

Effect of Hot Deformation on Impact Toughness of High Strength Steel

Sandeep Kavathekar, Vijay Hiwarkar, Vinayak Pawar and Rajkumar Singh

Abstract—High Strength steel offers good combination of strength and toughness properties. These properties of high strength steel are strongly influenced by the hot deformation and controlled cooling parameters. The hot deformation behavior of low carbon high strength steel and its effects can be entailed and detailed by the analysis of microstructural and mechanical properties. In the present study, hot deformation was carried out in the temperature range of 1060°C to 1300°C followed by natural air cooling and forced air cooling. The microstructures were characterized by Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). The mechanical behavior was investigated by hardness, tensile and Charpy V-notch impact tests. The test results indicate that, decrease in deformation temperature from 1300°C to 1060°C increases the impact strength from 13J to 31J. The microstructure evaluation shows that the toughness of the steel was enhanced by the formation of fine Bainitic sheaves and finer bainitic packets in lath-like bainitic structure at lower deformation temperature.

Index Terms—High strength steel, mechanical properties, toughness, bainite sheaves.

I. INTRODUCTION

Automotive components are traditionally made using the forging process with steels which can be categorized as ferritic/pearlitic and quench tempered steels. The problems with these conventional steels are that they have either low strength (ferritic/pearlitic steels) or poor toughness (quench tempered steels). Moreover, in order to achieve good mechanical properties after forging, heat-treatment processes such as hardening, tempering and stress relieving are required. By using High Strength Steels (HSS) all the above mentioned heat-treatment processes after forging can be replaced with controlled cooling. Further, HSS offers excellent hardness properties like martensitic steel and gives suitable relative toughness properties resembling the pearlitic steel. Hence, High strength steel is the most preferred steel used for manufacturing critical automotive component by forging [1], [2].

High strength steel universally comprises of ferrite and cementite. High strength steel has a plate-like microstructure

or a fine non-lamellar structure that forms in steel at temperature of 250-550 °C. It is obtained, when austenite is cooled rapidly enough to avoid forming pearlite, but deferred long enough to avoid martensite. The phase thus formed is called Bainite. It has certain hardness properties of martensite & some toughness properties of pearlite. The extraordinary concentration of dislocations in the ferrite present in this microstructure makes it harder than it normally would be.

Bainite gives the hardness values in between the pearlite and martensite because of which no supplementary heat treatments are required [1], [2]. Formation of bainite comprises both diffusional and displacive mechanism [3], [4]. Bainite transformation comprises cooperative competition of sympathetic nucleation and ledge wise growth [5].

The manufacturing processes used to make parts with these steels have a great impact on the microstructure and hence, properties of the steel. It has been reported that bainite packets size is dependent on the austenization temperature range. At lower austenization temperature range bainite packets are finer and it becomes coarser as the austenization temperature increases. The change in packet and block size intensely effect on the toughness of the steel. Increased size of bainite packets shows lowered absorbed energy and toughness [6]. Some researchers consider that packet size is the dominative substructure for controlling the toughness [7], whereas, some considers, it is the size of block [8].

Deformation parameters also affect the microstructure. At lower deformation temperature, bainite is very fine (20-40 nm thick), which makes Bainitic steel strong as well as tough [9]. As the cooling time increases morphology changes from small dot-shaped (granular bainite) to elongated block-shaped (lath-like bainite) [10]. Lath-like bainite gives high toughness as compare to granular bainite [11].

II. EXPERIMENTAL WORK

A. Material

Low carbon micro-alloyed High Strength Steel has been used for this forging experiment. Metallographic examinations and microstructures (OM-images & SEM-Images) of the as-received material is shown in Fig. 1.

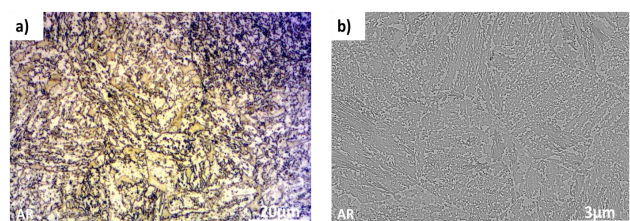


Fig. 1. Microstructure of the as-received steel. a) OM image and b) SEM image.

