

Crystalline Phase Changes due to High-Speed Projectiles Impact on 304L Steel

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ABSTRACT

High yield 304L steel is well known for its employment in manufacturing. The quenched and tempered low-carbon alloy has a minimum yield strength of 40-50 ksi. Also, 304L offers good corrosion resistance and weldability. Traces of Chromium and Nickel in 304L give it the desired corrosion resistance properties. So, it is an ideal candidate for pressure vessels and the petrochemical industry applications. The physical characteristics and molecular structure of 304L steel are also well known; however, little is known about the high-velocity impact on this metal alloy's crystalline structure and material phase changes. The effects of high-speed velocity impact on the crystalline structure and material phase changes due to impacts are studied herein experimentally. The high-speed impact on the crystalline structure's inevitable phase change is examined, let alone the atomic reorganization resulting from the impact on the 304L steel. The effects of an impact on the crystalline structure are assessed by impacting 304L steel plates (15.4 x 15.4 x 1.27 cm) with Lexan projectiles. A two-stage light gas gun accelerates these projectiles to a velocity of 6.70 km/s at the point of the impact. The impacted plates' surfaces are prepared for the Electron Back Scatter Diffraction (EBSD) microscope inspection. Nine regions on each impacted plate area are examined and analyzed. Each part (90x90) square microns were cut off the test samples, keeping with the required surface finish standards. These regions are selected from the area immediately under the impact crater to locations not physically affected by the impact.

Observations of collected EBSD images show that the predominant phase is Body-Centered Cubic (BCC); Face-Centered Cubic (FCC) and Hexagonal-Close-Packed (HCP) phases are also indexed. Since these crystalline structures are the most expected lattice formations, the samples are post-impact examined for molecular structure allocation changes. The results were then tabulated according to the region's relative impact crater. Previous research, A36 steel results show that post-impact inspection of HCP phase change, in iron specifically, is completely and rapidly reversible during impact. However, in this study, traces of HCP were found at some locations in all post-impact stages. This study also indicates that the BCC crystalline structure remained the dominant phase structure after impact, and it is valid with all test samples and all levels of shock loading. High pressure and the temperature quickly affect the target material at 6.70 km/sec velocity. The damage zone develops within 5 microseconds at this velocity due to impacting momentum

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Introduction

High yield 304L steel is a unique alloy known for its employment in construction and has many global applications. The quenched and tempered low carbon 304L stainless steel plate has a minimum tensile strength of 70 ksi and a yield strength of 0.2% of 25 ksi. [1]. It also provides good ductility, first-class toughness, corrosion resistance, and weldability. Traces of Chromium and Nickel in 304L give it the desired corrosion resistance properties. These properties make 304L an ideal candidate for applications in pressure vessels and petrochemical industries. High velocity impact on metals often causes surface damage and permanent deformation. The Electronic Spectral Microscope (ESM) can only detect the effects on the crystalline and atomic levels [2,3].

The physical characteristics and molecular structure of 304L steel are well known. Backscatter Diffraction and Transition Electron Microscopy have identified evidence of microstructural phase transition and modifications. Hixon, Gray, and Dougherty discovered that body-centered cubic (BCC) alpha-iron (α) undergoes

a fully reversible phase transition to Hexagonal Close Packed (HCP) epsilon-iron (ϵ) at room temperature and 13.00 GPa [4-6]. Plate areas are examined. Each region is approximately (90x90) square microns. These regions are selected from the area immediately under the impact crater to locations not physically affected by the impact.

The effects of high-speed velocity impact on the crystalline structure and material phase changes are studied herein experimentally. The high-speed impact on the crystalline structure's inevitable phase change is examined, let alone the atomic reorganization resulting from the impact on the 304L steel. The effects of an impact on the crystalline structure are assessed by impacting 304L steel plates (15.4 x 15.4 x 1.27 cm) with Lexan projectiles. A two-stage light gas gun accelerates these projectiles to a velocity of 6.70 km/sec at the point of the impact [7-8]. The impacted plates' surfaces are prepared for the Electron Back Scatter Diffraction (EBSD) microscope inspection. Nine regions on each impacted plate area are examined. Each region is approximately (90x90) square microns. These regions are selected from the area immediately under the impact crater to locations not physically affected by the impact.

