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DEVELOPMENT OF A MODEL FOR PREDICTION OF DEFORMATION IN BLACKSMITH PRODUCTION OF MOULD BOARD PLOUGHSHARE PRE-FORM

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ABSTRACT
The process of producing implements by manual methods such as blacksmithing is laborious, time consuming. Despite these drawbacks, the technology remains one of the major sources of producing simple and cheaper tools and implements for many communities. This paper presents a mathematical model developed to predict and optimize the quantum of work in form of the deformation of the metal pre-form, needed by the blacksmith during the production of a mould board ploughshare. A blacksmith with body mass index of 26.5 kg/m^2 was used for the experiment to test the model. The model was analyzed using factorial design and validated using Taguchi design and regression analysis. Pre-form deformation of 14.57 x10^{-06} m and 12.42 x 10^{-06} m were obtained using factorial and Taguchi designs respectively within an average production time of 24 minutes. The results of regression analysis on the data generated using full factorial design, indicate that all constants in the regression equation were significant with $p < 0.01$, except the size of hammer with $p = 1.00$. The results showed that the model is adequate to predict the deformation of the mould board ploughshare with accuracy of R-Sq = 98.4%   R-Sq (adj) = 98.2% and error of 0.2% at 95% confidence level. The model is expected to assist in the reduction of fatigue resulting from arbitrary choice of hammer size, inappropriate height as well as unnecessary number of blows and consequently leading to improved productivity in the areas of production of agricultural, industrial and domestic tools to meet local needs.
***Keywords**: Mathematical modeling, blacksmith, ploughshare, deformation, factorial and taguchi designs.*

INTRODUCTION
Although indigenous tools and methods of manufacture are being replaced with modern ones as technology advances, they still find relevance in most indigenous African societies. Despite their short-comings in not meeting increasing consumer needs, new service conditions and material requirements, they still play important roles in the economic well-being of the people, especially the rural populace and will continue to be relevant in the lives of many Africans, most especially Nigerians. Therefore, there is the need to identify areas of further development and improvement of the production methods for improved productivity. The rural populace is applying the indigenous tools and processes in various ways, such as in agricultural as well as for industrial and domestic applications at affordable cost. In Nigeria, farmers still use manual labour and basic hand tools, such as hoes, cutlasses, machetes, and only occasionally employ labour saving tools like draught animals, plows or tractors (Takeshima and Salau, 2010). About 86 percent of the total agricultural land under cultivation in Nigeria is prepared using hand tools technology, i.e. simple tools such as hoes, machetes, sickles and wooden diggers, as opposed to draught animal technology and engine- powered technologies, which account for 4 percent and 10 percent of the land cultivation respectively (Oyedemi and Olajide, 2002). Also, a study on the use of tools and implements by women in agricultural production up to and including harvest was carried out by International Fund for Agricultural Development (IFAD) in five Sub-Saharan countries, i.e. Burkina Faso, Zambia, Uganda, Senegal and Zimbabwe (IFAD, 2011). It was found that more than 70% of food production work (planting, weeding and harvesting) was being done by women in Africa and when attempts had been made to introduce new tools for cultivation or other operations, they had often been rejected by the rural people.

This is a clear indication that introduction of new tools and methods may not necessarily have immediate acceptance or impact on the lives of the rural populace and hence improvement of existing ones may be a better option. In a survey conducted in 2007, Nigeria was ranked the 2nd poorest country in the world whereas Bauchi State was ranked 22 poorest State out of the 36 States of the country (Wikipedia, 2012). Of course, this situation has manifested itself in the various crises being faced throughout the country, particularly the North East Sub-region which could be attributed to poverty and unemployment. Therefore, any attempt to improve the living conditions of the people by enhancing the production methods used in their various trades will translate into economic growth and social stability. A lot of work has been done in the field of indigenous tools, mostly by archeologist and anthropologist (Micheal and Baba, 2009) while little work has been done by scientists/engineers.

