The effect of cyclic heat treatment on the structure of 5140 steel after cold plastic deformation

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Abstract. The objective of this work are experimental research of steel 5140 damages appearance under cold plastic deformation and healing continuity defects characteristic study by following periodic heat treatment. The experimental research of deformation defects continuity appearance in steel 5140 with the granular and lamellar perlit under cold plastic deformation in dependence to original structure was conducted. The deformation defects appearance pattern in steel, their growth in dependence to degree of deformation, microstructure and capacity for healing in the process of cold forging are seemed to be pertinent are explored. It was concluded, that at early deformation stages independently of perlit morphology in steel 5140 the damage is related to micropore appearance in ferrite. The possibility of defects healing by periodic heat treatment is found out. For damage changes studying in the process of cold plastic deformation and healing heat treatment the following experimental design was used: the preliminary periodic heat treatment – deformation with varying degrees – healing periodic heat treatment – deformation up to failure. The periodic heat treatment with phase recrystallization is shown to bring about more full healing damages in comparison with recrystallization annealing. Herewith the microdefects critical size increases up to 2 micrometers, and invertible damage stage extend to 0.4.

Keywords: medium carbon steel, deformation defects, periodic heat treatment, perlit, phase recrystallization.

1. Introduction

The cold forging progressive methods development for high-level express operations demands nomenclature expansion of constructional steel using marks and development of multistage technical processes that consist of several cycles «deformation – heat treatment». In this regard, traditional technologies of hardening still by heat treatment with providing high-degree hardwearing and other mechanical properties of different steel marks stay still pertinent [1-7]. One of this kind of research perspective objects is medium-carbon steel 5140, that is ever-growing used in machine industry due to high mechanical and performance characteristics.

Currently, there is an active search for fundamentally new non-traditional ways to strengthen steels [8-11]. At the same time, the possibilities of traditional methods of heat treatment to improve the physical and mechanical properties of steel have not yet been exhausted.

In the process of cold forging, the metal suffers measurable plastic deformations. For this reason deformation defects appearance in steel, their growth in dependence to degree of deformation, microstructures and capacity for healing in the process of cold forging are seemed to be pertinent.

The research efficiency is proved true by theoretical underpinning good correlation and experimental results. Phenomenological failure theory allows by using results of mechanical tests for plasticity to calculate the level of metal damage in any deformation process, for which the plasticity boundary value problem [12-14] is figured out. However, periodic heat treatment influence on steel 5140 plasticity under combined stress state conditions and capacity for damages healing are not studied.
The purpose of the work is experimental research of steel 5140 damages appearance under cold plastic deformation in dependence to original structure and healing continuity defects characteristic study by following periodic heat treatment.

2. Materials and methods
For damage changes studying in the process of cold plastic deformation and healing heat treatment the following experimental design was used: the preliminary periodic heat treatment – deformation with varying degrees – healing periodic heat treatment – deformation up to failure. Periodic heat treatment was conducted under following conditions:

Conditions 1.
The preliminary periodic heat treatment included following operations:
1) heat up the sample in the furnace to 960\(^\circ\)C,
2) soaking the sample in the furnace of 6 hours,
3) oil hardening + heat up the sample to 760\(^\circ\)C,
4) soaking the sample in the furnace of 1 hour,
5) cooling the sample with furnace up to 680-700\(^\circ\)C,
6) soaking the sample in the furnace of 1 hour,
7) heat up the sample to 770-780\(^\circ\)C,
8) soaking the sample in the furnace of 1 hour,
9) cooling the sample with furnace up to 680-700\(^\circ\)C,
10) soaking the sample in the furnace of 1 hour,
11) cooling the sample with furnace up to 300\(^\circ\)C,
12) further air cooling the sample.

Healing periodic heat treatment included following operations:
1) heat up the sample in the furnace to 760\(^\circ\)C,
2) soaking the sample in the furnace of half an hour,
3) cooling the sample with furnace up to 680-700\(^\circ\)C,
4) soaking the sample in the furnace of half an hour,
5) heat up the sample to 770-780\(^\circ\)C,
6) soaking the sample in the furnace of half an hour,
7) cooling the sample with furnace up to 680-700\(^\circ\)C,
8) soaking the sample in the furnace of half an hour,
9) cooling the sample with furnace up to 300\(^\circ\)C,
10) further air cooling the sample.

