Experiment Study on Hardening Behavior of Slab Cold Roll-Beating Forming

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Abstract. New production technologies have been developed over these last few years as answers in response to new market needs, such as higher production flexibility, lower volume batches, more complex shapes for final pieces and new materials. Cold roll-beating is an advanced precision plastic forming technology to better meet the current requirements. To investigate a material's behavior in cold roll-beating forming operations, in this paper the principle of slab cold roll-beating was briefly introduced and slab cold roll-beating experiments were carried out, and results of the analysis conducted on the produced pieces in terms of metallographic structure and hardness distributions were reported. Our results show that the cold roll-beating forming can cause the metal surface to harden while improving the mechanical properties of the material, which is interesting in order to understand a material's behavior when it is subjected to this peculiar deformation process; furthermore, it is of great guiding significance for further applications of the new forming technology.

Keywords: Cold Roll-beating, Material behavior, Stress-strain evolution, Metallographic structure.

1. Introduction

With increasingly drastic marketing competition and the rapid updating of products, many drawbacks associated with the traditional die forming process are reflected day by day, such as long production preparation time, large tonnage equipment, poor processing flexibility and high manufacturing costs [1-3]. Recently, as opposed of the traditional cutting machining method using the plastic forming process, many scholars are now committed to the new dieless precise plastic forming process [4-6].

The cold roll-beating forming technique is a near-net shaping technology in which the rotating rigor roller with the specific tooth profile rolls and beats the blank at a high speed; because of the plasticity of metal itself, the surface metal of the blank flows, forming the work-piece via the cumulative deformation of continuous tiny regions along with the relationship of relative motion between the rigor wheel and blank [7-9]. During its initial research period, searches were conducted for the forming principle, finite element analysis, dynamic simulation and prototype equipment [10-12], all of which verified the feasibility of the cold roll-beating forming process. The present paper...
focuses on the metallographic structures and the hardness distribution of the produced pieces. These results are of relevant interest in understanding the material's behavior when subjected to this particular deformation process.

2. The Slab Cold Roll-beating Forming Process

High speed precision cold roll-beating is typical of precise plastic forming technology. During the forming process, by taking advantage of the inherent plasticity of rough material at ordinary temperatures, a roller of a certain shape and rotating at high speeds roll-presses and beats the rough blank intermittently, forcing the local metal of the rough surface to flow, and plastic deformations to accumulate in order to form the profile of the required part.

The working principle of slab cold roll-beating is shown in Fig. 1. The rollers of certain shapes are mounted on a rotating shaft that moves evenly at high speeds. During the cold roll-beating forming, the slab blank feeds horizontally, and the rollers, moving at high-speed rotations, beat the slab blank intermittently; afterward, the metal materials of the slab blank surface move a certain displacement due to high-speed impact of the rollers. The roller rotates around its own axis the moment the roller comes in contact with the slab as a result of the friction between them, thereby ensuring the rolling between the roller and the slab. The action is repeated until the specific shape is formed in the slab blank to satisfy the predetermined depth of cut (rolling reduction). O is the revolution center and rotation center, O' is the ration center of the roller. According to the relationship between the direction of the spindle tangential speed direction and the workpiece feeding direction, the roll-beating method can be classified into up-beating and down-beating. While the two directions are the same, the roll-beating is called up-beating (as shown in the Fig.1), otherwise the roll-beating is called down-beating.

![Fig. Principle of slab cold roll-beating forming](image)

3. Experiments

Three materials: copper, aluminum and 45# steel was selected to carry out slab cold roll-beating experiments. The metallographic structures and hardness distributions of the forming samples were observed and measured in order to further study the rules of the forming process.

3.1. Experiment system

The cold roll-beating forming experiments were carried out using self-developed cold roll-beating device which is mounted on a horizontal milling machine, the experimental equipment and instruments are shown in Fig. 2, where the material of the roller is 20CrMnTi which is carburization hardened and tempered, the surface hardness is 58-64HRC and the roughness is Ra 0.2-0.4.
3.2. Experimental results and analysis

Some work-pieces formed by cold roll-beating are shown in Fig.3. To further study the deformation law and plastic properties of the formed work-piece, TUKON2100B Micro Sclerometer was used to measure the hardness of different metal materials in different regions. Measurement locations and hardness distributions of the formed copper work-piece are shown in Fig.4.