This study seeks to develop a model with a view to improving the performance of the blacksmith and optimizing some of the production parameters: Size of hammer, Height of hammer drop and number of hammer blows during the production of a mould board ploughshare. It is expected that the model will assist in improving the productivity of the blacksmith. The productivity will be improved as it will reduce labour associated with arbitrary choice of hammer size, lifting the hammer to in-appropriate height and applying unnecessary number of blows for every type of implement produced, thus leading to fatigue accumulation, labour and time wastes. Additionally**,** local implement manufacturers do not use engineering methods and tools efficiently thereby leading to overdesigned products (Hameed *et al*., 2013). The designed moldboard ploughs which are still the most essential tillage tools in Nigeria have material and energy consuming dimensions resulting in unnecessarily cost allocation.

MATERIALS AND METHODS

Materials

The materials used for the study include:

A visual analogue display (VAD) scale (20 x 100 x 2000 mm); two-wire type-K thermocouple,{Chromel-alloy of nickel and chromium and Alumel-alloy of nickel} (-40^{o}C – 1200^{o}C); dual display digital multi-meter (MAS-345); 2.0 MP Techno digital phone camera;160 mm vernier caliper; 20 kg weighing scale; 250 kg HANA weighting scale; bevel protractor, (Lettura 5´) DELA INOX; digital counter, SX5136; 7 mm AISI 1020 mild steel plate; three sizes of hammer, 1 kg, 1.75 kg and 3.5 kg and Ablacksmith with Body Mass Index (BMI) =26.5 kg/m^2.

Methods

Ploughshare Production Process

Preliminary study of the production of the mould board ploughshare showed that it was a hand forging process, which comprises of the following stages: Pre-form cutting, heating and bending by hammering. The first stage in the production of the ploughshare is the calculation of the size of the pre-form followed by the drawing of a template. The template was then marked on a 7 mm mild steel plate and the pre-form was cut to shape. The pre-form was then heated to the desired temperature then removed from the fire and placed on a V-block. Using a hydraulic press, the pre-form was subjected to a compressive force against the V-block until it takes the shape of the V-block angle. The temperature was monitored by the use of the thermocouple and digital multi-meter. The hammer was raised to the selected height as set on the VAD and the number of blows controlled using the timer, are applied until when the pre-form took the shape of the angle on the V-block.

Determination of the Mass of the Ploughshare Pre-Form

Design of the initial piece of metal needed to produce a component (the pre-form) is one of the most important aspects in the design of the metal forming process. The design involves determination of the surface area, volume and mass of the metal plates as well as the quantity of metal plate to produce the number of pieces required. This is to enable efficient use of materials and make the process cost effective. The most commonly used material by the blacksmiths is mild steel plate of thickness ranging between 3 mm to 7 mm. For this study, a 7 mm A1020 mild steel plate was selected for the experiment. The mechanical properties of the metal are usually affected by increase in temperature thereby reducing the forging work (Kalpakjian and Steven, 2009).

The sample of the mould board ploughshare used for the analysis is shown in Plate 1 and sketched in Figure 1.

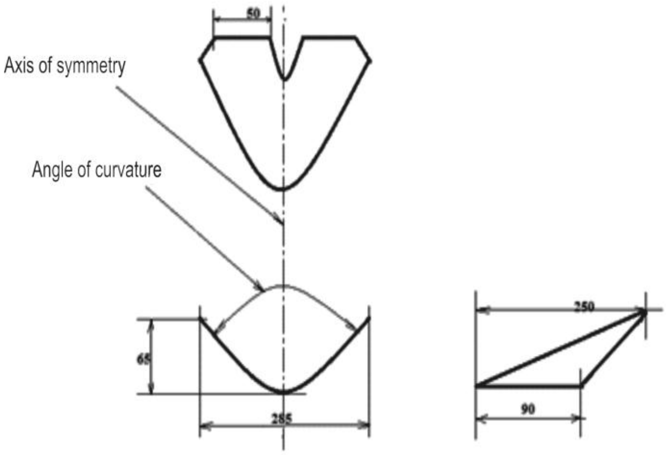

Plate 1: Sample of mould board ploughshare used for the analysis

Figure 1: Schematic diagram of the animal-drawn mould board plough share

The dimensions of the ploughshare were obtained by determining the average measurement of three samples obtained from different sources, while the approximate volume, V of the metal needed to produce a mould board ploughshare was obtained by calculating the surface area of the pre-form cut from the template and multiplying by the thickness of the metal plate.