Conditions 2.
The preliminary periodic heat treatment hosted in following sequence:
1) heat up the sample in the furnace to 760\(^\circ\)C,
2) soaking the sample in the furnace of 1 hour,
3) cooling the sample with furnace up to 680\(^\circ\)C,
4) soaking the sample in the furnace of 1 hour (5 cycles),
5) cooling the sample with furnace up to 300\(^\circ\)C,
6) further air cooling the sample.

Healing periodic heat treatment hosted in following sequence:
1) heat up the sample in the furnace to 760\(^\circ\)C,
2) soaking the sample in the furnace of half an hour,
3) cooling the sample with furnace up to 680\(^\circ\)C,
4) soaking the sample in the furnace of half an hour (2 cycles),
5) cooling the sample with furnace up to 300\(^\circ\)C,
6) further air cooling the sample.

3. Results and discussion

Photographs at the figure 1 show the steel 5140 microstructure to vary widely in dependence of periodic heat treatment conditions.

![Steel 5140 microstructure after periodic heat treatment](image1.png)

**Figure 1.** Steel 5140 microstructure after periodic heat treatment: 1000 magnification. a – under conditions 1; b – under conditions 2.

After the periodic heat treatment in accordance with conditions 1 the structure is 100% granular perlite with equally distribute in ferrite mold big (>1.2 micrometers) cementite granules (Figure 1a). Steel firmness after this treatment is 143 – 145 HB. In steel structure after periodic heat treatment under conditions 2 appreciable quantity of lamellar perlite (~30%) and small cementite granules (>1 micrometer), that are closely-pitched to each other, are presented (Figure 1b). The treated under conditions 2 steel has the firmness 158-164 HB.

The mentioned distinction in microstructure and steel 5140 firmness significantly effect on its plasticity in the process of cold plastic deformation. The figure 2 shows the steel plasticity diagram after periodic heat treatment under conditions 1 to be situated above the k stress state index within the studied value range.

![Steel 5140 plasticity diagram](image2.png)

**Figure 2.** Plasticity steel 5140 diagram after periodic heat treatment. Conditions:
- • – conditions 1;
- • – conditions 2.

The structure changes and steel 5140 firmness abating while using periodic heat treatment in the capacity of preliminary heat treatment under conditions 1 drive the plasticity increase up of 30%. 
Electron microscope analysis of deformed samples fractures allows to observe variant appearance and development of micro effects devises in dependence to degree of deformation $\Lambda$ and original steel structure. Of deformation degree $\Lambda < 1.35$ for steel after periodic heat treatment under conditions 1 and $\Lambda < 1.10$ after periodic heat treatment under conditions 2, when the damage did not exceed the value of $\omega = 0.4$, certain defects in the form of spherical shape micropores, that were situated inside ferrite grains (inside cleavage facets) and along grain boundaries (figure 3a).

For one and the same $\omega_1$ value the microdefects number and size after periodic heat treatment under conditions 1 and 2 are approximately the same. The carbide phase in steel 5140 after periodic heat treatment under presented conditions does not take part in shearing processes, that carry on the beginning deformation stages, for this reason micropores here evidently appear in accumulation dislocation points along grain and cells boundaries.

![Image](image1)

![Image](image2)

![Image](image3)

![Image](image4)

![Image](image5)

![Image](image6)

Figure 3. Steel 5140 fractures micro factors; 2000 magnification:

- a) – cyclic heat treatment under conditions 1 + deformation up to value $\omega_1 = 0.25$;
- b) – cyclic heat treatment under conditions 1 + deformation up to value $\omega_1 = 0.77$;
- c) – cyclic heat treatment under conditions 2 + deformation up to value $\omega_1 = 0.51$;
- d) – cyclic heat treatment under conditions 2 + deformation up to value $\omega_1 = 0.80$;
- e) – cyclic heat treatment under conditions 1 + deformation up to value $\omega_1 = 0.30$ + healing cyclic heat treatment under conditions 1;
- f) – cyclic heat treatment under conditions 1 + deformation up to value $\omega_1 = 0.77$ + healing cyclic heat treatment under conditions 1.

Of higher deformation degrees two microdefects development mechanisms can be observed in dependence to original steel structure. For steel with granular perlite (periodic heat treatment under conditions 1) the $\omega_1$ increase up to 0.77 sequentially leads to appreciable quantity of micropores appearance, their growth up to sizes $\sim$ 3 micrometers due to dislocation sink, distance decrease between micropores and finally their confluence. On micro fracture patterns this mechanism in the form of ductile failure areas, that are mainly situated nearby grain boundaries (figure 3b).
The used in this research microfracturing method allows, on the one hand, to correctly estimate only collected in the form of micropore damages. On the other hand, steel fracture studying with lamellar perlite after periodic heat treatment under conditions 2 (figure 3c, 3d) shows the micropore number in samples to change a little with deformation degree raising and obviously disagree with high calculation damage values $\omega_1$ for samples, which plasticity resource is considerably depleted yet.