Background and Definitions

The polymorphic transformation results from shock-loaded iron have been studied in several publications. Wang, S.J. et al. have studied phase transition in shock-loaded iron [9]. According to Wang, martensitic transformation α (BCC) in iron under shock-loading expressed a reversible and transient nature. He observed the transformation $\alpha \rightarrow \epsilon$ (BCC HCP) in iron under shock-loading. The results indicate two sequential martensitic reversible α -phase transformations in the refined microstructural fingerprints. These transformations occur even if no ' ϵ ' is retained in the post-shock samples. His observation of ambient temperature and atmospheric conditions shows that A36 Steel is stable in its BCC (α)-phase body-centered-cubic (BCC) crystal structure.

A similar behavior could also be observed in 304L steels. At high impacts or pressures, some phase changes occur. According to Wang BCC takes the form of HCP (ϵ), in other words, switch to the network (HCP) [8]. While the phase diagram for iron under hydrostatic pressure is well established it is difficult to ascertain what happens in iron when subjected to shock loading [4]. Understanding dynamic phase evolution is closely related to many iron and steel applications in blast and shock handling conditions, which should agree with Wang [9]. The results of microscopic examination of test samples are viewed. Examination of the prepared samples in the study depended on two kinds of microscopy EBSD and XRD. The first one is used to find the unit cell of the crystal system and determine the phase percentage with microstructure maps of the grain and phase. The second one is used to measure the lattice parameters and the orientation.

Crystalline Phase

In crystallography, crystal structure is an arrangement of atoms in a framework pertinent to the type of crystal called a unit cell. A set of atoms is arranged periodically and repeated in three dimensions on a lattice. Crystal lattices have an extended range of regular orders. The distance between a unit cell and one next to it is called Lattice-Distance. The three most common unit cells' arrangements are discussed in the following sections, namely Body-Centered-Cubic (BCC), Face Centered Cubic (FCC), and Hexagonal Close Packed (HCP). These arrangements are referred to as a particular phase structure [8]. Table 1 shows the chemical composition of 304L steel.

Table 1: Chemical composition (%) of 304L [1]

Elements	Symbols	304L
Iron	Fe	66.9 - 74.5
Nickel	Ni	8.00 - 10.5
Chromium	Cr	17.5 - 19.5
Manganese	Mn	0.00 - 2.00
Carbon	C	0.00 - 0.03
Copper	Cu	0.00
Molybdenum	Mo	0.00
Silicon	Si	0.00 - 1.00
Phosphorous	P	0.00 - 0.05
Vanadium	V	0.00
Sulfur	S	0.00 - 0.02
Titanium	Ti	0.00

Materials and Methods

Test and Measurement Protocols

The primary source of examination of our specimens is (EBSD).

The patterns effectively project the geometry of the lattice planes in the crystal. They give direct information about the crystalline structure and crystallographic orientation of the grain from which they originate.

Impact Experiment Geometry and Materials

Figure-3 shows photographs of the 304L target plates before and after impact, along with the sample preparation cutting T-shaped geometry, similar to the geometry used for the A36 targets. All the Target plates' details are mounted to a support plate explained in our previous work [10-16]. The target plates are cut into square shapes that fit conveniently inside the target chamber. Target plates are mounted to a support plate attached to the internal frame of the target chamber. All target plates have the same dimensions. They are 15.2 cm x 15.2 cm x 1.27 cm. They are impacted with a cylindrical Lexan projectile with a 5.6 mm diameter and 8.6 mm length. The target plates are impacted with projectiles at speeds selected to induce significant plastic deformation without completely penetrating the target. The visually observable damage on a typical target plate's front and back sides is observed. The crater diameter can be slightly more than three times the projectile diameter (~ 17 mm) for the faster impact velocity. The crater's depth measured from the flat region on the front surface was up to 6.6 mm, and the bulge on the back surface was up to 3.5 mm, measured from the flat region of the back surface. The visually observable damage on the front and back sides of a typical target plate is shown in Figure 1. The crater diameter can be slightly more than three times the projectile diameter (~ 17 mm) for this impact velocity.

