Surface treatments of forged steel AISI6F3 by using high power CO₂ laser

Amin D. Thamer¹, Mohammid Jasim Kadhim¹ and Ibrahim Abdu al kareem Ahmed¹
¹University of Technology, Department of Production Engineering and Metallurgy, Baghdad, Iraq

Abstract. The hardness of forging dies is highly affected by the hot forming processes; especially by the long exposure to a wide thermal range, which leads to a decline in the level of hardness due to the tempering of the microstructure, thus failure occurs and the die breaks. The microstructure and hardness have been studied to demonstrate the relationship between them and their direct effect on the regions generated by the laser treatment of high capacity. The selected samples were chosen within a combination of laser variables to reach the appropriate structure that achieves the best hardness and indeed the highest hardness value (965 Hv) with laser processing parameters included the power 3000 W, beam diameter 1mm and scanning speed 25 mm/s with its characteristic microstructure as well as its high cooling rate.

Keywords: Forged steel, Microstructure, Hardness, High power laser

1. Introduction
In order to promote the strength of the tools used in hot processes, one requires understanding the most failure mechanisms that effect on the tools surface during the service [1]. The deterioration mechanisms of forging dies occur with the accompaniment of several phenomena at the same time [2]. Hot strength is represented as the ability to resist stresses at high temperature [3]. The difference in the strength values of the different types of steel is due to the difference in the amount of alloying elements added to each type of steel. On the other hand, the factor of contact time for the dies is very important in hot forming processes, especially when used to produce thousands of pieces, although the time of contact does not exceed a few seconds, but the repetition of this process at the continuous production leads to the accumulation of heat on the surface of the dies and cumulatively with time resulting in a bad effect if the steel cannot withstand this heat.

It's certain that in cold forming processes, the main concern is fatigue cracking while in hot forming processes; it is excess wear, thermal fatigue and plastic deformation [4]. In such cases, the tools must withstand the high temperature in hot forming and the high pressure in cold forming [5]. In terms of mechanistic transformation, it is primarily based on the method of change in the crystalline structure achieved during this transformation. It is necessary to observe the change in the steel microstructure during the cooling process associated with austenite decomposition [6].

The change in morphologies as Widmanstatten and interagrnular ferrite was occurring in lower austenite decomposition temperature [7]. The source of growth of these morphologies was proposed by two mechanisms, in the first, the lateral movement of semicoherent interfaces by ledges is a control for the growth mechanism, the second, is the growth of ferrite during displacive transformation mechanism [8, 9].
Selective laser melting is one of the important manufacturing processes used in the technology of adding layers on the material surface for the purpose of building in tooling and functional parts, medical scanner and prototypes [10]. Microstructure was found to be associated with cooling rate and melt pool lifetime, estimated from the temperature signal [11]. Laser metal deposition using powder out of hot-working tool steel 1.2344 was shown that this hot working tool steel can be used to manufacture crack free parts through laser metal deposition [112].

The main features of laser melting of metallic substrates are minimizing the distortion of materials by laser beam, high depth-width ratios of fusion zone and high accuracy operation [13]. G. Telasang, J. Dutta, G. Padmanabham and I. Manna, in 2014, presented that the application of laser on hot work tool steel H13 with specific energy (100 J/mm²). They appeared that the distinct surface melting with a significant microstructure consisting of martensite, retained austenite and carbides within dendrite structure [14]. K. Darvish, Z.W. Chen⁎, M.A.L. Phan and T. Pasang, in 2018, have been studied the orientation of grain solidification for Co-Cr-Mo alloy through laser melting and showed that the increasing of the laser power up to 360 W whereas installing other laser variables will increase the size of the track while changing the ratio between width and depth of penetration [15].

The aim of this research is to study the effect of the use of continuous laser technology with high power for the surface treatment of forge steel, and to indicate the changes in the microstructure and hardness.

