Improving the machinability of leaded free cutting steel through process optimization

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Abstract

Free cutting steel grades are high sulphur grades which can be classified under two categories as Leaded and Non-Leaded. These grades are used for manufacturing components like Nuts, bolts, studs, hydraulic fittings, brake pistons where higher machining is required to get intricate shape. Machinability of these grades are affected by hard oxide inclusions and highly deformed manganese sulphide inclusions. At JSW, machinability of leaded free cutting steel is improved by various process modifications namely deoxidation through carbon and manganese, Tellurium (Rare earth element) addition and maintaining the oxygen level at 80-120ppm. Former one avoids the formation of hard SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} compounds, Tellurium addition forms PbTe compound at the tail of MnS inclusions which resists the deformation of MnS inclusions and increased oxygen level favours the formation of less deformable oxy-sulphide inclusions. Above process modifications have resulted in achieving the low silicate content, better aspect ratio of MnS inclusions in the final rolled product. They are assessed by the characteristics of chip formation and surface roughness of machined part.

Keywords: Ladle metallurgy, MnS inclusions, Tellurium and Vacuum carbon de-oxidation

1. Introduction:

Factors influencing machinability of leaded and non-leaded free cutting steels like Surface finish, Tool life, cutting force and formation of small, stable built up edges on cutting tool [1-3] has been improved through process modification through Tellurium addition. Unless the Te/S ratio in free cutting leaded steels exceeds 0.07, Te exists in soluble form in MnS Inclusions [5]. Compounds of Te forms when Te/S ratio exceeds 0.07. Te is present in steels up-to 3% in MnS inclusions [6-11] or as compounds such as FeTe, MnTe and PbTe [12-13]. As-cast structure of leaded free cutting steels reveals mostly Fe-Te compound [6,12,13] with Pb-Te formation occurring during subsequent soaking and rolling [6,13]. Additionally, Te additions have made MnS inclusions more resistant to deformation during hot rolling and more globular [15-19] by forming a liquid envelope that could accommodate strains thereby improving the aspect ratio of MnS inclusion [11] that plays a prominent role for chip breakage.

Te being surface active in nature forms a thin film on the grain boundaries or at interface between steel and other non-metallic phases like carbides, MnS and tellurides [3]. Such distribution favours decrease in internal energy which reduces the resistance to shear. This leads to initiation of micro cracks that in turn reduces effective shear strength at tool metal interface during machining. Liquid metal embrittlement of Te and its compounds around their respective melting points generates micro
cracks thereby reducing shear strength and ductility [20-21]. Globularisation of MnS inclusions were found to be by Tellurium enveloping the MnS inclusions in form of compounds like Pb-Te and Mn-Te. Both compounds Pb-Te and MnTe - MnS eutectic have melting points 1356 deg C and 1469 deg C [15,24]. During rolling process, these compounds melt and form liquid phases which is found to accommodate higher strains during rolling and restrict deformations of sulphide inclusions [14]. Also presence of Tellurium being hard phase weakens the Inclusion-matrix interphase. This enhances the possibilities of void formation during rolling deformation by de-cohesion from matrix [25]. Strain during deformations are accommodated at these voids eliminating the deformation of MnS inclusions.

2. Process Optimisation

Chemical composition of free cutting steels produced at JSW is shown in Table 1. Heat No Z001, steel made through existing practise of deoxidation through Si and Mn. Heat No Z003, steel with process modification through Tellurium addition with Mn deoxidation. Heat No Z002, steel with process modification through Mn, and Vacuum Carbon deoxidation.

**Table 1. Chemical composition of Free cutting steels produced at JSW**

| Heat No | Grade     | C % | Si % | Mn % | P %  | S %  | Ti % | Pb % | Te % | O2 PPM |
|---------|-----------|-----|------|------|------|------|------|------|------|--------|
| Z001    | En1A Pb   | 0.07| 0.06 | 1.13 | 0.061| 0.28 | 0.0010| 0.23 | 0   | 60     |
| Z003    | En1A Pb_Te| 0.07| 0.02 | 1.15 | 0.062| 0.28 | 0.0019| 0.25 | 0.025| 104    |
| Z002    | En1A Pb   | 0.07| 0.01 | 1.05 | 0.062| 0.25 | 0.0014| 0.25 | 0   | 110    |

Process optimization is carried out with the various changes to the existing secondary steel making techniques to enhance the machinability of free cutting steel. It has been discussed in the following section,

2.1 Existing practice of deoxidation:

Free cutting steels are produced through the process route of primary steel making with energy optimizing furnace and secondary steel making followed by continuous casting. During secondary steel making the steel tapped from energy optimizing furnace is de-oxidized with Si-Mn which enables the formation of hard silicate inclusions (Refer Figure 2). These inclusions reduce the tool life drastically and sometimes cause the premature failure of tools. So a new way of making this kind of steel has been explored at JSWSL to make this steel suit for its intended application.