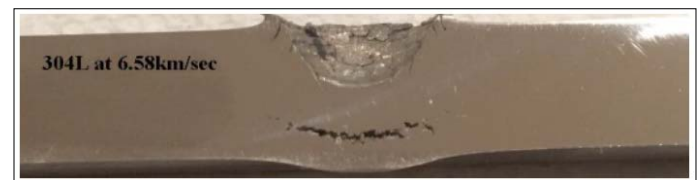


Figure 1: Crater Zone in 304L Targets Subject at 6.58Km/s

Target Plate Sectioning and Cross-Section Zones Slicing

Each impacted plate was initially cut in half through the center of the impact crater. The target materials were further cut into a T-Shape to expose six different cross-sections and prepare for microstructural analysis. A water jet machine cutting procedures were controlled to minimize the addition of temperature to the cutting surfaces. Figure -3 shows the selected locations of the center of the slide for EBSD viewing are designated as follows: Sample (1): Centered 75 mm away from the impact crater, the thickness is 12.7 mm
Sample (2): Centered 35 mm away from the impact crater, the thickness is 12.7 mm
Sample (3): centered 7.5 mm from the impact (the thickness is 12.7 mm,) on the other side of the T- Section.
Sample (4): Centered 20 mm and thickness is 12.7 mm
Sample (5): Centered 10 mm and thickness is 12.7 mm
Sample (6): Centered at the impact area Specific regions are selected and marked with letters (A, B, C, D, etc.) in any of these samples, as shown in Figures (8 and 9). The sample number and the area letter constitute the EBSD inspection and analysis locations.

Results and Discussion

EBSD has been used to examine the impacted samples in one suggested impact speed Figure 1. shows a cross-section view of an impacted specimen. The picture indicates the crack area and what to consider the immediate impact region: otherwise, regions are designated as distant spots. Examination of the prepared samples

in the study depended on two kinds of microscopy: First, EBSD is used to find the crystal system unit cell and determine the phase percentage with a microstructure map of the grain and phase. Second, XRD can measure the distance between the lattice parallel surfaces. This distance is defined as the lattice constant (d) [3].

Non-Impact EBSD Grain Structure View

As Received 304L Steel (non-impact), the results show it has three phases BCC, FCC, and some small percentage of HCP, as shown in figure 4. The actual phase of this kind of steel is BCC and FCC. EBSD effectuates grain Structure Phase Measurements. Figure-5 shows the grains boundary and the magnification of the microscopy 400X and the crystal orientation, with the phase percentage shown in Table-1. EBSD results of 304L steel plate show two phases, BCC and FCC, co-exist in their microstructure, both in significant amounts, yet with a trace of HCP with the non-impact ratios of 33.109 %, 66.718 %, and 0.1724 %. This result shows that the main phase contents of this kind of steel are BCC and FCC. Transition and change locations of the grains inside the crystal of non-impact 304L are examined. Before the shock, the angle range was (0-1.30°). Because the crystal system and stable raw material were not exposed to any load. 304L steel is a heat-resisting metal. Figure -5 shows the state system, and the misorientation angles are between (45-55°). This state means no orientation or dislocation in the plan of the crystal.

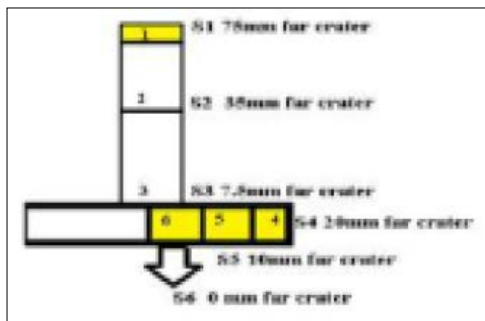


Figure 2: T-shaped Bars with Dimensions

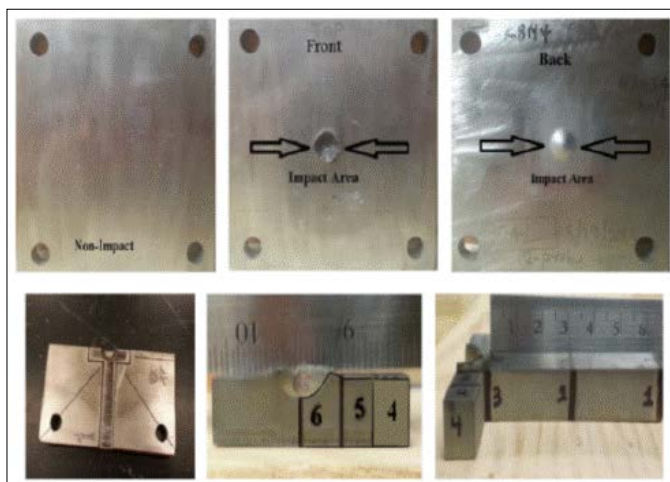


Figure 3: Non-impacts and Impact 30L steel and Impact at 6.58 km/sec. Location of Six Cross-Sectional Regions used for Microstructural Analysis