2. Experimental procedure
The alloy used in this study, classified as low-alloy steel type (AISI6F3mod.) is widely used in the production of closed forgings because of its proper hardness and toughness in addition to the lower cost of its manufacture compared to high-alloy steel. The chemical analysis of this alloy is shown in the table as well as in X-ray examination.

| Table 1. Chemical composition measured of the (6F3 mod.) as received |
| C% | Si% | Mn% | Cr% | Mo% | Ni% | V% |
|---|---|---|---|---|---|---|
| 0.55 | 0.25 | 0.75 | 1.10 | 0.45 | 1.65 | 0.10 |

A microscopic examination was performed to identify the compositions and phases generated as a result of the laser treatment using scanning electron microscope type VEGA3LM TESCAN COMPANY. Also an optical type of MTM-1A metallographic microscope was used with reflective lighting to determine the main layers during fusion and this device is suitable for analyzing the structure of different types of materials.

The high-capacity laser was used up to 3000 watts for the surface treatment of this type of the forge steel at the first time using a laser machine type LASERCELL 1005, TLF 1600, fast axial flow CO2, as showing in Figure 1 which is used in the laser research center at the University of Kielce with a possible movement up to six - axes.

![Figure 1. The laser processing machine at Laser Processing Research Center, University of Kielce, Poland.](image)
3. Results and Discussion

The basic microstructure features of as received steel are illustrated in Figures 2 and 3. The structure consists mainly of the spheroidized carbides with a matrix of ferrite due to the process of annealing which is widely used to reduce the hardness resulting from the carbides present in these types of steel and to improve the machinability and formability.

![Microstructure Image](image1)

**Figure 2.** (AISI6F3mod.), as-received, annealed state, with microstructure consists of spherical carbides in matrix of ferrite (white).

![EDS Analysis Image](image2)

**Figure 3.** EDS analysis to (AISI6F3mod.), as-received, appearing the most alloying elements.
Four samples were tested by laser treatment and within a combination of variables identified in the table 2 for the purpose of studying the layers formed for each sample.

**Table 2. The independent variables for laser processing**

| Samples | Power (W) | Beam dia. d(mm) | Speed v (mm/s) | Power irradiance \( P_A = \frac{P}{\pi r^2} \) W/mm² | Specific energy \( S = \frac{P}{d v} \) J/mm² | Interaction time \( t = \frac{d}{v} \) (s) |
|---------|-----------|----------------|----------------|---------------------------------|---------------------------------|-----------------|
| A       | 750       | 6              | 25             | 26.5                            | 5                               | 0.24            |
| B       | 1500      | 6              | 12             | 53                              | 20.8                            | 0.5             |
| C       | 2250      | 1              | 12             | 2866.2                          | 187.5                           | 0.08            |
| D       | 3000      | 1              | 25             | 3221.6                          | 120                             | 0.04            |

The optical microscopy examination to the samples after laser treatment performed within the variables shown in the table 2 has been made primarily clear of the impact of each surface with such treatment as depicted in Figure 4.

**Figure 4.** The samples that were tested by laser within conditions that depicted in the table 2.

Figure 5, indicated the different regions was observed. The heat-affected zone or hardening zone showed only as one area in the samples A, B due to the temperature not exceeding the austenitizing transition zone as in the samples C and D that exceeded the melting point and led to the emergence of more than one area.
Figure 5. Optical microscopy showing the regions related to laser treatment for samples (a) hardening area with martensite phase to the sample A, (b) hardening area with martensite phase to the sample B, (c) E and (d) D, indicated basically three region where M.Z is melting zone, P.M.Z is partial melting zone, H.A.Z is heat affected zone and B.M is base metal.

The reason for the emergence of these areas sometimes and the lack of other times is due to the conditions of treatment of each sample. It is noted in Fig. 6 samples A, B that the amount of specific energy to those samples was few (5 and 20.8 J/mm²) respectively, which did not result in melting, but the impact of heat, resulting in only a hardening. For samples C, D it is noted that the amount of specific energy is high (187.5 and 120 J/mm²) respectively, therefore, the melting and the formation of these regions were occurred.

The other evidence for the formation of these regions is the Figure 6 where it appears as gradient layers of samples D, C and one layer of sample A and B.

