has been straighted, indicating that the material grain refinement is relatively uniform, in the channel corner, flow-intensive, plastic deformation began.

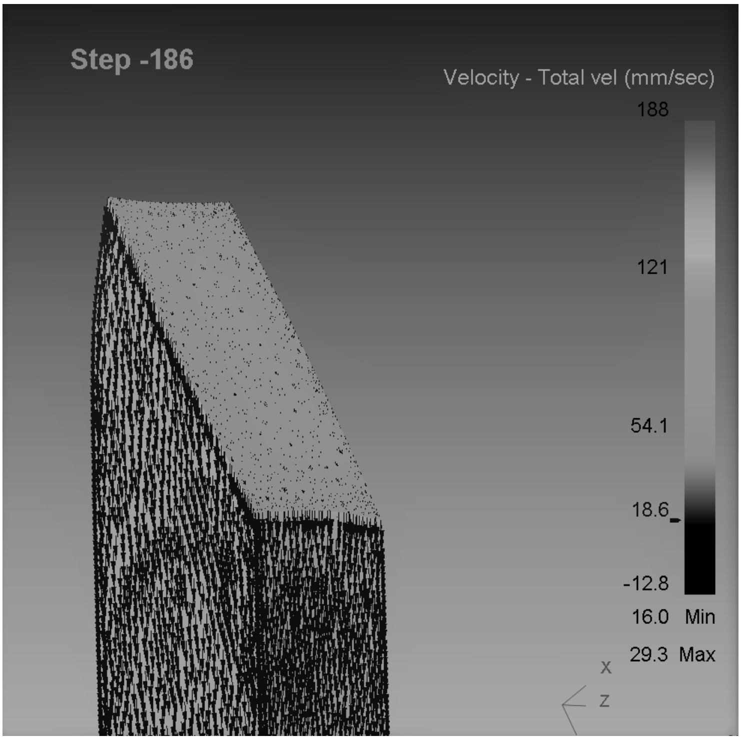

Fig. 7. Velocity distribution

4. Analysis of experimental results

4.1. Microstructure of 65Mn steels

Figure 88 shows SEM photos of samples before and after extrusion. The microstructure of samples before extrusion consists of large-size laminated pearlite and ferrite with an interlaminar spacing of 0.17 μm. When the heating temperature of samples were set to 850 °C, the internal original pearlite structure of samples after extrusion only showed significant plastic deformation, and the internal cementite structure was destroyed and resulted in fine-grained cementites with their average grain size of 0.25 μm.

After high temperature extrusion, 65Mn steel appeared in a severe plastic deformation, and its plasticity was also reduced. With the annealed cementites uniformly dissolved in ultrafine ferric matrix, the average grain size of ferrite is 0.45 μm. After samples extrusion, 65Mn steel showed grain dislocation due to shear force and resulted in crystal defects. This accelerated cementite spheroidization, initially forming lath cellular structure, then converted into sub-grain structure and finally converted into isometric ultrafine-grained structure [16].