The relative narrowing of the samples $\delta$ reached 52 and 63%, whereas the value $\delta = 68\%$ corresponds to the moment of macroscopic destruction. This suggests that the microcracks observed in the fracture (Figure 3c, d) arise at the stage of preliminary plastic deformation, and are not secondary, formed by branching cracks in the brittle fracture samples. If $\omega_1 = 0.51$, the microcracks have size less than 3.0 microns and are located mainly along the grain boundaries and along the interface boundaries (Figure 3c). With the increase of $\omega_1$ to 0.7 – 0.8 there is a crack growth along the borders with the formation of micro-voids, the size of which is commensurate with the grain size (~ 15 microns), as well as the development of in some cases, microcracks from the oncoming dislocation clusters merge with micropores or become blunt and cease to grow as a result of the exit of their top in the previously formed pore.

The difference in the mechanism of deformation defects determines the different level of plasticity of steel 5140 with granular and lamellar perlite.individual cracks directed from the boundaries to the center of the grain body (Figure 3g). Micro cracks, unlike pores, are more effective stress concentrators, so the appearance of the main crack and the destruction of steel after cyclic heat treatment in mode 2 occurs at lower degrees of deformation.

Depending on the extent of damage to the steel at the stage of preliminary deformation during heat treatment, microdefects are healed partially or completely. At $\omega_1 < 0.4$, microdefects of the continuity of steel completely disappear (Figure 3d); at $0.4 < \omega_1 < 0.8$, micropores and cracks up to 2.0 microns in size are completely healed. Defects of larger dimensions are only partially healed, and residual damage is observed in the steel (Figure 3e).

When heated above the temperature 727 °C, recrystallization processes develop, which is accompanied by the annihilation of dislocations, the release of accumulated deformation energy, the nucleation and growth of new grains in the deformed matrix. Migration of the boundaries of new grains through deformation defects leads to their healing [12-15]. In the subcritical temperature range (30-50 °C lower than the temperature 727 °C) microdefects with a size of no more than 1 micron are fully healed.

Further heating above the temperature 727 °C causes a polymorphic $\alpha/\gamma$ - transformation, in which there is an intense migration of interphase boundaries, disruption of interatomic bonds and acceleration of diffusion processes. The thermal cycle in the temperature range 727 °C, causing multiple repetition of $\alpha/\gamma$ - transformation, enhances healing of microdefects by the mechanism: time on the drain [16,17]. Double thermal cycle in the temperature area 727 °C under the above conditions, ensures complete healing of micro-defects with the size less than 2 microns.

When comparing the damage healing diagram in steel 5140 with similar diagrams constructed after recrystallization annealing of carbon, austenitic steel, aluminum, titanium, nickel alloys (figure 4) it can be seen that the section $0 < \omega_1 < 0.4$ has reversible damage, which is characterized by the healing of deformation defects in the process of heat treatment.

In the range of $0.4 < \omega_1 < 0.8$ there is a monotonic increase in residual damage. At $0.4 < \omega_1 < 1$, the ability to heal the damage decreases markedly. The value of $\omega = 0.4$ are related to mass education in wrought steel of micro-defects with a size of ~2 $\mu$m. The value $\omega = 0.8$ characterizes the completion of intense coalescence of micropores, growth of microcracks and the formation of microfibrils having dimensions commensurate with the size of the grain.

Compared with a single recrystallization annealing at subcritical temperatures, thermal Cycling with phase recrystallization extends the stage of reversible damage on average from 0.25 to 0.4, which, apparently, should be attributed to the critical size of treatable microdefects. The intensity of damage healing on the second part of the graph also increases, and the size and number of microdefects is significantly less than after recrystallization annealing.
Figure 4. The generalized residual damage diagram ($\omega_2$):

- ◆ – after a single recrystallization annealing for a number of steels and alloys [2, 3];
- for steel 5140 after cyclic heat treatment:
  - ◆ – under conditions 1;
  - ▲ – under conditions 2.

4. Conclusions
The steel 5140 damage on the beginning stages is determined to be attributed independently of perlit morphology to micropore appearance in ferrite. The steel 5140 periodic heat treatment with phase recrystallization leads to more full damage healing in comparison with recrystallization annealing. Herewith the microdefects critical size increases up to 2 micrometers, and invertible damage stage extend to $\omega = 0.4$.

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