The resulting martensite plates are in the same orientation of the grains in both regions. This indicates the newly formed crystals that grow epitaxial of the non-melted zone grains and the same orientation with the confirmation that this structure has a strong tendency to continue to grow epitaxial on the substrate and this is evident in the Fig.6 (c and d).
Figure 6. The gradient layers for laser processing as clearly shown for samples B, C and D in figure (b, c and d) while unclear for sample A in figure a.

The predominant phase of all these samples is the martensite, but the shape and size of this phase varies from one sample to another according to the cooling rate generated for each sample. The cooling rate has been calculated from equation \[ \lambda = c (T)^{-ci} \] Where, (T) is cooling rate, \( \lambda \) is dendrite arm spacing, C is material constant = 40 and \( ci = 0.3 \) and installed in the table 3. The variance of the martensite phase follows the dendrite structure, which in turn depends on the cooling rate. The higher the cooling rate, the lower the growth of the crystals and the dendrite is fine.

In the same way, for the details of the specimens as shown in Figure 7, some of which reached to the range of the austenitic transformation were it is only hardened, and others give a shallow fusion depending on to the laser treatment conditions, which generated a small amount of specific energy, power density related to the interaction time.
3.1 Cooling rate

The cooling rate is one of the important independent variables that determine the path of surface laser treatment in terms of the quality of the microstructures produced by the effect of this rate and thus on the total mechanical properties desired for the surface of the metal within the scope of this treatment. The laser processing variables related to the cooling rate were depicted in Table 3.

A review of the charts of the relationship between cooling rate and other variables related to laser surface treatment has shown many observations that can be summarized as follows:

1. The lower the interaction time, the more the cooling rate significantly until it reaches to 713000 (K/s) at 0.04 s for the sample D, as shown in the Figure 8.

2. The greater the power intensity, the greater the rate of cooling and significantly until it reaches to 713000 (K/s) at 3221.6 (W/mm²) for the sample D as shown in the Figure 9.

3. The increases in the specific energy up to 2866.2 (J/mm²), the high the cooling rate and significantly up to 450000 (K/s) for the sample C, as shown in the Figure 10.

Table 3. Laser processing variables (dependent and independent) related to the cooling rate.

| Samples | Power W | Beam diameter mm | Scanning speed mm/s | Power density W/mm² | Specific energy J/mm² | Interaction time s | Cooling rate K/s |
|---------|---------|------------------|---------------------|---------------------|----------------------|-------------------|-----------------|
| A       | 750     | 6                | 25                  | 26.5                | 5                    | 0.24              | 4.6X10⁴         |
| B       | 1500    | 6                | 12                  | 53                  | 20.8                 | 0.5               | 2.4X10⁴         |
| C       | 2250    | 1                | 12                  | 2866.2              | 187.5                | 0.08              | 4.5X10⁵         |
| D       | 3000    | 1                | 25                  | 3221.6              | 120                  | 0.04              | 7.13X10⁵        |

Figure 7. Structure of martensite within different zones that depicted in (a) and (b) related to samples A and B respectively.
Figure 8. Relationships of cooling rate with time interaction

Figure 9. Relationships of cooling rate with power density

Figure 10. Relationships of cooling rate with specific energy.
3.2 Micro – hardness

Micro-hardness represents the precise measure of the features of surfaces with fine microstructure of materials that contain multiple phases, when observing the diagrams of the relationships between the microscopic hardness of the melting zone and the dependent variables, the following can be explained:

When observing the diagrams of the relationships between the microscopic hardness of the melting zone and the dependent variables, the following can be explained:
1- The greater the interaction time, the less the hardness will reach to 465 Hv at 0.24 (s), as shown in Figure 11.
2 - The higher the power density values, the greater the hardness value, up to the value of 965 (Hv) at 3221 (W/mm²) as shown in Figure 12.
3 - The higher the specific energy, the greater the hardness to reach 945 Hv at 187.5 (W/mm²), as shown in Figure 13.

The best interpretation of this increasing is that the existence of some carbides are responsible for the development of hardness within these areas during the laser surface treatment.