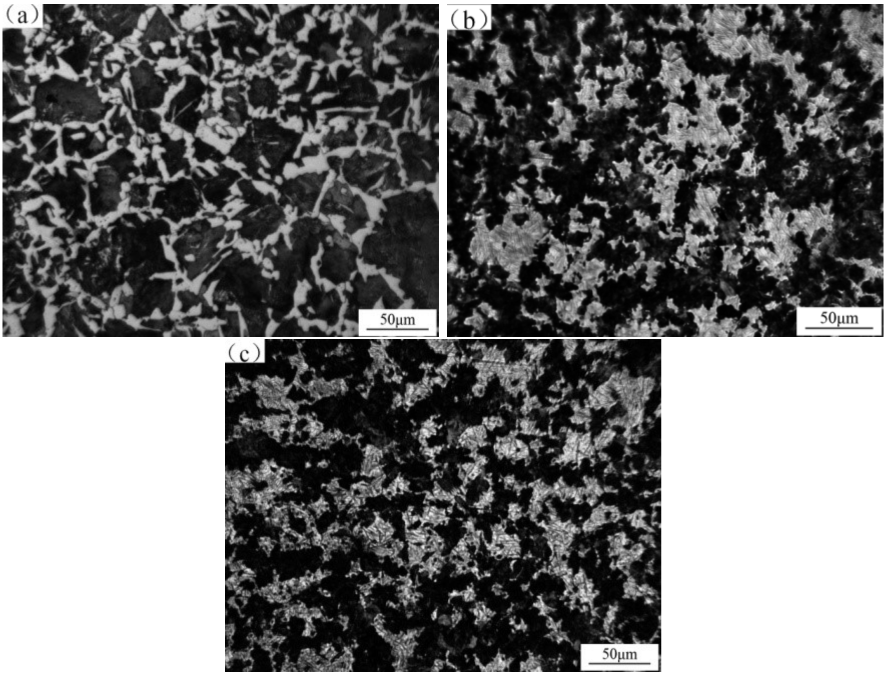

Fig. 8. Microstructure before and after extrusion
(a) Original microstructure before extrusion; (b) a cross-sectional microstructure after extrusion ;(c) alongitudinal cross-sectional microstructure after extrusion

4.2. Microstructure analysis of samples with heat treatment at different temperatures

After high temperature extrusion, 65Mn steel appeared in a severe plastic deformation, and its plasticity was also reduced. And then through the annealing, the plasticity and toughness of the samples were improved, and its chemical composition was homogenized, which also removed the residual stress, or obtained the desired physical properties. Therefore 65Mn steel by extrusion must be annealed before the application value. In this experiment, annealing was carried out at 500 ℃ and 700 ℃, and then the microstructure was analyzed.

Figure 9 shows the internal microstructure of the 65Mn steel after ECAE at 500 ℃, 700 ℃ for 1 hour. The grain defects occur due to the occurrence of large plastic deformation, With the annealing temperature change, the recrystallized grains appear before annealing at the temperature of 500 ℃. When the annealing temperature is 700 ℃, the recrystallized grains begin to grow and become coarse grain structure.

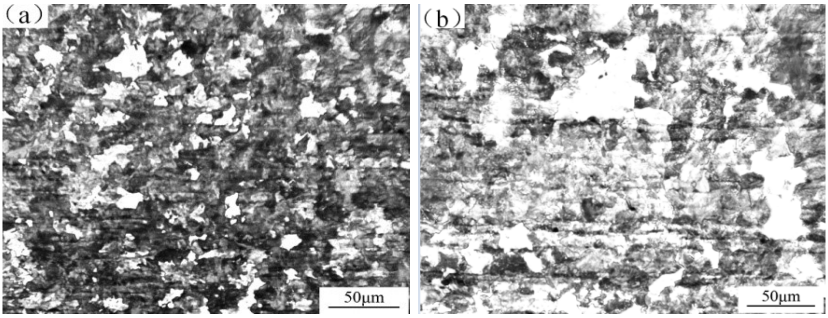

Fig. 9. The microstructure after annealing treatment
(a) annealing at 500 ℃;(b) annealing at 700 ℃

4.3. Mechanical properties of 65Mn steel

The microhardness of 65Mn steel varies significantly before and after ECAE treatment. The microhardness of samples is 305HV before extrusion and 380HV after extrusion and anneal, increasing by 25 % from 305HV to 380HV. This indicates a significantly increased hardness of 65Mn steel after being extruded.

As for the extruded sample, the microscopic structure is significantly refined with reduced grain size and increased number of grains, so its hardness is increased after extrusion. Meanwhile, 65Mn steel shows severe plastic deformation, enlarged internal dislocation density and increased lattice-distortion elastic energy during its extrusion, and thus its hardness and strength are improved with ECAE process.

5. Conclusions

1. Equal channel angular extrusion processing 65Mn steel process was to be simulated by using the Deform-3D software and Solidworks software. Numerical simulation and experimental results are consistent, show that the numerical model is viable for further research references also provide references for die design.

2. The mould internal angle size is set to 120 °.At 900 ℃ high temperature 65Mn steel was to be smooth realization of equal channel angular extrusion,who began to have plastic deformation of the channel corner, which region began to appear on grain refinement and ferrite grain size 0.45 μm.

3. The microstructures after hot equal channel angular pressing of 65Mn steel changed from mutual dissolution of Pearlite-ferrite and cementite, after 500 ℃, 700 ℃ after two temperature annealing grain recrystallization occurs, grew up. Material hardness changes before and after squeezing, hardness is improved, increased to 380 HV, relative hardness before extrusion increased 25 %.

4. The 65Mn steel rods in the experimental process, other than the head and tail,

because in the middle of the sample strain uniformity of equal channel angular extrusion, grain is relatively uniform. But due to the heat and friction factor and ECAP, local enough grain refinement, Interior and coarse grains, so this is the next step in the study process to solve the problem.

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Received August 7, 2017