Manuscript received May 24, 2019; revised December 27, 2019.

Sandeep Kavathekar is with the Kalyani Centre for Technology & Innovation (KCTI), Bharat Forge Ltd., Pune, Maharashtra, India (e-mail: sandeepkavathekar@bharatforge.com).

TABLE I: CHEMICAL COMPOSITION

Element	C	Mn	Si	S	P	Cr
Content	0.18	1.75	0.77	0.017	0.014	1.32

B. Forging Experiment

The hot deformation experiments were carried out on 1.5 ton RATTAN made hammer. To heat the billet 50 kW Induction billet heater of EMT Magatherm make was used for the experimentations. L/D Ratio for this billet was 1.5. Fig. 2 shows the details of deformation and its temperature ranges. Samples were deformed at each temperature. Two cooling rates were used post deformation i.e. natural air cooling and forced air cooling. Each sample was deformed by 60 %. Mounting of all the samples were done on STRUERS CITOPRESS-10 machine. A CARL ZEISS optical microscope with Image Analyzer software Z.2m was used for microstructure analysis. The Etching of the samples for examining the microstructure of the bainite was done with 2% Nital (5 to 10 Sec) while 4% picral (3 to 6 min) (4 gm picric acid in 100 ml ethyl alcohol) was used for grain size analysis. SEM images were captured using a SEM of CARL-ZEISS MA EVO18 make, equipped with an X-ray energy dispersion system operated at 5-20 kV.

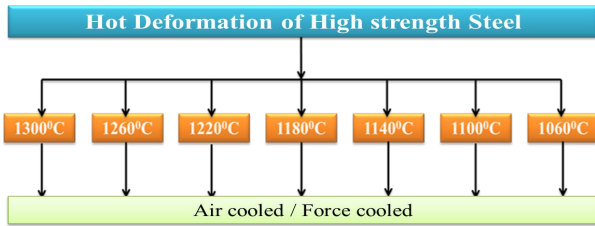


Fig. 2. Deformation flow chart.

C. Mechanical Testing: (Hardness, Impact and Tensile Test)

Hardness value of all forged samples with different forging temperatures and raw material were determined at a load of 3000 kg by using Brinell hardness tester. Impact toughness for all deformed samples was investigated with the help of Charpy impact testing machine of Zwick Roell make. 2 mm V-notch impact test samples were made as per ASTM-E23-12C. Ultimate tensile strength and Yield strength was measured with the help of tensile test on UTM of Zwick Roell make. The tensile test specimen & tests were carried out in accordance with ASTM E8 M.

III. RESULTS AND DISCUSSIONS

A. Hardness

Fig.3 shows the effect of hot forging temperature (ranging from 1300 °C to 1060 °C) on the hardness of the steel. Hardness of the as-received material was 34 HRc. Following can be observed from Fig. 3: For air cooled specimen, hardness was found to be fluctuating in between min 34 HRc to max 37 HRc. Similarly for forced cooled samples hardness varies between 34 HRc to 37 HRc. Thus, the forging temperature has no significant effect on the Hardness of the Air cooled samples or forced cooled samples. Similarly,

when normal air cooling and forced air cooling is compared, these cooling rates also do not have any significant effect on the hardness of the as forged samples.

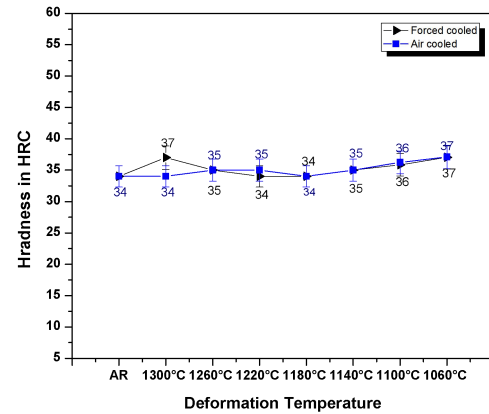


Fig. 3. Effect of hot deformation temperature on Hardness of High strength steel.