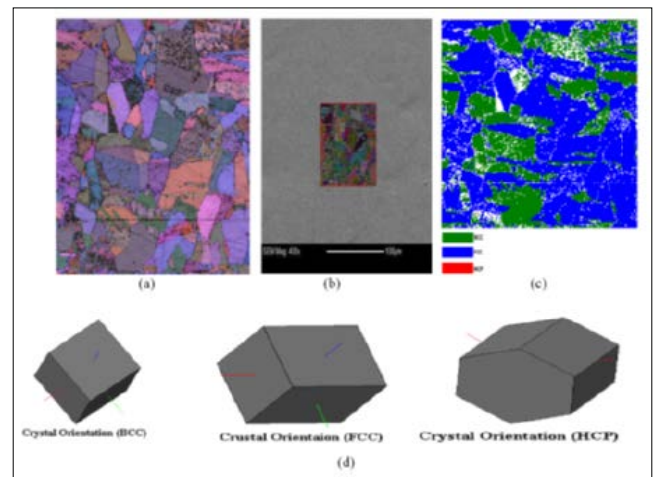


Figure 4: Non-Impact Microstructure Photo of EBSD

Table 2: Non-Impact Phase Percentages of 304L Steel

Crystal Unit Cell Structures	Non-Impact 304L Steel Phase
BCC	33.1092 %
FCC	66.718 %
HCP	0.1724 %

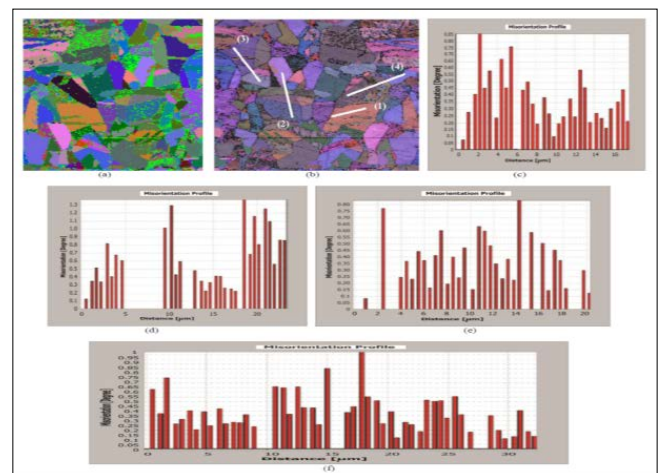


Figure 5: Figure 4 (c) Misorientation angle measured along four different lines in the non-impacted 304L steel, the sample shows: a) EBSD shows less noise, b) EBSD shows grains, c) Line 1, d) Line 2, e) Line 3, and f) Line 4

Impact Velocity of 6.7 km/s on 304L Steel

The following locations are selected for comparison and analysis Cross-section Location 1-C (75 mm from impact center) In this site sample 75 mm away from the crater, the 304L steel in this site was not affected, phase crystalline stayed the same, and did not shows any sign of the formation of the plastic or twinning. Figure-8 shows the EBSD microscopy data for location 1-C in the 304L steel target after an impact velocity of 6.58 km/sec. The figure shows the polished sample, grain, 400X magnification, the map's original length, and the phase distribution.

Cross-Section Location 6-A (0 mm from Impact Center)

Figure-9 shows the EBSD microscopy data for location 6-A in the 304L steel target after an impact velocity of 6.58 km/sec. The figure shows the polished sample, grain, 400X magnification, the

map's original length, and the phase distribution. Although the location is close to the arc shot vicinity, the image of the EBSD microscope became apparent and did not show any change in the particle size or the presence of any form of plastically. This behavior means that the alloy was not affected by the shock under a high temperature and a high pressure.

Cross-Section Location 6-B (0 mm from Impact Center)

Figure-10 shows the EBSD microscopy data for location 3-A in 304L steel target after an impact velocity of 6.58 km/sec. The figure shows the polished sample, grain, 400X magnification, the map's original length, and the phase distribution. Table 4 lists the Impact phase ratios of 304L steel at 6.58 km/sec sample location 6-B.

Cross-Section Location 6-C (0 mm from Impact Center)

Figure-11 shows the EBSD microscopy data for location 6-C in 304L steel target after an impact velocity of 6.58 km/sec. The figure shows the polished sample, grain, 400X magnification, the map's original length, and the phase distribution. No significant or dramatic changes occurred post-impact of 304L steel under this high speed of impact.