Table 4. Laser processing variables related to the hardness.

| samples | Power W | Beam diameter mm | Scanning speed mm/s | Power density W/mm² | Specific energy J/mm² | Interaction time s | Micro-hardness Hv |
|---------|---------|------------------|---------------------|---------------------|----------------------|--------------------|-------------------|
| A       | 750     | 6                | 25                  | 26.5                | 5                    | 0.24               | 465               |
| B       | 1500    | 6                | 12                  | 53                  | 20.8                 | 0.5                | 851               |
| C       | 2250    | 1                | 12                  | 2866.2              | 187.5                | 0.08               | 945               |
| D       | 3000    | 1                | 25                  | 3221.6              | 120                  | 0.04               | 965               |

Figure 11. Relationships of microhardness with time interaction
4. Conclusion

From this study, conclusions can be brief as following:

1- The best result recorded for micro-hardness was to the laser combination power (3000 W), beam dia. (1) and speed (25 mm/s), and the lowest value was to the power (750 W), beam dia. (6) and speed (25 mm/s).

2- The microstructure evolution related to specific energy for each sample which determined the most features of this microstructure.

3- The ultimate cooling rate was found for laser combination, power (3000 W), beam dia. (1) and speed (25 mm/s).

4- The main phase for the structures of all samples is the martensite and differs in terms of shape and size related to the laser surface treatment.

5- There is a gradient of the microstructures which begins with the melting zone and then partial melting through the heat affected area and the base metal where it is a fine dendrite and sometimes completely non-dendrite due to non-fusion, but the hardening.

6- Precise selection of laser treatment variables will determine the required microstructures of the surface that effect on the mechanical properties positively.
References
[1] Semiatin S L 2005 Introduction to bulk-forming processes, ASM Handbook, vol. 14A, Metalworking: Bulk Forming, Materials Park, OH: ASM International, pp. 1–7.
[2] Altan T T 2005 Cold and Hot Forging Fundamentals and Application, ASM International, Ohio.
[3] Summerville, Venkatesan K, Subramanian C 1995 Wear processes in hot forging press tools, Mater Design 16 289-294.
[4] Mesquita R A and Arbor A 2016 Michigan, tool steel properties and performance, version date.
[5] Babu S, Ribeiro D, Shivpuri R 1993 Material and Surface Engineering for Precision Forging Dies, The Ohio State University199921. K. Lange, L. Cser, M. Geiger, J.A.G, Kals, Tool life and tool quality in bulk metalng Proc. Inst. Mech. Eng. 207 223-239.
[6] Wujiao X, Wuhua L, Yusong W 2014 Experimental and theoretical analysis of wear mechanism in hot-forging die and optimal design of die geometry Wear 318 78-88.
[7] Yin J, Hillert M, Borgenstam A 2017 Morphology of Proeutectoid Ferrite, Department of Materials Science and Engineering KTH Royal Institute of Technology Stockholm Sweden 48 1425–1443.
[8] Honeycombe R W K and Bhadeshia H K D H 1995 steels, Microstructure and Properties, 2nd ed., Edward Arnold, London.
[9] Spanos G, Reynolds W T and Vandermeer R A 1991 Metall. Trans. A 22A 1367–80.
[10] Bhadeshia H K D H 2001 Bainite in Steels, Transformation, Microstructure and Properties 2nd ed., the Institute of Materials, London.
[11] Yasaa E and Kruth J-P 2011 Microstructural investigation of Selective Laser Melting 316L stainless steel parts exposed to laser re-melting, aCatholic Procedia Engineering 19 389 – 395.
[12] Kusinsk J, Kac S and Kopia A 2012 Laser modification of the materials surface layer – a review paper Bulitin of the Polish Academy of Science 60 4.
[13] Kadhim M J, Ibrahim S and Sabea Hamm mod A 2013 The influence of laser specific energy on laser sealing of plasma sprayed yttria partially stabilized zirconia coating Optics and Lasers in Engineering 51 159–166.
[14] Patra D, Gopinnath M, Kumar A 2019 Effect of tempering on laser remelted AISI H13 tool steel, Department of Mechanical Engineering, Indian Institute of Technology, Kharagpur, India, Surface and Coating Technology.
[15] Bohlen A, Fribe H, Hunkel M, Vollertsen F 2018 10th CIRP Conference on Photonic Technologies [LANE 2018], Science Direct Procedia CIRP 74 192–195.