B. Tensile Test Results

Room temperature tensile test was carried out on the samples forged at different forging temperatures (1300°C, 1260°C, 1220°C, 1180°C, 1140°C) and for the as received material also. Fig.4 shows the effect of deformation temperatures on the tensile strength. Tensile strength for as-received sample was 1127 MPa. Following can be observed from the Fig. 4: There is no significant effect of the forging temperature (1300°C to 1140°C) on the Ultimate tensile strength of the air cooled and forced cooled samples. Further, the cooling rate (normal air cooled and forced air cooled) does not have any significant effect on the tensile strength of the as forged samples.

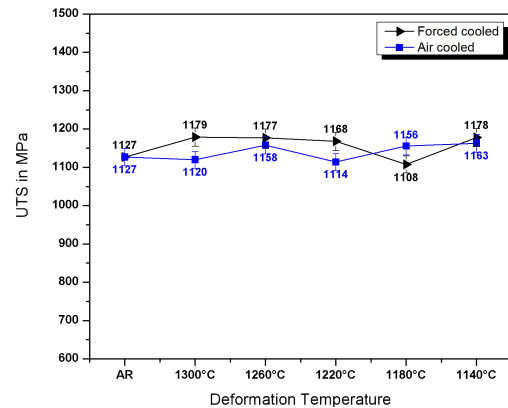


Fig. 4. Effect of hot deformation temperature on Ultimate tensile strength of High strength steel.

Similar behavior was observed in case of yield strength also which is presented in the Fig. 5.

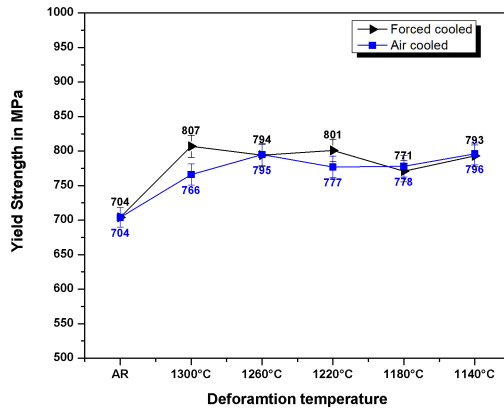


Fig. 5. Effect of hot deformation temperature on yield strength of High strength steel.

C. Impact Properties

Charpy impact tests were done on all deformed specimens (1300°C, 1260°C, 1220°C, 1180°C, 1140°C, 1100°C, 1060°C) and raw material at room temperature. Fig. 6 shows the graph of deformation temperatures Vs. Impact strength. The results indicate the following: The Impact strength or toughness of the steel increases with reducing deformation temperatures or forging temperatures of the steel. As we find the 12J impact strength in as-received material and it gives the incremental trend with the reducing forging temperatures. From temperature 1300°C to 1140°C, the variation in impact strength is linear for both air cooled and force cooled samples. Below 1140°C the change in impact values were exponential (16.9 J to 31.1 J for air cooled and 18.3 J to 30.6 J for force cooled).

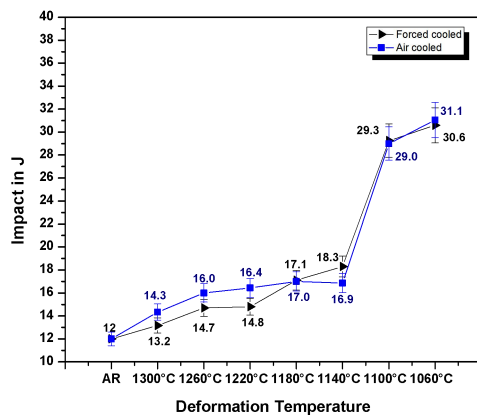


Fig. 6. Effect of hot deformation temperature on impact strength of High strength steel.