Cross-Section Location 6-E (0 mm from Impact Center)

Figure-12 shows the EBSD microscopy data for location 6-E in the 304L steel target after an impact velocity of 6.58 km/sec. The figure shows the polished sample, grain, 400X magnification, the map's original length, and the phase distribution. No significant or dramatic changes occurred post-impact 304L steel under this high impact speed. Although the lowest impact affected A36 steel, let alone an even more effect on the HY100 steel, the existence of FCC having a high percentage significantly have affected the results. Before impact (BCC and FCC), since FCC is a transitional phase before transfer and reaches the hexagonal HCP phase. This is why the percentage of FCC is high through all locations of samples of 304L. The selection sample 6 locations C is a low percentage of error and higher confidence as illustrated and discussed in chapters 6 and 7.

One 304L target plate from the impact velocity condition was evaluated. The geometry of the damage zone in the 304L target due to impact velocity is shown in Figure 7. Additionally, the depth and width of the hole on the front side are measured with a caliper. Enlarged views of the impact section give special attention to scanning for more than one point on that section's surface. Figure 8 shows the misorientation angle of the crater (45-55°). The plastic deformation is deformed, and the grains dislocate the plane to another plane as a twinning deformation.

The real phase of this kind of steel is BCC and FCC. In this kind of steel, the choice is only one high-speed impact of 6.58 km/sec, and after that, it was found that the high speed of A36 steel has had the biggest share of the appearance of change-phase HCP and twinning deformation. Of all the results stated above in the tables and images as shown here of this iron alloy type, this type of steel 304L does not change its crystalline phase during impact shock under high temperatures and pressure. This phenomenon is because this type of alloy has the initial phase before impacting BCC and FCC since FCC is the transitional first phase to reach the hexagonal HCP phase. So, the percentage of FCC is high throughout all locations and samples of 304L. The grained stability on the crystalline level did not exceed the plastic limits or twinning deformation crystalline. This stability shows that this kind of Iron alloy shocked unimpaired under high pressure,

and the temperature has been the crater area test and near crack figures as shown in figure 9.

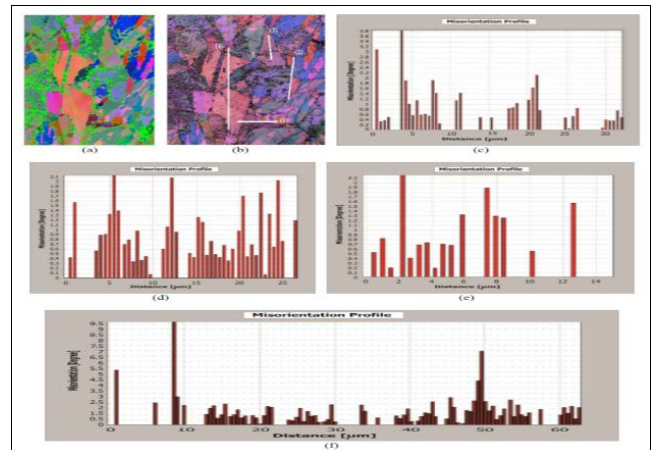


Figure 6: Figure 4 (d) Misorientation angle measured along four different lines in the impacted 304L steel, sample location 6-A after impact velocity of 6.58 km/sec shows: a) EBSD shows less noise, b) EBSD shows grains, c, d, e, and f are the Lines (1, 2, 3, and 4) respectively

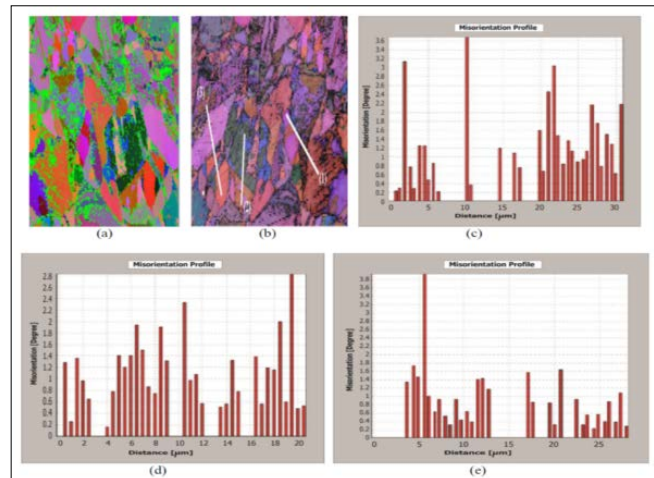


Figure 7: Figure 4 Misorientation angle measured along four different lines in the impacted 304L steel, sample location 6-B after impact velocity of 6.58 km/sec shows: a) EBSD shows less noise, b) EBSD grains, c) Line 1, d) Line 2, and e) Line 3