Volume of pre-form metal plate, V = 258475 mm^3 while the approximate mass of the pre-form, $M_s = \rho V$ = density of mild steel x volume of share=

$$7850 \times 258475 \times 10^{-9} = 2.03 \text{ kg} \quad (1)$$

Experimental Design

The full factorial design is an experimental design that requires a large number of experiments to be carried out in order to determine the most desirable combination of parameters along with the significance of each. This method is laborious, complex and uneconomical. To overcome this problem Taguchi suggested a specially designed method that uses set of orthogonal arrays (OA) to study the entire parameter space with lesser number of experiments to be conducted. Initially it was developed for improving the quality of goods manufactured and later its application was expanded to many other fields in Engineering, such as Biotechnology. Taguchi method is effective and more popular in industries, as the OA approach considers the entire parameters with lesser number of trials or experiments, as compared to other methods (Krishnaaiah and Shahabudeen, 2012). Additionally, Taguchi method uses the loss function approach for the measurement of the performance characteristics deviating from the desired value. These values of loss functions were converted to S/N (Signal-to-noise) ratio, which was used to allow control of the response as well as to reduce the variability about the response. ANOVA was used to calculate the statistical confidence associated with the conclusion drawn (Serin and Tugrul, 2010). Usually, there are three categories of the performance characteristics to analyze the S/N ratio. Which are: "Nominal is better", "Larger is better" and "Smaller is better" (Athreya and Venkatesh, 2012).

Detailed Experimental Procedure

In order to carry out the experiment, a preliminary trial test was conducted to establish the appropriate values of the variables such as size of hammer (M), height of hammer drop (H) and the number of blows (N) needed for the conduct of the final experiment. Establishment of the values was achieved by a brainstorming discussion with some blacksmiths and practical production of three samples of the plough shares as well as visual and video coverage. During the practical production stage, a local blacksmith workshop at Muda Lawal market in Bauchi metropolis was used for the experimental work. The blacksmith used for the conduct of the experiment to test the model has a body mass index (BMI) of 26.5 kg/m^2 as can be seen in Plate 2 while material used was a 7 mm thick A1020 mild steel plate. A safe working temperature range between 800^oC and 1000^oC was used and measured using a two-wire thermocouple. A digital counter and video coverage were used to measure the number of blows and production time respectively. All set-ups and tools in the workshop were maintained except for the addition of a visual analogue display (VAD) to facilitate measurement of height of hammer drop. During the trial test three levels of the variables were identified as shown in Table 1.

Table 1: Range of parameter values for the preliminary experiment

Sample Number	Size of hammer, M (kg)	Height of drop, H (m)	Number of blows, N	Production time, T (min.)
1	1.75	0.5- 0.80	246	23.21
2	1.75	0.81- .25	289	23.52
3	1.75	1.26- .40	320	24.14
Average				=23.62

During the actual experiment, three levels of hammers, M1= 1 kg, M2= 1.75 kg and M3 =3.5 kg were used.

Plate 2: The layout of the experimental set-up

Development of the Deformation Model

In developing the model, the first stage is to determine the amount of force needed to bend the mould board ploughshare metal pre-form to the required angle of curvature as shown in Figure 1.

Determination of Bending Force, F_b

The bending force for sheets and plates is estimated by assuming that the process is one of simple bending of a rectangular beam (Kalpakjian and Steven, 2009). Thus, the bending force, F_b is a function of the strength of the material, σ_u, the length, L, of the bend, the thickness, t_p, of the plate, and the die opening, W as shown in Figure 2.

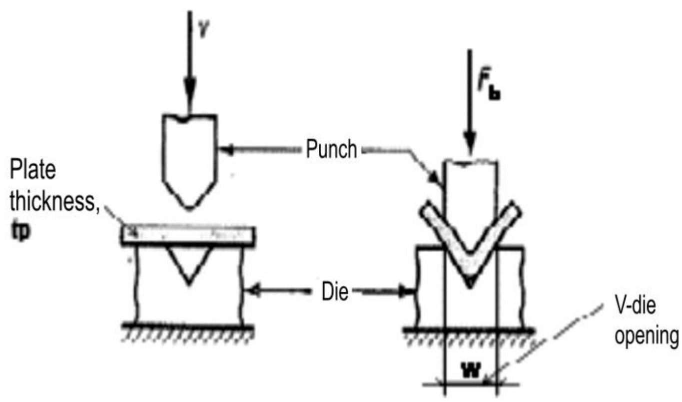

Figure 2: V-bending operation on a plate (Kalpakjian and Steven, 2009).