D. Microstructural Investigation

1) Optical imaging

From previous investigation it is found that impact toughness increases with reduction in deformation temperature while the same has insignificant effect on tensile and hardness properties. To investigate the reasons behind this behavior, microstructure analysis was carried out. From the OM micrographs of as-received material (Fig. 1) and forged samples at various temperatures (Fig. 7) following can be observed: It is observed that Bainitic microstructure with higher grain size as well as coarser sheaves of bainite is present in the as received material. With decrease in forging temperature from 1300 °C to 1060 °C, finer grains and

sheaves of bainite are obtained. Lower deformation temperature 1060 °C, results in fine Bainitic sheaves and causes improvement in the toughness of the steel. Similar results were obtained by Yi Luo, Zhi-Jun *et al.* [11].

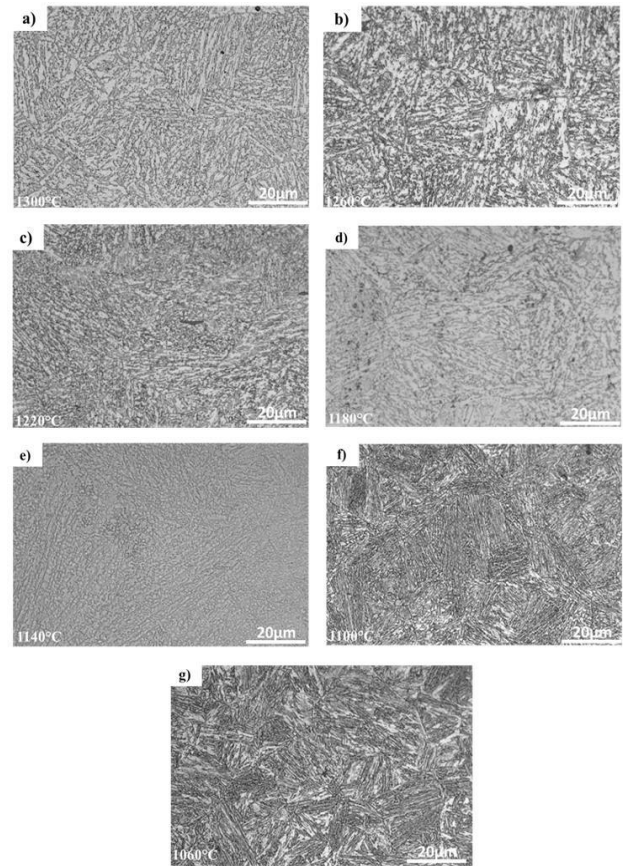


Fig. 7. Light optical micrographs of air cooled low carbon High strength steel deformed at a) 1300°C, b) 1260°C, c) 1220°C, d) 1180°C, e) 1140°C, f) 1100°C and g) 1060°C.

2) Scanning Electron Microscopy

Fig. 8 illustrates the SEM images of all the forged samples with different temperature ranges. Following can be observed from the SEM analysis: Granular morphology is observed at deformation temperature 1300 °C, as shown in Fig. 8(a). Microstructures of granular bainite consist of equiaxed ferrite structure. With reduction in deformation temperature (1260 °C to 1140 °C) morphology transformed into mixture of granular bainite and Lath-like bainite as shown in Fig. 8(b) to Fig. 8(e). Lath-like bainite comprises the thin, long parallel ferrite laths. Fig. 8(f) to Fig. 8(g) shows that 100% lath-like bainite morphology is observed with lower temperature deformation samples (1100°C to 1060°C). These transformations in morphologies with reduction in deformation temperature cause improvement in impact toughness [12].

E. Bainitic Sheaves Width, Bainitic Packets Size and Grain Size

Subsequent analysis of microstructure shown in Fig. 9. Clearly indicates that, at higher deformation temperatures coarser width of Bainitic sheaves was observed which becomes fine at lower forging temperatures. Decrease in deformation temperature results in fine width of sheaves and this helps to explain the increase in impact strength. Crack propagation is very slow in the presence of fine sheaves as

compare to the same for coarse Bainitic sheaves [11], [12]. Reduction in Bainitic sheaves width at lower deformation, a huge amount of strain energy accommodated by the material, by releasing this strain energy, thin plate form of Bainitic ferrite is obtained [10], [13].