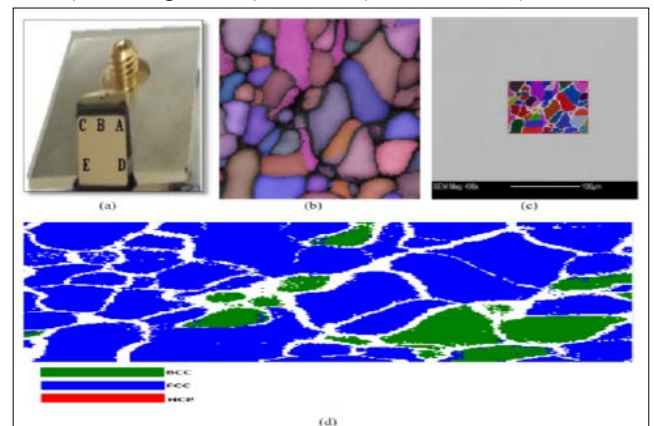


Figure 8: Figure 4 EBSD data from 304L steel, sample location 1-C, after impact velocity of 6.58 km/sec showing: a) polished sample, b) grain, c) 400X magnification and the original length of the map, and d) phase map.

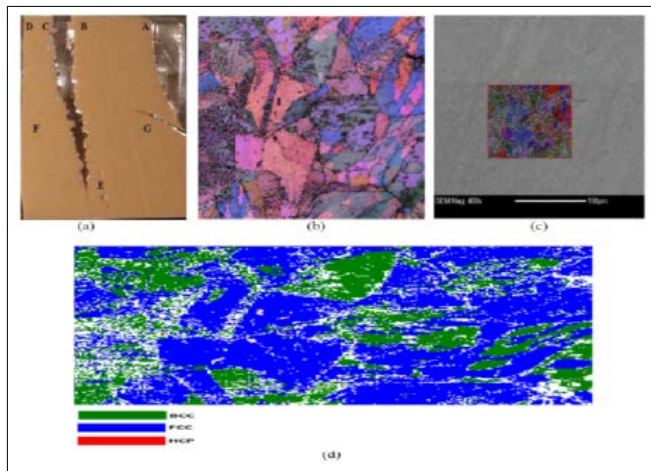


Figure 9: Figure 4 EBSD data from 304L steel, sample location 6-A, after impact velocity of 6.58 km/sec showing: a) polished sample, b) grain, c) 400X magnification and the original length of the map, and d) phase map

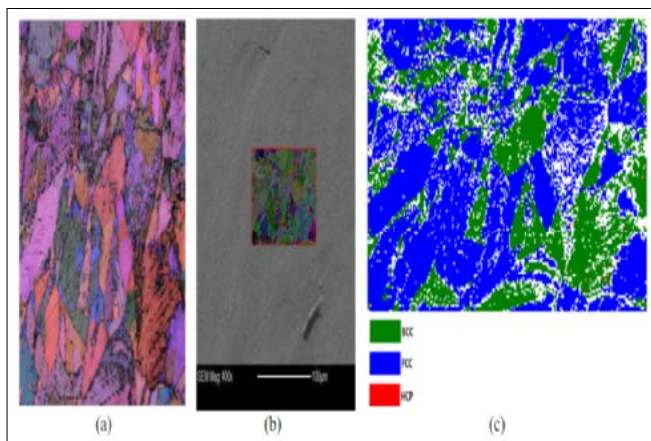


Figure 10: Figure 4 EBSD data from 304L steel, sample location 6-B, after impact velocity of 6.58 km/sec showing: a) grain, b) 400X magnification and the original length of the map, and c) phase map.

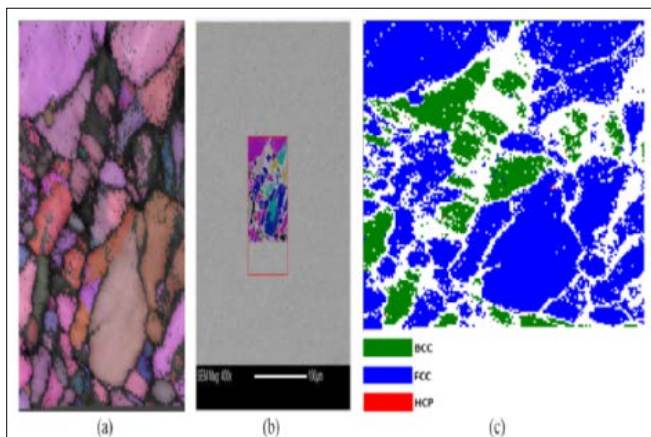


Figure 11: Figure 4 EBSD data from 304L steel, sample location 6-C after impact velocity of 6.58 km/sec showing: a) grain, b) 400X magnification and the original length of the map, and c) phase map.