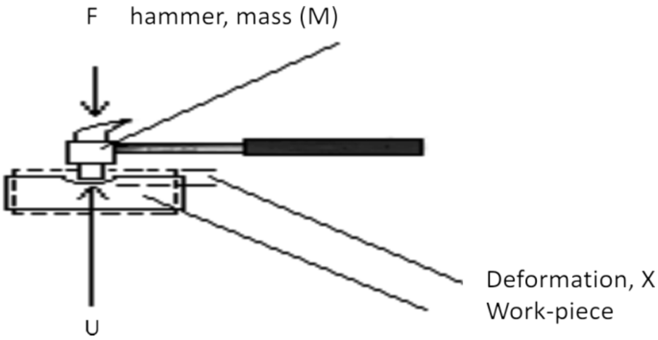

Figure 3: The physics of hammer (Mollet, 2013)

Excluding friction, the maximum bending force, F_b for a V-die is expressed as in Equation (2).

$$F_b = \sigma_u . L . \frac{t_p^2}{W} \quad (2)$$

This Equation applies well to situations in which the punch-tip radius and the plate thickness are relatively small compared to the die opening, W (Kalpakjian and Steven, 2009).

Estimation of the Blacksmith's Forging Load

In the traditional forging process, the bending force needed to produce the ploughshare obtained in Equation (2) is being provided by the blacksmith through hammer blows, hence an equation for the work performed by the blacksmith is required.

The following assumptions were made in developing the model:

(i) The difference between curvilinear motion and linear motion of the hammer as the blacksmith is applying the blows is negligible.

(ii) The difference in deformation of the metal plate along the axis of hammer blow (lateral) and that in the transverse direction is negligible (Poisson's effect).

(iii) The arm length remains constant irrespective of hammer handle length.

Consider the following analysis of hammer as depicted in Figure 3. When a hammer strikes the metal plate it decelerates at a rate, a (ms^{-2}), from its initial impact speed, U (ms^{-1}), to a speed of zero over a distance of x (considered as a deformation).

The distance x includes the lateral/vertical displacement of the metal plate as well as the maximum indentation (deformation) achieved on the metal plate.

The deceleration rate, a can be determined as:

$$a = \frac{U^2}{2x} \quad (3)$$

Newton's Second Law of Motion is given by Equation (4) (Mollett, 2013):

$$F_h = M.a \quad (4)$$

Substituting Equation (3) in Equation (4), the obtained Equation is given in Equation (5).

$$F_h = \frac{M.U^2}{2x} \text{ (Mollett, 2013)} \quad (5)$$

Equation (5) gives the force input due to acceleration of the hammer applied by the blacksmith. However, the total force also includes the component due to gravity, F_g (Deform, 2011) given by Equation (6).

$$F_g = M.g \quad (6)$$

Therefore total forging force, F_f can be expressed as in Equation (7).

$$F_f = F_h + F_g = \frac{M.U^2}{2x} + M.g \quad (7)$$

For striking the hammer from a height H, the work done, W_f is given as:

$$W_f = \left(\frac{M.U^2}{2x} + M.g\right).H \quad (8)$$

However, the amount of work can be measured at the end of the forging when the required number of blows to finish the production of the mould board ploughshare has been attained. Hence, the estimated total deformation can be obtained using Equation (9).

Total deformation (X) = Deformation(x) per hammer blow × Total number of hammer blows (N) (9)

The potential and kinetic energy combined equation derived to determine the forging load exerted by the blacksmith as in Equation (9) is the same load that needs to be applied by the blacksmith to bend the metal pre-form on the V-die block. Therefore, equations (4) and (9) are equal, giving Equation (10).

$$\sigma_u . L . \frac{t_p^2}{W} = \frac{M.U^2}{2x} + M.g \quad (10)$$

The initial impact speed of the hammer, U can also be determined from measurement of height of hammer drop, H and the time of drop, t as U =H/t. Solving Equation (10) to find x and multiplying the result by total number of blows, N gives total deformation (X) as:

$$X = \frac{1}{2t^2}\left(\frac{W.M.H^2}{\sigma_f . L . t_p^2 - W.M.g}\right).N \quad (11)$$

For a given pre-form material and working within a safe forging temperature of between 800°C – 1000°C (Kalpakjian and Steven, 2009), V-die, size of pre-form, the parameters H and N can be measured for different sizes of hammer M. As the blacksmith is striking the heated metal, number of blows (N), height of the hammer drop (H) for every blow and the timing (t) of each sequence of the process can be measured. Thus, equation (11) gives the model that can predict the amount of work (in terms of deformation) performed by the blacksmith in order to produce the mould board ploughshare.