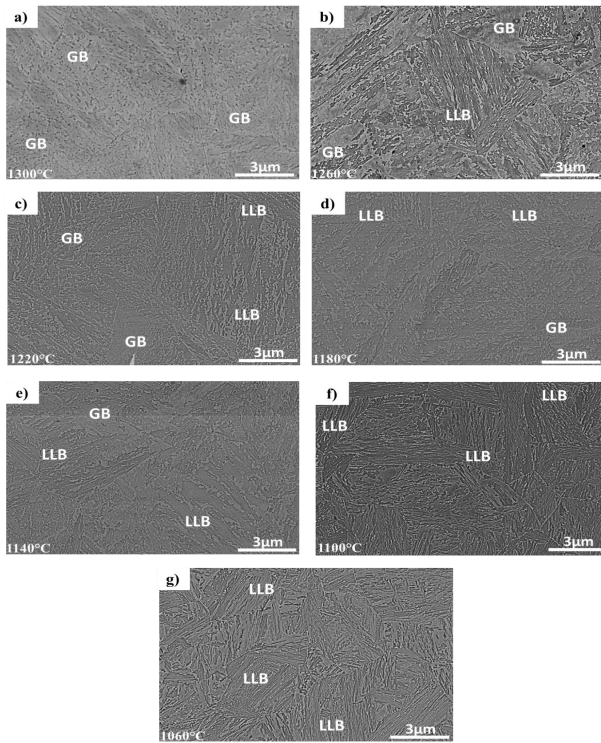


Fig. 8. SEM images of air cooled low carbon High strength steel deformed at a) 1300°C, b) 1260°C, c) 1220°C, d) 1180°C, e) 1140°C, f) 1100°C and g) 1060°C.

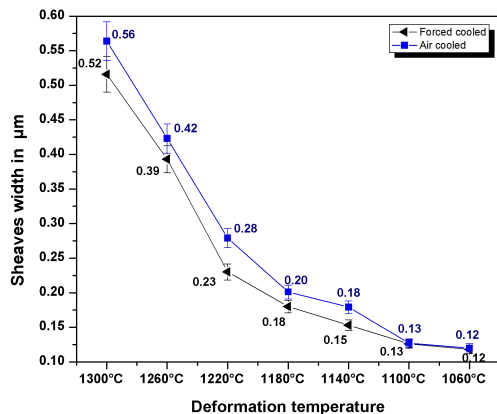


Fig. 9. Effect of hot deformation temperature on Bainite sheaves.

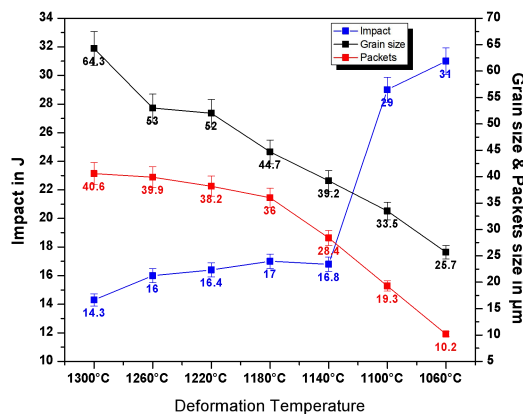


Fig. 10. Effect of hot deformation temperature on Grain size and packets of Bainitic steel.

Fig. 10 shows the prior austenite grain size and Bainitic packet size with respect to various forging temperatures. As deformation temperature decreases, smaller Bainitic packet sizes are observed which is because of refinement of prior austenite grain size. This also decreases Bainitic packets as well as width of sheaves which results in improvement in impact toughness [6], [7].