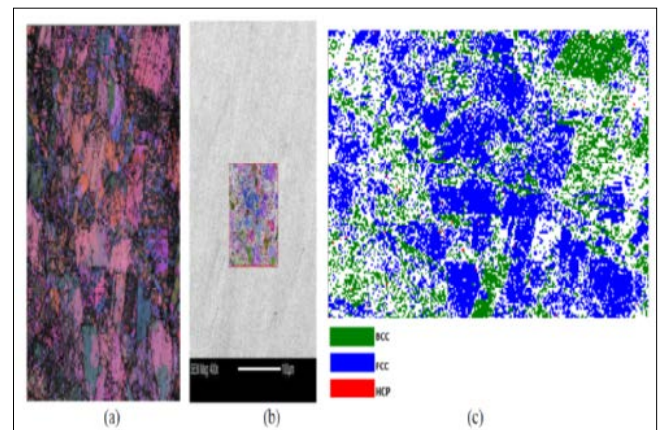


Figure 12: Figure 4 EBSD data from 304L steel, sample location 6-E, after impact velocity of 6.58 km/sec showing: a) grain, b) 400X magnification and the original length of the map, and c) phase map.

Throughout the results, images and tables indicate that 304L steel is slightly changed due to impact. Some steel's crystal phase is changed from BCC to FCC and HCP. The presence of HCP proves that the phase crystal has changed, and plastic deformation and twinning start forming on the grains' plane. They left the plane near the crater's arc and altered the BCC, HCP, or FCC crystal phase. The crystalline system remained organized. Among other things that were not observable due to the microscope's possibility of reading the arc crater's immediate area, the results in those areas deviated and cannot be relied upon. Sample G is selected because of the low error percentage and higher confidence illustrated.

FCC existed with insignificance pre-impact and became significant post-impact at the point of impact and the surrounding areas. However, this occurred with a lower percentage and became insignificant again away from the point of impact. The EBSD imaging samples (post-impact) observed that the grain size significantly decreased closer to the impact area (Arc of the projectile) plane that EBSD cannot scan. This area's error was so high and confidence so little, as shown at location A1, so the result is the average area.

From the above figures and diagram, it is evident that:

- The non-impacted zone does not have any HCP or a significant amount of FCC
- Increasing impact momentum increased the HCP Percentage.
- Near the crater, the HCP is higher percentile than in a region farther away.

Grain size near impact is compacted near the impact site. A light gas gun uses a gunpowder hole to fire a plastic piston into a pump tube filled with helium or hydrogen. The diluted gas is compressed as the piston moves through the pump tube. The petal valve separates the light gas from the release tube under high pressure. Deformation, which consists of slipping and twinning, is highly inelastic. At this point, it has become dominant and irreversible.

While examining 304L steel-post impact, the effects were visible to the naked eye, but the microstructure was also significantly changed. One observation was 'twinning.' twinning was present closer to the impact area and gradually dissipated further from the impact zone. Twinning was most significant during the testing of the samples from the 6.7 km per second speed impact. Another

observation of the samples from the EBSD imaging (post-impact) was that the grain size significantly decreased closer to the impact area. Further away from the impact area, the grain size was less affected and resembled pre-impact sizes. It was also discovered that the higher speed impact samples showed more evidence of a reduction in grain size than in the slower speed impact samples [15].

More research is needed to examine different orientations to observe how twinning is formed concerning the impact area. Observing different orientations should also provide further insight into the decreasing grain size around the immediate impact area. Another point of interest would be to test hardness, pre-and post-impact, to examine the material's behavior change. The presence of HCP (post-impact) leads to the probable conclusion of an increase in brittleness. The preliminary results and post-impact observations beyond 13 GPa, sub-structural evolution, and mechanical behavior of 304L steel agree with many types of research on similar experimental after-shock data on similar iron and alloys, such as in Gray, Hayes, and Hixon [4].

Regarding orientation and rotation, additional evidence of twinning in the examined samples by the EBSD has been tabulated as phase-ratio changes. When the changes in the misorientation profile range from 55 to 60 degrees in a range of 0.02 mm length between two points. This is clear evidence of the existence of twinning. Conversely, a change of 0.1 to 3.0 degrees indicates no twinning deformation.