RESULTS AND DISCUSSION

Plough Share Deformation

The model Equation (Equation 12) developed was solved using MINITAB 16 software with the following as input parameters:- W=0.115 m, t=1440 s (24 minutes), L=0.18 m, t_p= 0.007 m, σ_f= 120 Mpa, g = 9.81 m/s^2. When Equation 12 is solved with the values above and deformation values are converted to the S/N ratio values, the results are seen in Table 2. The corresponding Pareto ANOVA results are also shown in Table 3.

Table 2: Full factorial deformation results based on average production time of 24 minutes

Sample No.	Size of hammer, M (kg)	Height of drop, H (m)	Number of blows, N	Deformation, x (m)	S/N_d
1	1	1	1	2.7520009E-06	-111.207
2	1	1	2	3.0635482E-06	-110.276
3	1	1	3	3.4270200E-06	-109.302
4	1	2	1	5.8785345E-06	-104.615
5	1	2	2	6.5440289E-06	-103.683
6	1	2	3	7.3204391E-06	-102.709
7	1	3	1	1.0341010E-05	-99.709
8	1	3	2	1.1511690E-05	-98.777
9	1	3	3	1.2877484E-05	-97.803
10	2	1	1	2.7520009E-06	-111.207
11	2	1	2	3.0635482E-06	-110.276
12	2	1	3	3.4270200E-06	-109.302
13	2	2	1	5.8785345E-06	-104.615
14	2	2	2	6.5440289E-06	-103.683
15	2	2	3	7.3204391E-06	-102.709
16	2	3	1	1.0341010E-05	-99.709
17	2	3	2	1.1511690E-05	-98.777
18	2	3	3	1.2877484E-05	-97.803
19	3	1	1	2.7520009E-06	-111.207
20	3	1	2	3.0635482E-06	-110.276
21	3	1	3	3.4270200E-06	-109.302
22	3	2	1	5.8785345E-06	-104.615
23	3	2	2	6.5440289E-06	-103.683
24	3	2	3	7.3204391E-06	-102.709
25	3	3	1	1.0341010E-05	-99.709
26	3	3	2	1.1511690E-05	-98.777
27	3	3	3	1.2877484E-05	-97.803

Table 3: Pareto ANOVA result of S/N ratios for deformation by factor level

Level	Size of hammer, M (kg)	Height of drop, H (m)	Number of blows, N
1	-104.231*	-110.262	-105.177
2	-104.231*	-103.669	-104.245
3	-104.231*	-98.763*	-103.271*
Delta	0.000	-11.499	-1.906
Rank	1	3	2

*Optimum values.

The optimum levels of parameters for deformation are summarized in Table 4.

Table 4: Optimum values of parameters for deformation

Parameter	S/N value	Level	Actual value
Size of Hammer (M)	-104.231	1	1 kg
Height of Drop (H)	-98.763	3	0.65 m
Number of Blows (N)	-103.271	3	265

Calculation of optimum value of deformation using full factorial design

Using the optimum values of parameters from Table 4, the optimum deformation (X_{opt}) can be calculated using equation (12) as adopted from Vankanti and Ganta (2014).

$$X_{opt}= \frac{T}{N} + \left(M1 - \frac{T}{N}\right) + \left(H3 - \frac{T}{N}\right) + \left(N3 - \frac{T}{N}\right) = 12.42 \ \text{x}10^{-06}\text{m} \quad (12)$$

where, T = time (s), M1 = first level hammer size (1 kg), N3= third level number of blows (330), H3 = third level height of hammer drop (1.26 m), N = total number of readings (27).

Validation result of plough share deformation

The response result of the validation test using the Taguchi design show the level of significance of the parameter on the ploughshare deformation is presented in Table 5.