Fig.4(b) shows the hardness change in the measurement points along the normal direction of the groove bottom; the distance between the first point and the bottom surface is 18 µm, the distance between other every two measuring points is 50 µm. Fig.4(c) shows the hardness change in the measurement points along the normal direction of the groove side; the distance between the first point and the side surface is 18 µm, and the distance between every other two measuring points is 50 µm. As shown in Fig.4(d), from the surface to the interior, the hardness variation tendencies are basically the same and the overall tendency is from big to small, which illustrates that the hardness improves after the cold roll-beating formation. Plastic deformation causes the work to harden and the hardness is improved, and to some degree, mechanical properties, such as impact resistance and wear resistance, are enhanced.
Comparing the hardness of Fig.4(b) with Fig.4(c), the hardness of the groove bottom is higher and the hardness of the surface reaches HV136. While the roller is beating the slab blank, the component force perpendicular to the bottom is the greatest, and the interior of the material will stop the metal from flowing. This enlarges both deformation degree and deformation region, thus the hardening layer reaches the thickest point and the cold hardening is at its most obvious, which is in accordance with the simulation results and metallographic structure distribution.

![Fig. 5 Hardness distribution and harden stratum measurement of AL work-piece](image)

Measurement locations and hardness distributions of the formed aluminum work-piece are shown in Fig. 5. Fig. 5(b) shows the hardness change in the measurement points along the normal direction of the groove bottom; the distance between the first point and the bottom surface is 25 µm, and the distance between other every two measuring points is 30 µm. Fig. 5(c) shows the hardness change in the measurement points along the normal direction of the groove side; the distance between the first point and the side surface is 20 µm, and the distance between every other two measuring points is 30 µm.

When comparing Fig. 5(d) with Fig. 4(d), the surface hardness of the AL work-piece is relatively smaller. The slab cold roll-beating is a type of single-point accumulative forming technology, and the forming process is one of high speed, high impact and instantaneous striking. During the forming process, heat will inevitably be produced, and temperatures will be particularly higher at the contact point. There is no time for the produced heat to diffuse, which causes the temperature at the contact position to increase. The aluminium is a single-phase solid solution, and the interior crystal growth is related only to the temperature gradient. Its melting point is lower and reaches the re-crystallization temperature, at which point the metal is softened; as such, the hardness and strength of the metal material with re-crystallization in contact with the roller decreases. At the same time, due to the defects of the roller, the metal at the deepest position inside the groove bottom may be offset slightly. From Fig. 5 (d), it can be seen that the hardness of the surface metal decreases. The force of the hardness in the bulged region is smaller, thus the hardness changes are likewise smaller.

Measurement locations and hardness distributions of the formed 45# steel work-piece are shown in Fig.6. It shows the hardness changes in the measurement points along the normal direction of the groove bottom; the distance between the first point and the bottom surface is 25 µm, and the distance between every other two measuring points is 30 µm. Fig. 6(c) shows the hardness change of the measurement points along the normal direction of the groove side; the distance between the first point and the side surface is 15 µm, and the distance between other every two measuring points is 30 µm.
Fig. 6 Hardness distribution and harden stratum measurement of 45# steel work-piece

As shown in Fig. 6 (b) and (c), 45# steel has two types of phases, i.e., pearlite and ferrite. There are differences between the hardness values at the measurement points for different textures. From an overall perspective, the hardness distribution decreases gradually from the surface to the center. As can be seen in Fig. 6(d), the hardness of the third and fourth points at the hardness curve of the groove side increases; this is because the first and second points are at the border region of the ferrite and pearlite, the third and fourth points are just at the pearlite region. The positions of the measurement points can be seen from the Fig. 6(c). There may be a small amount of offset in the roller axis during the forming process, which will also occur on the groove bottom; there are also a few smaller bulges on the groove bottom, which causes a smaller degree of hardness.

From the above hardness distribution curves of three different materials, during the cold roll-beating forming process the impact force reaches the highest point in the groove bottom region, which is in direct contact with the roller. At the same time, due to the resistance of the interior material, the deformation degree and deformation region are larger; the deformation resistance increases and the hardening layer thickens. Also, cold-work hardening is found, which causes the hardness and the strength of the formed surface to increase, and improves the impact resistance and wear resistance. As for the metal material formed by cold roll-beating, the fiber texture becomes even more compact, and the direction of the metal fiber is streamlined in accordance with that of the slab blank deformation. Due to the transient local impact at high speed, temperatures rise in the contacting region between the roller and slab blank. For metals with a lower re-crystallization temperature, re-crystallization occurs in the contacting region, which causes the hardness and strength to decrease and the plasticity to improve.

4. Conclusions
Cold roll-beating is a plastic forming method that combines local dynamic loading and single-point accumulation; it is die-less and without constraints and has wide application prospects. In this paper, the cold roll-beating forming process was studied using experimental; the material behaviors in slab cold roll-beating forming operations were analyzed. Works with different materials formed by cold roll-beating, metallurgical structure changes, and hardness distribution were analyzed. The experimental results show that the cold roll-beating forming can cause the metal surface to harden and also improve the mechanical properties of the material to some degree.

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