Misorientation is calculated from one orientation's product (or composition) and the other's inverse. Figure 9 shows the angle phase crystalline transition in the grain boundaries of non-impact 304L steel. The raw material is stable and precise, and the prominent grain of the misorientation angle is in tiny crystals ranging from 0-1.60°. The misorientation angles at 3mm, far from the projectile's impact arc. The HCP phase in this location increased. Twinning was also noted to have risen- all lines show that the new deformation starts here and changes the BCC phase to FCC and HCP.

Discussion

EBSD results of 304L steel plate show two phases, BCC and FCC, co-exist in their microstructure, both in significant amounts, yet with a trace of HCP with the non-impact ratios of 33.109 %, 66.718 %, and 0.1724 %. This result shows that the main phase contents of this kind of steel are BCC and FCC.

Post-impact examination of the 304L steel cross-sections samples 1 to 6 shows the percentage values of HCP were, in sequence, 0.0188 %, 0.1225 %, 0.221 %, 0.281 %, 1.6445 and 1.699 %, with an estimation error of less than 10 % as shown in Table 6.7. One test location point was selected about 2000 microns away from the edge of impact. Analyzing the EBSD test results showed that this type of steel 304L does not change its crystalline phase during impact shock under a high temperature and pressure. This type of alloy already has a significant amount of FCC phase combined with the original BCC that exists in the pre-impact test. FCC is a transitional phase pre-formed to the hexagonal HCP phase. This explains that the high percentage of FCC throughout all test point locations for the 304L steel and the phase alteration did not exceed the plastic limits or twinning deformation. Grains in this alloy are obviously more stable at the crystalline level. These iron alloys show resistance to phase changes behavior under high pressure shocks even close to the crater and impact holes, as the figures.

The cross-sections post-impact test sample show the percentage values of HCP at sections 1, 2, 3, 4, and 5, are in order: 0.0188 %, 0.1223 %, 0.221 %, 0.281 %, and 1.644 % respectively. However, at cross-section number 6, at the impact site, selected point C, at 1000 micron from the hole's edge, shows an insignificant value of HCP 0.092 % and 9.17 % accuracy. The location test of point A result has been ignored, which shows a low confidence error of more than 20 % and an HCP percentage of 1.699 %, which is less reliable than point C.

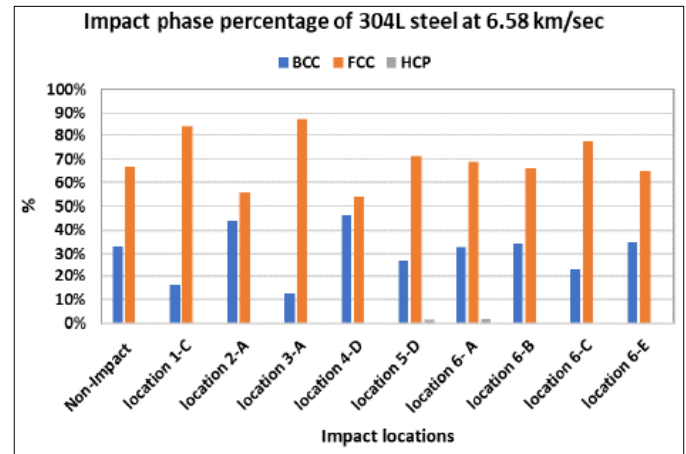


Figure 13: Impact phase percentage of 304L steel at 6.58 km/sec vs. sample location

Conclusion

The 304L steel show has three phases: BCC, FCC, and some small percentage of HCP 33.109 %, 66.718 %, and 0.1724 %, respectively. The real phase of this kind of steel is BCC and FCC. In this kind of steel, the choice is only one high-speed impact of 6.58 km/sec, and after that, it was found that the high speed of A36 steel has had the biggest share of the appearance of change-phase HCP and twinning deformation. For the 304L steel, the percentage of HCP ratio is at the section's samples 1 to 6, 0.0188 %, 0.1225 %, 0.221 %, 0.281 %, 1.6445 % and 1.699 %. Of all the results stated above in the tables and images as shown in chapter 4 of this iron alloy type, this type of steel 304L does not change its crystalline phase during impact shock under high temperatures and pressure. This type of alloy has the initial phase before impacting BCC and FCC since FCC is the transitional first phase to reach the hexagonal HCP phase. This is why the percentage of FCC is high throughout all locations and samples of 304L. The grained stability on the crystalline level did not exceed the plastic limits or twinning deformation crystalline. This shows that this kind of Iron alloy shocked unimpaired under high pressure, and the temperature has been the crater area test and near crack figures as shown in chapter 4.

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