Table 5: Response result of S/N ratios for deformation (larger is better)

Level	Size of hammer, M (kg)	Height of drop, H (M)	Number of blows, N
1	-104.20*	-110.20	-105.13
2	-104.22	-103.69	-104.23
3	-104.25	-98.77*	-103.30*
Delta	0.05	11.43	1.83
Rank	3	1	2

*Optimum values

The optimum values above were then substituted in Equation (13) to obtain the optimum deformation, X_{op}.

$X_{opt} = \frac{T}{N} + \left(M1 - \frac{T}{N}\right) + \left(H3 - \frac{T}{N}\right) + (N3 - \frac{T}{N}) = 14.57 \times 10^{-06}$ m (13)

Validation of model using regression analysis of full factorial data

In order to validate the model Equation (11) developed to predict the deformation of the plough share, regression analysis was conducted. The total deformation data obtained from Table 2 using full factorial was subsequently used to generate the regression Equation (14) using the MINITAB 16 software.

Total deformation = 0.000013 + 0.000000 Size of Hammer – 0.000014 Height of Drop-0.000000 Number of Blows (14)

Validation of model using regression analysis of Taguchi design data

As done for full factorial design, data generated using Taguchi design was used for the regression analysis and the regression Equation (15) was obtained.

Total deformation (m) = - 0.000013 - 0.000000 Size of Hammer (kg) + 0.000014 Height of Drop (m) + 0.000000 Number of Blows (15)

DISCUSSION

Analysis of Ploughshare Deformation

Analysis of the deformation shows that the optimum combination of parameters is M1/M2/M3, H3 and N3 as shown in Table 3. This indicates that for maximum deformation to occur, any size of hammer could be used (M1/M2/M3) but at maximum height (H3) and with maximum number of blows (N3). The same combination of parameters was obtained using Taguchi design. However, a maximum deformation of 14.57 x 10^{-06} m was obtained using Taguchi design as against full factorial value of 12.42 x 10^{-06} m. It is obvious that maximum deformation will be achieved due to effects of inertia and potential energy as a result of working with the largest hammer and at highest hammer dropping height. Table 3 shows that the size of hammer is most significant then followed by number of blows, while the height of drop is less significant.

Regression analysis on deformation model

The results of regression analysis on data generated using full factorial design indicate that all constants in the regression Equation (14) are significant as their $p < 0.01$, except the size of hammer with $p = 1.00$. The regression equation developed from the data obtained by solving the model is to serve as a further confirmation of the adequacy of the developed model. The result also shows that the model is adequate to predict the deformation of the share with accuracy of R-Sq = 98.4% R-Sq (adj) = 98.2% and error of 0.2% (R-Sq - R-Sq (adj)). The significance of this is that the developed model of Equation (11) proved adequate in predicting the deformation of the ploughshare at 95% confidence level. Thus, the model could as well be used to optimize other parameters, thus enhancing the overall productivity of the blacksmith. Similarly, analysis of data generated from Taguchi design confirmed that the model is adequate to predict the plough share deformation, with R-Sq =98.6% and R-Sq (adj) = 97.8%. Both full factorial and Taguchi designs agree that the developed model is adequate to predict the deformation of the ploughshare.

CONCLUSIONS

A model to predict the performance of blacksmith during the production of a mould board ploughshare was developed, tested and validated. The model proved adequate with values of R-Sq = 98.4% and R-Sq (adj) = 98.2%, giving an error of 0.2% at 95% confidence level, to predict the work in terms of the deformation, with maximum deformation of 14.57 x 10^{-06} m obtained using Taguchi design as against full factorial value of 12.42 x 10^{-06} m. Using optimum combination of parameters of any of the three sizes of hammers (M1 = 1 kg/M2 = 1.75 kg/M3 = 3.5 kg) but at maximum height (H3 = 1.26 m) and with maximum number of blows (N3 = 330). The significance of the model is that there will be fatigue reduction on the part of the blacksmith as it will avoid arbitrary choice of the production parameters during the production of the mould board ploughshare. The parameters used by the blacksmith (Size of hammer, height of hammer drop and number of hammer blows) can be adjusted by incorporation of the VAD display and a timer. The result of the study proved that local blacksmithing processes could be scientifically developed to improve its productivity by simplifying the production processes through control of the production parameters, thereby making blacksmithing more attractive and make more people develop interest in the job.

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