IV. CONCLUSION

Following can be concluded for the present work:

1. This change in microstructure was found to have no significant effect on the tensile properties and hardness properties of the HSS.
2. Change in bainite morphology is observed with different deformation temperatures (from 1300°C to 1060 °C). It is observed that deformation at higher forging temperatures leads to formation of granular bainite morphology while at lower deformation temperature lath-like bainite morphology is formed.
3. Transformation of lath-like bainite morphology results in decreased Bainitic packet size from 41µm to 10 µm. Similarly bainite sheaves thickness was reduced from 0.5 µm to 0.1 µm as the deformation temperature reduced from 1300°C to 1060 °C.
4. The change in microstructure has significant effect on the impact properties of the material. Increase in impact strength is observed, as the deformation temperature decreases from 1300°C to 1060 °C (impact toughness changes from 12J to 31J). Refinement of bainite packets and thinner bainitic sheaves eventually forming lath-like Bainitic microstructure contribute to improvement of the impact strength.
5. The change of cooling rate from natural air cooling to forced air cooling does not have any significant effect on the change in microstructural and morphological behavior of bainite.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

A Executed DOE, Collected and Analysed of data and wrote the technical paper; B, C Designed the DOE, Guided in analysis of data and checked the technical paper; D Guided in analysis of data and helped to reach final conclusion. Also reviewed and approved the technical paper.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the extended support provided to this work by KCTI (Kalyani Centre for Technology and Innovation) for providing financial funding, laboratory and library facilities. The authors also acknowledge the support provided by Bharat Forge Ltd, Pune and DSIR (Department of Scientific and Industrial Research), Govt. of India. I would like to express special thanks and gratitude to review committee and top management of Bharat Forge Ltd for granting the permission to publish/ present the research work. The authors are also thankful to the management of Defence Institute of Advanced Technology

(DU), Pune for providing all test facilities for research and publication.

We would also like to show our gratitude to Mr. Shreyas Kirwai (KCTI) for the comments that greatly improved the manuscript.

REFERENCES

- [1] R. W. K. Honeycombe and H. K. D. H. Bhadeshia, *Steels Microstructure and Properties*, 3rd ed., 2006, University of Cambridge, Elsevier Ltd, ch. 2, pp. 45-47.
- [2] H. K. D. H. Bhadeshia, *Bainite in Steels: Transformations, Microstructure and Properties*, 2nd ed., 2001, (Great Britain) Institute of Materials, ch. 2, pp. 45-47.
- [3] B. C. Muddle and J. F. Nie, *Formation of Bainite as a Diffusional-Displacive Phase Transformations*, Scripta Materialia, vol. 47, pp. 187-192, 2002.
- [4] T. Moritani, N. Miyajima, T. Furuhara, and T. Maki, *Comparison of Interphase Boundary Structure between Bainite and Martensite in Steel*, Scripta Materialia, vol. 47, pp. 193-199, 2002.
- [5] H. S. Fang, J. B. Yang, Z. G. Yang, and B. Z. Bai, *The Mechanism of Bainite Transformation in Steel*, Scripta Materialia, vol. 47, pp. 157-162, 2002.
- [6] A. D. Schino, I. Gutierrez, B. Lopez *et al.*, "Toughness and ductility improvement in complex microstructure HSS by means of microstructural parameters optimization (Mistreto)," in *Proc. European Commission, Directorate-General for Research*, 2010.
- [7] C. F. Wang, M. Q. Wang, J. Shi, W. J. Hui, and H. Dong, "Effect of microstructure refinement on the strength and toughness of low alloy martensitic steel," *J. Mater. Sci. Technol.*, vol. 23, no. 5, 2007.
- [8] T. Inoue, S. Matsuda, Y. Okamura, and K. Aoki, "The fracture of a low carbon tempered martensite," *Transactions of the Japan Institute of Metals, J-Stage*, vol. 11, no. 1P, pp. 36-43, 1970.
- [9] S. Chatterjee and H. K. D. H. Bhadeshia, "Phase transformations in steels," *Mater. Sci. Technology*, vol. 22, pp. 645-649.
- [10] L. Y. Lan, C. L. Qiu, D. W. Zhao, X. H. Gao, and L. X. Du, "Microstructural characteristics and toughness of the simulated coarse grained Heat affected zone of high strength low carbon bainitic steel," *Materials Science and Engineering A*, vol. 529, pp. 192-200, 2011.
- [11] F. G. Caballero, H. Roelofs, S. Hasler, C. Capdevila, J. Chao, J. Comide, and C. Garcia-Mateo, "Influence of bainite morphology on impact Toughness of continuously cooled cementite Free Bainitic steels," *Materials Science and Technology*, vol. 28, 2012.
- [12] C. Garcia-Mateo and F. G. Caballero, "Ultra-high-strength bainitic steels," *ISIJ International*, vol. 45, no. 11, pp. 1736-1740, 2005.
- [13] G. Krauss, "Martensite in steel: Strength and structure," *Materials Science and Engineering A*, vol. 40, pp. 273-275, 1999.