**Figure 1.** Micrographs showing silicate inclusions along with MnS
2.2 Process modification through Tellurium addition:

Heats are taken with Tellurium addition with modified VCD practise resulted with an Oxygen level of 104 PPM. Morphology of inclusions were studied through SEM in Backscattered mode. Pb-Te compounds were found to cling around the tail of MnS inclusions (Refer Figure 2). Pb-Te compounds resists deformations of MnS inclusions and volume fraction of Pb-Te is found to be higher than the Mn-Te.

**Figure 2.** SEM Micrograph of Process modified heat - En1APb with Te addition

2.3. Process modification through Vacuum Carbon Deoxidation Route:

Free cutting steels require higher oxygen content for better machinability. So, Si and Al levels are restricted to as low as possible to maintain higher oxygen in steel bath. At JSWSL, to achieve the above requirements steel refining is carried out through Mn and C deoxidation practise at low vacuum levels.

**Figure 3.** SEM Micrograph of Process modified heat - En1APb VCD Heat
3. Results and Discussions:
Experiments were done to study the effect of process modifications on the machinability of rolled products.

After primary steel making, primary deoxidation of steel is carried out through Fe Mn alloy additions followed by other alloys to meet the grade chemistry. This is followed by optimisation of Oxygen content in steel bath through de-oxidation practise by Carbon addition under Vacuum, as efficiency of O2 removal is higher at low vacuum levels. Heats treated by Vacuum Carbon Decarburisation practise was found to finish with higher levels of O2 PPM compared with heats with Si, Mn deoxidation (Refer Fig 4). Heats were analysed for nature of inclusions formed before Pb addition, after Pb addition.

![Figure 4. Comparison of Oxygen and Silicon levels in Free Cutting Steels at JSWSL](image)

Heats with Process modifications and existing heat were subjected to plunge tests at similar cutting speeds. The chips formed after machining were analysed (Refer Figure 6) to study the chip nature along with roughness of machined samples.

![Figure 5. Comparison of Roughness values of rolled samples after machining](image)

Heat Z001 processed through usual Si-Mn deoxidation practice resulted in continuous chips (Refer Figure 6). Chips from Z003 were found to be discontinuous with good curling nature. Heat Z002 also exhibited semi-continuous chip formation with comparatively high chip length to Heat Z003 without prominent curling chips (Refer Figure 6).
The inclusion samples from the rolled bars manufactured from the JSWSL heats were analysed and the observations are listed. (Refer Table 2)

**Table 2** Observation of inclusions in rolled product from JSWSL heats

| Heat Number | Nature of Process Modification | Inclusion Observation |
|-------------|--------------------------------|-----------------------|
| Z001        | Deoxidation primarily by Si    | Pb tailed MnS inclusions along with Silicate inclusions (Refer Fig 1) |
| Z002        | Te addition with deoxidation by VCD | PbTe compound at tail of MnS inclusions (Refer Fig 2) |
| Z003        | Deoxidation primarily by VCD   | Pb tailed MnS inclusions (Refer Fig 3) |

**Figure 6.** Comparison of Chips from different heats after machining

**Figure 7.** Elemental Mapping of Te added Heat - Z003
Elemental maps of Te added heat shows presence of PbS inclusions (Refer Figure 7 - Site A) along with MnS inclusions (Refer Figure 7 - Site B) with Te forming along the tail of MnS inclusions as an envelope.

Aspect ratio studies were done on the three heats to study the morphology of inclusions. Typical MnS inclusions were analysed through optical microscopy at 1mm from surface at 100X. Microstructural evaluation was also carried out in longitudinal direction to assess for the morphology of inclusions formed at core, mid radius and surface. Inclusions pertaining to Heat No: Z001 was found to have elongated inclusions with less globularity. Heat Nos: Z002 and Z003 were found to have globular inclusions. No significant morphology differences could be found between heats Z002 and Z003.