Copyright © 2020 by the authors. This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited ([CC BY 4.0](https://creativecommons.org/licenses/by/4.0/)).



Sandeep V. Kavathekar was born on March 22, 1984. He has completed the M.Tech in materials science and technology from Materials Engineering Department, Defence Institute of Advanced Technology (DIAT), Pune, Maharashtra in 2016. His major fields of studies are in hot deformation behavior of high strength steel, its effects on microstructure and mechanical properties of high strength steel.

He has eleven years of experience in Bharat Forge Ltd. Pune. Currently he is working as a deputy manager at Kalyani Centre for Technology & Innovation (KCTI), Bharat Forge Ltd., Pune, Maharashtra, India.



Vijay Hiwarkar was born on May 21, 1978. He has completed the PhD in metallurgical Engg and materials science from IIT Bombay, Maharashtra, India in 2011. Currently he is working as an assistant professor at Defence Institute of Advanced Technology (DIAT), Pune, Maharashtra, India. He has industrial experience in Global R&D Centre, Crompton Greaves. Ltd. Mumbai. (2010-2014)

His areas of research are in thermo-mechanical processing of metallic materials, texture and microstructure development in materials, electrical steels and electron backscattered diffraction.

Dr. Vijay Hiwarkar was awarded with the Best oral presentation in MR-08 in 2008, the cert. of recognition in creating intellectual wealth for CG by filing an Indian patent on the 10th In-house National Technology Day, Crompton Greaves Ltd in 2011, cert. of recognition in creating intellectual wealth for CG by filing an Indian patent on the 11th In-house National Technology Day, Crompton Greaves Ltd in 2012, cert. of excellence in recognition of nurturance at Crompton Greaves Ltd in 2014.



Vinayak P. Pawar was born on June 1, 1982. He has completed the M.Tech in materials, manufacturing and modelling from Mechanical Engineering Department, IIT Bombay, Mumbai, Maharashtra, India in 2011. His major fields of studies are in heat treatment, failure analysis, material characterization, surface coating, additive manufacturing, electron beam welding, friction stir welding, corrosion fatigue testing. He has 13 years of experience in Bharat Forge

Ltd. Pune. Currently he is working as a manager at Kalyani Centre for Technology & Innovation (KCTI), Bharat Forge Ltd., Pune, Maharashtra, India.



RKP Singh was born on July 2, 1947. He has completed the Ph.D. in formability behavior of extra deep drawing steel from IIT Madras, Chennai, Tamilnadu in 1993 and M Tech in ferrous process metallurgy steel from IIT Bombay, Mumbai, Maharashtra, India in 1974.

He has more than two decades of experience in manufacturing, research and development of materials. Currently he is working as the Sr. director at Kalyani Centre for Technology & Innovation (KCTI), Bharat Forge Ltd., Pune, India. Dr. Singh was awarded with figures in marquis book of "Who-is-Who in Science & Engg", figures in "2000 Outstanding Scientist of 21st Century" compiled by International Biographical Centre, Cambridge, England. He is a life fellow of Indian Institute of Metals, life member for ASME, ASNT, TMS and ISNT, member and Apex committee, prime minister's Ph.D. Program.