Table 3. Aspect Ratio of Inclusions of different heats

| Heat No | Grade     | Site Of Interest | No Of Inclusions (On Aspect Ratio Basis) | Aspect Ratio % |
|---------|-----------|------------------|----------------------------------------|----------------|
|         |           |                  | 1-6 | 7-10 | >11 | 1-6 | 7-10 | >11 |
| Z003    | En1APb_Te | Surface          | 22  | 1    | 0   | 96  | 4    | 0   |
|         |           | Core             | 19  | 0    | 0   | 100 | 0    | 0   |
| Z002    | En1APb    | Surface          | 22  | 3    | 1   | 85  | 12   | 3   |
|         |           | Core             | 14  | 3    | 1   | 78  | 17   | 5   |
| Z001    | En1APb    | Surface          | 17  | 5    | 1   | 74  | 22   | 4   |
|         |           | Core             | 13  | 5    | 1   | 68  | 26   | 5   |

4. Conclusions:

JSW has taken various trials through process optimisation for manufacturing free cutting steels. Three kind of processes were analysed in detail. In normal deoxidation practise heats, silicate inclusions were observed. In VCD heat, aspect ratio of inclusions was found to be better than normal deoxidation practise heat. In Te added heat, aspect ratio of inclusions is found to be better than other two heats with 96% of inclusions at surface and 100% inclusions at core are falling within an aspect ratio 1-6. Surface roughness values were also found better for Tellurium processed heat followed by VCD and normal deoxidation heat. Chips formation was found to be discontinuous with good curling tendency in heat with Te compared to VCD heat where chips were semi discontinuous with comparatively low curling to Te added heat. Both VCD and Te added heat exhibited low level of Silicate type inclusions thereby enhancing good machinability.
References

[1] S. Nakamura: Development of Production Process and Quality Improvement Free-Machining Steels, ISIJ, Tokyo, (1984), 187.

[2] R. A. Joseph and V. A. Tipnis: Influence of Metallurgy on Machinability, ASM, Chicago, (1975), U.

[3] R. H. Aborn: The Role of Metallurgy, Particularly Bismuth, Selenium and Tellurium in the Machinability of Steels, American Smelting and Refining Co., New York, (1968). – Compounds formed by Te, MnTe PbTe

[4] R. C. Spencer, C. D. Nagell and R. Richmond: Metal Prog., 82 (1962), Dec., 73.

[5] Li Daizhong, Gao Shuqin, Zhang Liefu, Wang Zeyu and Dong Xinquen: Steel Research (China), 56 (1985), 537.

[6] T. Malmberg, G. Runnsjo and B. Aronsson: Scand. J.Metall., 3 (1974), 169.

[7] T. B. Smith and D. B. Clayton: Nature, 198 (1963), 380.

[8] M. Hugo, J. Bellot, J. Frey and M. Gantois: Rev. Metall., 68 (1971), 397.

[9] D. Bhattacharya and D. T. Quinto: Metall. Trans. A, 11A (1980), 919.

[10] Li Daizhong, Gao Shuqin, Zhang Liefu, Wang Zeyu and Dong Xinquen: Steel Research (China), 56 (1985), 537.

[11] A. Josefsson: The 3rd Int. Symp. Industrial Use of Selenium and Tellurium, Selenium-Tellurium Devel. Assoc.Inc., Darien, CT, (1984), 148.

[12] W.J.M. Salter and F. B. Pickering: J. Iron Steel Inst., 205 (1967), 973.

[13] J. Bellot and M. Gantois: Trans. Iron Steel Inst. Jpn., 18 (1978), 536.

[14] E. Navara and K. Easterling: Metal Sci., 6 (1972), 211.

[15] T. Kato, S. Abeyama, A. Kimura and S. Nakamura: High Productivity Machining-Materials and Processes, ASM, New Orleans, (1985), 189.

[16] T. Araki, S. Yamamoto and Y. Uchinaka: Tetsu-to-Hagane, 54 (1968), 444.

[17] A. Hautmann: Stahl Eisen, 88 (1968), 62.

[18] J. Bellot and M. Gantois: Trans. Iron Steel Inst. Jpn., 18 (1978), 546.

[19] H. Ohtani, T. Hashimoto and Y. Kamada: Sumitomo Metals, 38 (1986).

[20] D. Bhattacharya: Embrittlement by Liquid and Solid Metals, ed. by M. H. Kamdar, TMS-AIMS, Warrendale, PA, (1984), 367.

[21] J. R. Rellick, C. J. McMahon, Jr., H. L. Marcus and P. W. Palmberg: Met. Trans., 2 (1971), 1492.

[22] Ward, R. G. (1962). An introduction to the physical chemistry of iron & steel making. Edward Arnold.
[23] Turkdogan E T and Fruehan R J 1999 *Fundamentals of iron and steelmaking* The Making, Shaping, and Treating of Steel vol. 2, ed R J Fruehan (Pittsburgh: The AISE Steel Foundation)

[24] K. Kishi and H. Eda: Wear, 38 (1976), 29

[25] H. F. Fischmeister, E. Navara and K. Easterling: Metal Sci., 6 (1972), 211.

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